# ORGANIC MATTER AND RICE

INTERNATIONAL
RICE RESEARCH
INSTITUTE

The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockefeller Foundations with the help and approval of the Government of the Philippines. Today IRRI is one of 13 nonprofit international research and training centers supported by the Consultative Group for International Agricultural Research (CGIAR). The CGIAR is sponsored by the Food and Agriculture Organization (FAO) of the United Nations, the International Bank for Reconstruction and Development (World Bank), and the United Nations Development Programme (UNDP). The CGIAR consists of 50 donor countries, international and regional organizations, and private foundations.

IRRI receives support, through the CGIAR, from a number of donors including:

the Asian Development Bank
the European Economic Community
the Ford Foundation
the International Development Research Centre
the International Fund for Agricultural Development
the OPEC Special Fund
the Rockefeller Foundation
the United Nations Development Programme
the World Bank

and the international aid agencies of the following governments:

Australia
Belgium
Brazil
Canada
Denmark
Fed. Rep. Germany
India
Japan
Mexico
Netherlands
New Zealand
Philippines
Saudi Arabia
Spain
Sweden
Switzerland
United Kingdom
United States

**ISBN 971-104-104-9**

# CONTENTS

## ORGANIC SOURCES OF PLANT NUTRIENTS

## DECOMPOSITION OF ORGANIC MATER
## IN WETLAND RICE SOILS

ORGANIC MATTER AND SOIL PHYSICAL PROPERTIES

ORGANIC MATTER AND PLANT GROWTH

MANAGEMENT AND EVALUATION OF ORGANIC MANURES
IN RICE-BASED FARMING SYSTEMS

# FOREWORD

The idea of *The International Conference on Organic Matter and Rice* was conceived in October 1980 in Beijing, China, at a meeting of Dr. Xiong Yi, director, Institute of Soil Science, Academia Sinica; Dr. Nyle C. Brady, then director general of the International Rice Research Institute (IRRI); and Dr. D. J. Greenland, IRRI deputy director general. The objective was to bring together agronomists, economists, fertilizer experts, organic chemists, plant nutritionists, and soil scientists to discuss the role of organic matter in rice production within the context of increasing fertilizer prices.

The plan was for China, the world’s largest user of organic manures, to consponsor the conference with IRRI. But because of Dr. Yi’s indisposition, IRRI organized the conference with financial assistance from the German Agency for Technical Cooperation (GTZ). The conference was held at IRRI, Los Baños, Laguna, Philippines, 27 September to 1 October 1982.

Ninety scientists from 15 countries participated in presentations, discussions and poster sessions, which covered: the potential of organic manures in rice production, organic sources of plant nutrients, decomposition of organic matter in wetland rice soils, organic matter and soil physical properties, organic matter and plant growth, and management and evaluation of organic manures. The consensus was that organic materials can play an important role in rice production, especially in fertilizer-deficient countries. The need for more information on the chemistry of organic processes in wetland soils and their effects on rice also emerged.

Dr. F. N. Ponnamperuma coordinated the conference activities. He was assisted by a committee consisting of Drs. S. K. De Datta, I. R. Fillery, D. J. Greenland, H. U. Neue, and I. Watanabe, and Mr. G. Alvez. Dr. Ponnamperuma also acted as technical editor of the papers. The volume was edited by Dr. Stephen Banta, assisted by Mrs. Corazon V. Mendoza.

I hope that this book will be a useful source of knowledge about what we know and what we do not know, and thereby help to set new research directions and to develop integrated soil health management systems.

M. S. Swaminathan
Director General

# POPULATION, RICE PRODUCTION, AND FERTILIZER OUTLOOK

R. W. Herdt and P. J. Stangel

In 1981 global consumption of fertilizer was just under 94 million t, having increased by 73% since 1971. Worldwide, N consumption was 60.4, phosphorus 13.4, and potassium 20.1 million t. Asia is the leading fertilizer-consuming region, having applied 25.6 million t in 1980/81, compared to North America's 19.1 and Western Europe's 16.1 million t. Rapid expansion in the production capacity of several Asian countries has enabled the production in the region to increase rapidly, but imports are still required in many countries, including India and China. Estimates indicate that the industry should be able to meet demand in the year 2000 with relatively little problem. Given current technology it is estimated that urea can be produced for under $300/t in developing countries that have natural gas, and for about the same cost in developed countries, even with natural gas costing twice the 1981 price of $2.75/million cubic feet. The world price of urea in 1982 was less than $200/t.

The likely level of rice demand and production was calculated for eight Asian countries using a policy model of the rice sector that permits examination of the impacts of alternative levels of irrigated land, fertilizer prices, fertilizer availability, and rice imports or exports. Using medium growth rate assumptions, population alone will increase the demand for rice by 37% between 1980 and 2000. The impact of income and population together will cause demand to grow by 55 to 65%. With reasonable expectations on the rate of growth of irrigated area and new rice technology, holding prices of fertilizer at their 1980 levels, about 50 million t of rice will have to be imported by the year 2000 to meet Asia's demand. If fertilizer prices double, the required level of rice imports will be about 20% higher. Thus, unless productivity of fertilizer, irrigation, and land can be improved, Asia will have massive rice deficits in the year 2000.

Fertilizer has become a major input into the world's food supply, especially over the past 20 years. According to FAO estimates, in 1960 world fertilizer consumption totaled 23 million t of nutrients, and by 1961 it had increased to 94 million t (FAO

---

Agricultural economist and head, Department of Agricultural Economics, International Rice Research Institute, P.O. Box 933, Manila, Philippines, and deputy managing director, International Fertilizer Development Center, P.O. Box 2040, Muscle Shoals, Alabama, 35660, USA.

1982). Although there are many ways to compute the production contribution of that fertilizer, using the rough rule of thumb of 10 to 1, the increase could have accounted for 710 million t of grain. Over the same period, world population grew from 3 to 4.4 billion (UN 1981). These global figures give some hint, but little real insight into the role of fertilizer in helping meet world food needs. Certainly fertilizer has been important, but of more interest is how important it is likely to be in the future, given today's agricultural technologies.

This paper will largely ignore the source of fertilizer and concentrate instead on how much fertilizer may be needed to produce the food required for the future. The first part reviews the world fertilizer situation, the growth in fertilizer use in major consuming areas, and the likely impact of rising energy costs of fertilizer production. The second part discusses the factors associated with success in meeting future demand for rice. The third part presents the results of an attempt to determine the conditions under which the demand for rice will successfully be met.

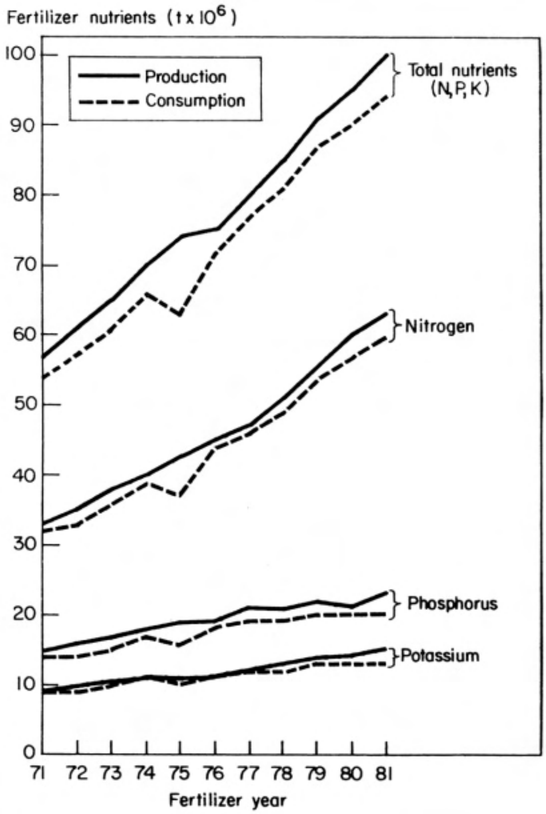
## FERTILIZER TRENDS AND FUTURE PROSPECTS

Both global production and global consumption of fertilizers have increased sharply since 1950 (IFDC 1979), not only because of technologIcal improvements in the production of fertilizer which have resulted in lower costs per unit of nutrient, but also because of the development of fertilizer-responsive cultivars of maize, wheat, and rice. North America, Asia, Western Europe, and the USSR dominate in the production of fertilizer, producing 64% of the world’s total in 1981. This included 69% of the nitrogen, 63% of the phosphorus, and 58% of the potassium. Production slightly exceeds consumption of each nutrient in most years, probably because of differences in reporting production and consumption, overformulation and overweights of fertilizers, unreported losses, use of fertilizer for nonfertilizer purposes, unreported inventories, and the necessity of having some fertilizer in the distribution system at all times. The actual excess varies, but has averaged about 5%, except in unusual market situations like 1974.

**Table 1. World fertilizer nutrient consumption, 1971-1981.**[a]

| Year[b] | Consumption (t × $10^3$) | | | |
|---|---|---|---|---|
| | N | P | K | Total |
| 1971 | 31842 | 8707 | 13615 | 54164 |
| 1972 | 33383 | 9293 | 14350 | 57026 |
| 1973 | 35771 | 9913 | 15328 | 61012 |
| 1974 | 38519 | 10648 | 16988 | 66155 |
| 1975 | 36801 | 10102 | 16222 | 63125 |
| 1976 | 43587 | 10747 | 17705 | 72039 |
| 1977 | 46103 | 11696 | 19042 | 76841 |
| 1978 | 49444 | 12114 | 19014 | 80572 |
| 1979 | 53674 | 13024 | 20277 | 86975 |
| 1980 | 57282 | 13210 | 19894 | 90386 |
| 1981 | 60381 | 13354 | 20132 | 93867 |

[a] Source: FAO (1981), IFDC (1982). [b] 30 June–1July.



**1.** World fertilizer production and consumption, 1970-80.

## Consumption

Global consumption of N, P, and K totaled only 11 million t in fertilizer year 1950 (1 July I949 to 30 June 1950). This climbed to nearly 23 million t by 1960, 54 million t by 1971, and just under 94 million t by 1981—a 750% increase in 30 years and a 73% increase since 1971 (Table 1).

Phosphorus was the dominant fertilizer nutrient worldwide in 1950, comprising 42% of total nutrients. By 1981 it had dropped into second place at 21%. Nitrogen is now the most important fertilizer nutrient consumed worldwide (Fig. 1). The dominance of N in most fertilizer markets has been steadily increasing, from 28% of total nutrients (N, P, and K) consumed in 1950 to 64% in 1981 (Table I). Nitrogen use has increased nearly 15-fold since 1950.

North America, Asia, Western Europe, and the USSR consume the major share of the world's fertilizer. Collectively, the nations in this group accounted for 79% of the fertilizer consumed in 1972 and 81% of the world total in 1981 (Table 2). Asia experienced major increases in fertilizer use during the 1970s and by 1980 had become the world center for fertilizer use. Eastern Europe accounted for 10% of the fertilizer consumed and Africa, Latin America, and Oceania (as a group) for another 10% of the world total in 1981.

**Table 2. World consumption of fertilizer nutrients by major region or country 1980/81.** [a]

| Major region or country | Consumption (t × $10^3$) | | | |
|---|---|---|---|---|
| | N | P | K | Total |
| Africa | 1,824 | 487 | 330 | 2,641 |
| Latin America (Mexico through Argentina) | 2,835 | 1,149 | 1,542 | 5,526 |
| North America | 11,604 | 2,444 | 5,007 | 19,055 |
| Asia | 21,254 | 2,290 | 2,029 | 25,573 |
| Western Europe | 9,474 | 2,361 | 4,238 | 16,073 |
| Eastern Europe | 4,846 | 1,375 | 2,727 | 8,948 |
| USSR | 8,262 | 2,089 | 4,070 | 14,421 |
| Oceania | 282 | 530 | 188 | 1,000 |
| World total | 60,381 | 12,725 | 20,131 | 93,237 |

[a] Source: FAO (1981), IFDC (1982).

Africa accounted for only 3% of world nutrient consumption in 1981. Its average use was only 13 kg/ha of arable land and permanent crops, well below the world average of 62 kg/ha in 1979 (Table 3).

Latin America accounted for 6% of world consumption in 1981. Average use of NPK in Latin America was 26 kg/ha or less than one-half of the world average in 1979.

North America is one of the centers of fertilizer consumption, accounting for 20% of the world total in 1981. Fertilizer use in the United States averaged about 91 kg/ha of NPK, about 47% above the world average in 1979.

Asia has emerged as the leading region in fertilizer consumption because of steady growth throughout the area, particularly in India and China. Total fertilizer use was 27% of the world total in 1981. Use of N accounted for 83%; use of P and K accounted for 9% and 8%, respectively. Average fertilizer use in Asia was 53 kg/ha, not much under the world average in 1979. Use of N per hectare was slightly above the world average, whereas the use of P and of K were well below the world average.

Historically, Western Europe had been the leading region in fertilizer use, holding this position as recently as 1972, when its nations consumed 13.5 million t of NPK or 24% of the world total. Western Europe still has the highest per-hectare use of fertilizer in the world, averaging 182 kg/ha in 1979. Some countries use extremely high levels, averaging double, and, in the case of the Netherlands, triple Europe’s average and 4-10 times the world average. However, in the 1970s, fertilizer use in Western Europe stagnated, showing only a 1.4% annual increase. Future changes in use will be highly dependent upon changes in economic conditions. Farmers are aware of the P and K reserves that have built up in soils in recent years and use them when economic conditions warrant. Present low prices for feed grains and food, coupled with a depressed economy, indicate that growth in N use will be moderate and that absolute consumption of P and of K are likely to decline.

## Key fertilizer countries

High prices of energy combined with the trend toward public ownership of the majority of the world’s ammonia capacity have a major effect on the structure of the fertilizer industry and particularly the N component (Harris and Harre 1979). Nowhere is this more evident than in the key producing and consuming countries of Asia, North America, and Europe.

Six countries (the United States, China, the USSR, India, the Netherlands, and Japan) accounted for 59% of world N production and consumption, 44% of imports, and 42% of exports in 1981. Three of these — the United States, the USSR, and China — account for half of world production and consumption and 30% of the exports and imports of N. Japan and the Netherlands, through minor producers and consumers of N, supply almost 15% of world exports and, therefore, play an important role in the international N trade. Obviously, events in any of these countries which influence N production or use will have a significant impact on N availability throughout the world. Therefore, some discussion of the specific situations in each of these countries is appropriate.

*Japan.* Starting in the mid-l960s, Japan began a deliberate plan to become the world's leading exporter of N. By the early 1970s Japan had reached a production capacity of more than 4.6 million t of ammonia per year with 75% aimed at the

**Table 3. Average fertilizer nutrient application per hectare[a] in regions of the world and in high-intensity countries, 1979.[b]**

| Region/country | Av application (kg/ha) | | | |
|---|---|---|---|---|
| | N | P | K | Total |
| Africa | 9 | 2 | 2 | 13 |
| Reunion | 94 | 43 | 80 | 217 |
| Mauritius | 91 | 10 | 115 | 216 |
| Egypt | 176 | 15 | 2 | 193 |
| North and Central America | 47 | 10 | 19 | 76 |
| Martinique | 108 | 40 | 90 | 238 |
| St. Lucia | 118 | 39 | 63 | 220 |
| St. Vincent | 141 | 13 | 49 | 203 |
| United States | 55 | 11 | 25 | 91 |
| Mexico | 35 | 5 | 2 | 42 |
| South America | 11 | 7 | 8 | 26 |
| Venezuela | 26 | 8 | 12 | 46 |
| Brazil | 13 | 12 | 15 | 40 |
| Colombia | 27 | 6 | 11 | 44 |
| Europe | 103 | 29 | 50 | 182 |
| The Netherlands | 564 | 43 | 119 | 726 |
| Belgium | 231 | 54 | 155 | 440 |
| Federal Republic of Germany | 197 | 54 | 133 | 384 |
| USSR | 32 | 11 | 16 | 59 |
| Asia | 43 | 6 | 4 | 53 |
| Japan | 158 | 74 | 125 | 357 |
| Republic of Korea | 199 | 43 | 72 | 314 |
| China | 106 | 9 | 2 | 117 |
| Oceania | 6 | 11 | 16 | 33 |
| New Zealand | 55 | 404 | 198 | 657 |
| New Caledonia | 50 | 22 | 50 | 122 |
| World | 40 | 9 | 13 | 62 |

[a] Includes arable land and permanent crops. [b] Source: FAO (1981).

export market. However, Japan has almost no oil or natural gas, the key raw materials of the N industry; thus, most of its raw materials have to be imported, and production is very sensitive to changes in the price of energy.

Rising costs of energy, coupled with large quantities of ammonia appearing in international trade from production units based on inexpensive natural gas, have placed great pressure on Japan's N industry, and many plants have been closed. As of August 1982, 1.7 million t of ammonia capacity per year has been permanently closed, some of which has also been dismantled. Japan may close an additional 1 million t of capacity by 1985, leaving it with 1.9 million t of capacity. This will serve a domestic demand for fertilizer of 0.7 million t, an industrial demand of 0.4 million t, and leave an export capability (including 0.2 million t of byproduct N) of about 0.5 million t of N. Should this occur, Japan will no longer be a major force in the N export market. This has strong implications for other countries in Asia, most notably China, as the majority of Japanese exports have in recent years been destined for China. In 1979 nearly all (90%) of Japan's urea and 50% of its ammonium sulfate exports went to China, and loss of this supply will almost certainly trigger a reshaping of the N sector in China as well as elsewhere in Asia.

*China.* China has surprised the world with the rapid advancements it has made in both N production and consumption. It is the world's leading consumer and third only to the United States and the USSR in N production. As a result of an ambitious program to install thirteen 1,000 t/day ammonia and companion urea units, China's production of N has risen dramatically in recent years (Feng 1982). Production of N in 1970 was estimated to be 1.5 million t. It climbed to nearly 10 million t by 1981. China reportedly has an additional 1 million t of N capacity under construction, due for completion before 1985.

Equally dramatic increases have occurred in N consumption, from 3.2 million t in 1970 to 11.8 million t in 1981. As a result, China, which imported nearly 1.8 million t in 1980 (mainly from Japan, the Middle East, Western Europe, and the United States), is likely to remain a major importer for the foreseeable future.

*India.* India has experienced a remarkable growth in its N sector over the past decade, although not as marked as that of China. Nitrogen use totaled 1.3 million t in 1970 and nearly tripled by 1981, reaching 3.5 million t. Preliminary estimates indicate consumption reached 3.7 million t in 1982. This represents an annual growth rate of over 15%. Analysts attribute this increase not only to favorable weather conditions but also to improved government policies that enhance availability and make it profitable not only for farmers to use fertilizer but also for industry to produce and distribute it. Current forecasts call for consumption to reach 7.4 million t of N by 1984/85 and 8.4 million t by 1987/88 (Pattel and Pandy 1982).

Production of N has also increased sharply over the past decade, from 0.8 million t in 1970 to 2.2 million t by 1981. This increase, however, was insufficient to meet demand and has required a steady increase in imports, which in 1981 reached 1.5 million t. These imports come mainly from Eastern Europe, the USSR, and Western Europe, with some also coming from Japan and the United States. Prospects are high that India will remain a major importer of N for the foreseeable future.

*The United States.* The US is the world's largest producer, exporter, and importer of N fertilizer, and is second only to China in N consumption. As a result, events that affect N production or consumption in the US have a strong impact on the N industry worldwide. Because of high costs of production, low prices, and stagnant consumption due to low farm prices of feed grains, a considerable portion (5.1 million t) of US N capacity was idle in 1982. These factors, coupled with the deregulation of natural gas prices (scheduled to be completed by 1985), which will raise feedstock costs in line with world energy prices, have made it unattractive to invest in new N facilities. While the US has historically been a net exporter of N, the current situation has changed such that it is likely to become a major net importer in 1982. Preliminary figures for the first quarter of 1982 indicate that the US had a net import balance of 400,000 t of N (TVA, private communication). The majority of these imports come from the USSR, the Netherlands, and Trinidad. Barring a major shift upward in the price of feed grains and fertilizer, the US is likely to remain a major net importer of N for at least the next 3-4 years. This could reach 1.5-2.0 t/year by 1984 should N consumption, which is now stagnant, resume its normal growth rate of 4-5%/year.

*The USSR.* The USSR has the world’s largest installed ammonia capacity, is second in N production, and is a major exporter of N fertilizer. Nitrogen production, which was 5.4 million t in 1970, climbed to 10.2 million t in 1981. Nitrogen consumption, which was 4.6 million t in 1970, also increased approximately 80% by the end of the decade and was nearly 8.3 million t by 1981. As a result of this growing surplus in production, the USSR has emerged as a significant exporter of N fertilizer, with exports totaling slightly more than 1 million t in 1981. This total export promises to increase sharply in the immediate years ahead as additional capacity (3.1 million t) comes onstream by 1984. A major share of these exports is destined for the US and Western Europe (mainly as ammonia) and India (as urea). While the main reason for the rapid expansion of its N industry is to help achieve self-sufficiency in feed grain production (some of the exported N is exchanged for P), domestic consumption of N has lagged behind government targets. This, coupled with the need for the USSR to earn foreign exchange to finance imports of feed grain and its ample supply of natural gas, leads to the conclusion that the USSR will be a major exporter of N.

*The Netherlands.* In recent years, the Netherlands has emerged as a major exporter of N fertilizers, with steady increases from 0.6 million t in 1971 to nearly 1.2 million t in 1981. It has been a major supplier of N to Western Europe, the US, and, more recently, to India and China. At least one new ammonia plant is expected to come onstream before 1985, and the Netherlands may fill part of the void left in international trade when Japan phases out of the export market. This may change should the Netherlands Government drastically alter its policy on feedstock prices to the export units.

## Fertilizer forecasts

Forecasting fertilizer use at a time when the entire fertilizer sector is in a state of flux is difficult. Political turmoil or an economic crisis in one or more of the leading fertilizer-producing or -consuming countries can cause a major change in growth rates and render meaningless the forecasts made before the disturbance. As uncertain as these forecasts are, however, they do serve as a guide for policymakers, marketing executives, and investors in developing plans for fertilizer development. Although several researchers have estimated fertilizer demand for various stages in the future, most have relied on those projections developed by the United Nations Industrial Development Organization (UNIDO 1978, 1980) of the Food and Agriculture Organization (FAO)/UNIDO/World Bank Working Group (FAO 1981c). Therefore, only forecasts from those two groups will be discussed here.

*Nitrogen consumption.* The Working Group estimated world N consumption to be 71.43 million t by 1985, whereas UNIDO (1978) estimated it to be 78 million t. The Working Group also estimated N use to be 85.95 million t for 1991. UNIDO (1978) estimated consumption to be 84.0 for 1988 and 145.5 million t for 2001. A later study (UNIDO 1980) forecast a lower figure for the year 2000 — 110 million t. Because of the present economic uncertainties in the world, the initial estimates by UNIDO (1978) are perhaps too high, particularly for the year 2000. Most probably future studies will lower these figures even further.

*Phosphorus consumption.* The recent decline in P consumption in Western Europe, Japan, and South Korea and the near static situation for the United States have made all but the most recent forecasts seem quite high. UNIDO (1978) estimated world P consumption to be 16.5 t for 1983, 19.9 t for 1988, and 33.5 million t for 2001. The FAO/UNIDO/World Bank Working Group (FAO 1981c) estimated P demand to be 15.8 t for 1983, 17.2 t for 1985, and 21.5 million t for 1991. Phosphorus consumption is becoming increasingly sensitive to crop-P fertilizer price ratios. Should these be favorable over the coming years, particularly in the developing countries, the consumption forecasts developed by the Working Group may prove to be conservative. On the other hand, if the present economic uncertainty in the world continues for some time, the Working Group's estimate (FAO 1981c) is probably quite accurate.

*Potassium consumption.* A recent forecast by the FAO/UNIDO/ World Bank Working Group (FAO 1981c) estimates consumption of K to be 25.5 million t in 1985 and 31.6 million t in 1991. The 1991 figure represents an increase of 11.6 million t or about 60% above the 1981 figure of 20.5 million t. An earlier UNIDO estimate (1978) forecast somewhat higher levels of consumption. These were 25.7 t for 1983, 33.1 t for 1988, and 55.5 million t of K for 2000. The UNIDO estimates were made when K prices were lower and crop-fertilizer price ratios were somewhat more favorable.

### Impact of energy costs on fertilizer costs

There is growing concern regarding the impact rising energy prices will have on the production costs and price of fertilizer. Mudahar and Hignett (1982) estimated the energy used in fertilizer production, distribution, and application during 1973 to be only 1.5% of the total commercial energy consumed in the world. While fertilizer consumes a relatively small portion of the world’s commercial energy, approximately 88% of the total energy consumed by the fertilizer sector is used for the production of fertilizer. The remaining 12% is used in its packaging, distribution, and application (Blouin and Davis 1975). Production uses approximately 90%, 50% and 50% of the total energy used to create and apply N, P, and K, respectively.

Urea, the most common N source for developing countries, is the most energy intensive of all fertilizers. The energy required to produce a 50-kg bag of urea is equivalent to that found in 58 liters of gasoline (Mudahar and Hignett 1982). This amount is 8.5 times the amount of the energy needed to produce triple superphosphate and 18.5 times the energy required to produce muriate of potash. Rising energy costs are likely to influence the feedstock costs and the capital requirements needed to produce fertilizer; their greatest effect is likely to be on N production.

*Feedstock costs.* Approximately 80% of the world's ammonia capacity uses natural gas as the feedstock. Naphtha and fuel oil — products of oil-refining processes — account for about 10% and 6%, respectively, of worldwide feedstocks. The proportion of world ammonia capacity based on natural gas is likely to increase because of its general availability and low cost compared to oil and its derivatives (Mudahar and Hignett 1982).

Several countries with large ammonia production capacities depend on naphtha or fuel oil for feedstock; naphtha contributes 61% in Japan, 48% in India, 100% in South Korea, and 69% in Turkey, while fuel oil contributes 30% in the Federal Republic of Germany, 54% in China, 15% in India, and 31% in Turkey. The rapid rise in oil prices has had a direct and immediate impact on these feedstocks, which are easy to transport and have a wide range of alternate uses. At 1982 naphtha prices, ammonia production based on naphtha is very expensive. Naphtha was selling for about $340/ t as of July 1982 (Table 4). On the basis that 0.9 t naphtha is required to produce 1 t ammonia, feedstock costs alone ($306/ t of ammonia) exceeded the July 1982 price of ammonia ($142/ t) by more than $160 (Green Markets 1982, European Chemical News 1982). Similar unfavorable production costs exist for ammonia plants using feedstocks based on imported fuel oil. These simplified calculations show that the recent rise in oil prices has rendered uneconomic most ammonia plants that use imported naphtha or fuel oil as their feedstock. These conditions explain why Japan has scrapped more than 1 million t of N capacity since 1975 and plans to close another 1 million t by 1985. The current difficulties of the N industry in South Korea stem directly from the high cost of its feedstock. Several countries of Western

**Table 4. Prices of bulk fertilizers and fertilizer raw materials, 1980-82.** [a]

| Product | Price (US$) | | | |
|---|---|---|---|---|
| | 1980 [b] | 1981 [b] | 1982 [b] | 1982 [c] |
| Urea | 158 | 195 | 145 | 127 |
| Ammonia | 140 | 135 | 142 | 142 |
| Ammonium sulfate | 65 | 94 | 86 | 77 |
| Phosphate rock | 36.50 | 42.50 | 40.00 | 32.00 |
| Phosphoric acid | 3.72 | 3.72 | 3.30 | 2.90 |
| Diammonium phosphate | 260 | 225 | 200 | 175 |
| Triple superphosphate | 190 | 197 | 142 | 137 |
| Muriate of potash | 106 | 115 | 95 | 72 |
| Sulfur | 122 | 132 | 110 | 110 |
| Naphtha | 400 | 360 | 320 | 340 |
| Natural gas | 1.96 | 2.33 | 2.90 | 2.95 |

[a] Source: Green Markets (1982). [b] Price as of 1 January. [c] Price as of 1 July 1982.

Europe have also had the same problem and have either closed their plants or converted them to use natural gas.

The price of natural gas varies widely throughout the world. In certain developing countries such as in the Middle East, the price of gas may be only the cost of a gathering system. In developed countries, where opportunity costs are high, the price on an energy-equivalent basis will most closely reflect that for imported oil. This is precisely the situation in Western Europe and what is emerging in the United States. Until recently the price of natural gas in the US had been set artificially low by the government, but the government is now in the process of deregulating the price and plans to have it fully decontrolled by 1985. As a result, natural gas prices have risen steadily since 1973 and have had a marked effect on production costs of ammonia plants. Natural gas feedstock costs were $13.68 for 1973, $43.32 for 1977, and $88.54/t for 1981. As long-term contracts signed in the early 1970s expire, new gas is available at feedstock costs alone ($152/t), which exceed the current international price of ammonia. A similar situation exists in a number of countries in Western Europe. Consequently, in the United States more than 5 million t of ammonia capacity is now idle and up to 2 million has already been dismantled (Tennessee Valley Authority 1982).

*Plant investment costs.* An indirect effect of rising energy costs is their impact on plant investment — particularly equipment costs — as well as on the cost of borrowed capital. Mudahar and Hignette (1982) estimated the capital costs of a 1,000 t/day ammonia and 1,700 t/day urea complex based on natural gas and constructed in the US in 1983 to be about $232 million. Only $47 million was required for a similar-sized plant built as recently as 1973. The estimated costs for constructing plants in developing countries are even higher; the World Bank (Sheldrick 1980) estimated total investment costs for a similar-sized plant to be $220 million for a developed site, $300 million for a developing site where some infrastructure exists, and $400 million for a developing country site at a remote location (Table 5).

*Realization price.* The term “realization price” is one used by financial institutions (Sheldrick 1980) in determining whether capital invested in a given project will have a return on investment comparable with that available from other markets. Applied to fertilizer facilities and current costs of capital, the realization price of a N facility is the price at which the new unit, if efficiently operated (90% of design capacity), will provide return on the capital invested comparable to other alternatives (currently 15-20%/year). It serves as a basis for deciding whether current or projected prices are likely to be sufficient to attract investments in fertilizer facilities. On the basis of investment costs of $220 million, $300 million, and $400 million for an ammonia urea complex built on sites in a developed country, in a developing country with some infrastructure in place, and in a grassroots location in a developing country, respectively, the realization prices for bagged urea were calculated at $252.43, $242.78, and $272.16 (Table 5). The current price of urea is $127/t, f.o.b. bulk US Gulf Coast (Table 4). Even with a $30/t allocation for bags and bagging, present prices are still well below the price needed to attract new investment. Of course, it is assumed that all investors (public or private) in fertilizer factories desire some return on their money.

**Table 5. Estimated investment, production cost, and realization price (1980 US$/t) for urea.**[a]

| Parameter | Developed site[b] | | Developing site | |
|---|---|---|---|---|
| | | | Some infrastructure | Grassroots – remote area |
| Total investment ($ $\times 10^6$) | 220.00 | 220.00 | 300.00 | 400.00 |
| Raw material costs | | | | |
| Gas price (Mcf) | 3.00 | 4.50 | 1.50 | 0.80 |
| Gas cost | 105.00 | 157.50 | 52.50 | 28.00 |
| Other variable costs/t | 16.00 | 16.00 | 16.00 | 16.00 |
| Fixed costs/t | 64.09 | 64.09 | 82.45 | 105.72 |
| Production costs/t | 185.09 | 237.59 | 150.95 | 149.72 |
| Capital charge (15%)/t | 67.34 | 67.34 | 91.83 | 122.44 |
| Realization price/t ex-factory | 252.43 | 304.93 | 242.78 | 272.16 |

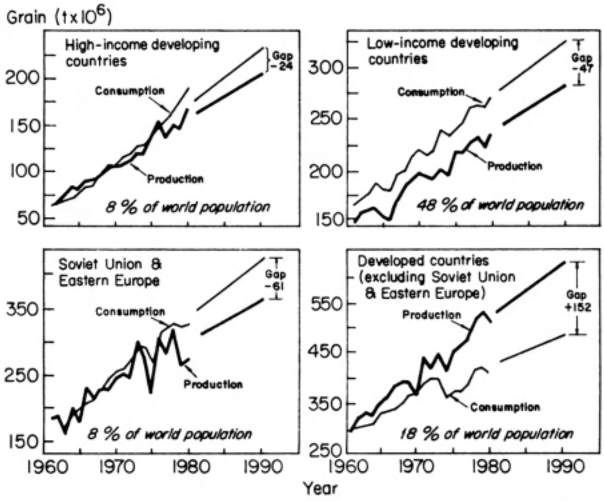
[a] Source: Sheldrick (1980). Basis: 1,000 t ammonia/day, 1,660 t bagged urea/day, operating at 90% capacity based on 330 days. [b] Based on gas prices of $3.00/Mcf and $4.50/Mcf.

Investors may not receive a commercially expected return on their money for plants built at developing sites because of the larger capital charges — $67.34/t for units built at a developed site, $91.83/t for those at a developing site with some infrastructure, and $122.44/t for those at a developing site with no infrastructure. The investors may not realize a reasonable return on invested capital since the capital charges for plants built in remote areas may be higher than any advantage gained through availability of cheap feedstock — a point frequently overlooked in some circles.

## PROJECTING THE ASIAN RICE SITUATION: A POLICY FRAMEWORK

A number of national and international organizations make projections of the demand and supply for food, or for particular food commodities, and the usual conclusion is that a deficit (or surplus) of a given amount will occur at some stated time in the future. These may be aggregated for countries within given regions and presented as in Figure 2. The term “deficit” is used in such projections to indicate the amount of food that would have to be supplied from some source other than domestic production of the countries included. Most such analyses recognize that projected deficits will be larger if incomes grow more rapidly than if they grow less rapidly because higher incomes mean higher demand for most foods.

This kind of projection does not suggest, however, that there will be a gap between the total quantity supplied and the total quantity consumed. Those two quantities, by definition, must always be equal. The interesting issue is how they are equated at any particular time and place. The differences between production and consumption shown in Figure 2 were filled through imports from other countries or regions. If the deficit in a country grows over time, the foreign exchange cost of meeting it with imports increases. That increase in foreign exchange cost may encourage national leaders to allow rice prices to rise to discourage domestic consumption and encourage domestic production.



**2.** Production and consumption of grain by major world region (Source: Barr 1981).

When rice prices rise relative to the cost of inputs like fertilizer, farmers are encouraged to increase production. Also, when rice prices rise, people consume relatively less rice, so supply and demand are equated at a higher price. If an increased rice price is intolerable, and if a country has the capacity, systems of rationing may be used to ensure that the quantity supplied is available to consumers at an acceptable price, even if a deficit might otherwise seem inevitable. If output grows more rapidly than the trend rate, then the projected deficit may be eliminated without raising prices or large imports. This is the condition that most countries would like to achieve and toward which they strive. On the other hand, if fertilizer becomes more expensive relative to food, farmers may use less of it, or at least slow down the rate of increase in use, and hence the rate of growth of food output may slow.

Thus the future rice situation depends on the rate of growth in rice demand, which in turn depends on population and income growth, the rate of growth in rice production, which is related to fertilizer use, and the acceptability of the resulting level of rice prices and imports.

To look at the future prospects for rice production and at the role fertilizer may play in meeting the demand for rice, we use a policy simulation model that has been developed to project the supply and demand for rice in the major rice-dependent countries of Asia. Through computer manipulation we measure the impact of different levels of important parameters and policy instruments on retail rice price (in real terms), rice imports, and direct government policy expenditures. This section outlines the concepts behind the model, presents the data used, and describes the main features of the projections for selected countries. The last section presents the results of the projections.

## Outline of the model

The essential nature of the model can be stated very concisely: demand and supply for rice are projected, and the resulting equilibrium price is computed. Demand is determined by growth rates of population and income. Production is determined by the area of land cultivated with various rice technologies (irrigation, cultivars, and fertilizer), while the use of each technology is determined partly by government policies and partly by farmer behavior. Supply is equal to production plus imports, where imports are determined by government policy decisions. The equilibrium market price for rice is the result of the fixed supply intersecting the sloping demand curve. In addition to rice production and price, the model internally determines the demand for fertilizer based on the relative rice/fertilizer price.

Three policy instruments are included in the model:

1. rate of growth of irrigated land,
2. price of fertilizer and the rate of growth of fertilizer availability (all available fertilizer need not be used), and
3. level of rice imports or exports.

Externally fixed variables include land available for rice, the rate of adoption of modern cultivars, the rates of growth of population and per capita income, the milling ratio, and the marketing margins. Target variables calculated by the model include the direct government financial cost of irrigation investment, fertilizer subsidy (or implicit tax), and rice imports. The policy problem is to achieve the desired level of rice supply and price while keeping the fiscal cost at a tolerable level. A five-year cycle is used. The model first simulates events for 1965,1970, 1975, and 1980; then projections are made for 1985,1990,1995, and 2000. The historical period is simulated in nominal prices while the projections assume constant real prices. More explanations of the details for individual countries are given after the general discussion of factors affecting demand and supply.

### Future demand for rice

The demand for rice in a country at some future time depends on: 1) the current level of demand, 2) the rate of growth of population, 3) the rate of growth of per capita income, 4) the income elasticity of demand for rice, 5) the price of rice relative to the prices of consumption substitutes for rice, 6) the direct and cross price elasticities of demand for rice, and 7) the tastes and preferences of a community.

It is difficult to simultaneously examine variation in all these factors. Also, it is impossible to project the availability and prices of consumption substitutes without a full model of the food sector of each country. That task is far beyond the space available here. Therefore, the availability and prices of consumption substitutes are assumed constant and omitted from further explicit mention. This also eliminates the need to explicitly consider the cross price elasticities. The demand for rice in a given country at a given point in time is found as:

$$D = aTY^{n}P^{e}$$

where $a$ = a constant term
$D$ = the demand for rice
$T$ = the total population
$Y$ = the per capita income
$n$ = the income elasticity of demand for rice
$p$ = the retail price of rice
$e$ = the price elasticity of demand for rice.

There is considerable uncertainty about the numerical value of each of these parameters. Historical data exist for population and income for most countries, although for some countries even the historical data may not be known with precision. Projecting future values is even more uncertain. Income and price elasticities can be estimated only by relatively sophisticated techniques, and the estimates that are available cover a surprisingly wide range.

*Population growth.* The most widely used population estimates and projections are those of the United Nations, which makes a range of projections based on individual country data. Because population growth is the most important factor affecting future demand for rice, slight differences in future growth rates will have a large impact on future demand. A simple projection of past population growth rates is likely to overstate the rate that will occur, because population growth rates have been changing in many countries. China and India had an average population growth rate of 2.1% per year between 1960 and 1970 and 1.9% between 1970 and 1979 (IBRD 1981). Bangladesh grew at 2.4% in the 1960s and at 3.0% in the 1970s;

Indonesia grew at 2.0% in the 1960s and at 2.3% in the 1970s. Other countries experienced similar changes.

The United Nations updated its projection of population in mid-1980 using information on changes occurring in fertility and mortality rates (UN 1981). Because population growth is the net difference between the birth and death rates, and because death rates tend to decline with development while birth rates tend first to rise and then to decline, population projections that reflect fertility and mortality trends are better indicators of future changes than are past rates of growth.

The medium population projection made by the UN shows that world population will increase to 6.1 billion in 2000 from its 1980 level of 4.4 billion. This implies that approximately 75 million additional persons per year will be added to the world's population. Most of this population increase will be concentrated in the world's less developed regions. The more developed regions are growing at 0.7% annually, a rate expected to decline to 0.4% per year in 2000. The less developed regions are growing at 2.1% per year, and are expected to be growing at 1.8% by the year 2000. Among the less developed regions, Africa is growing most rapidly, but Asia has the largest absolute size. Not only are populations growing more rapidly in the less developed countries, but there is greater uncertainty about how rapidly they are growing, as shown in Table 6.

The UN Department of International Economic and Social Affairs used national data, studies, and statistics that were available in mid-1980. Demographic estimates were prepared on the basis of available data on population, age and sex structure, and levels of fertility and mortality for different time periods. The method successively applied age - and sex-specific survival rates to the base year population to calculate the number of survivors in each age-sex category at the end of each 5-year period. The second step was to determine the number of births in each 5-year period by applying age-specific fertility rates to the corresponding number of women in each age class.

*Income growth.* The income concept that best reflects the factors influencing the demand for rice is personal disposable income, but statistics reflecting that concept are not available on a comparable basis for the countries of interest here. Gross national product (GNP) per capita is available for most countries and is the best usable measure, even though its accuracy is open to question for many developing countries. In any case, the absolute income level is not critical for the exercise because demand is estimated for past and future periods using a given definition of income.

Past rates of growth in GNP would seem to be the best indicators of future growth

**Table 6. Population projections for the year 2000.**[a]

| | 1980 | Low | Medium | High | High as % of low |
|---|---|---|---|---|---|
| World | 4432 | 5837 | 6118 | 6336 | 1.09 |
| More developed | 1131 | 1232 | 1272 | 1304 | 1.06 |
| Less developed | 3300 | 4604 | 4846 | 5032 | 1.09 |

[a] Source: UN (1981).

**Table 7. Growth rates of population and income, and elasticities of rice demand with respect to income and prices used in the base run for projecting the future rice situation.**

| | Projected growth rate of | | | Income elasticities | | | Used in base run | |
|---|---|---|---|---|---|---|---|---|
| | Population[a] | | Income cap[b] | USDA | FAO | IFPRI[c] | Income elasticity | Price elasticity |
| | 1985 | 1995 | | | | | | |
| *South Asia* | | | | | | | | |
| India | 1.73 | 1.49 | 2.0 | 0.3 | 0.4 | 0.45 | 0.45 | –.50 |
| Pakistan | 2.51 | 2.00 | 1.4 | 0.3 | 0.3 | 0.23 | 0.30 | –.60 |
| Bangladesh | 2.73 | 2.34 | 2.0 | 0.3 | 0.3 | 0.49 | 0.45 | –.50 |
| Sri Lanka | 1.91 | 1.39 | 2.1 | 0.3 | 0.4 | 0.46 | 0.40 | –.60 |
| Nepal | 2.33 | 2.17 | 0.5 | 0.3 | 0.3 | 0.08 | 0.20 | –.60 |
| *Southeast Asia* | | | | | | | | |
| Malaysia | 2.21 | 1.69 | 5.7 | 0 | | 0.05 | 0.05 | –.20 |
| Thailand | 1.97 | 1.57 | 5.3 | 0 | 0.2 | 0.03 | 0.03 | –.30 |
| Philippines | 2.31 | 1.93 | 3.5 | 0 | 0.2 | 0.25 | 0.25 | –.40 |
| Indonesia | 1.54 | 1.25 | 5.0 | 0 | 0.7 | 0.39 | 0.50 | –.60 |
| Burma | 2.31 | 2.00 | 2.0 | 0 | | 0.49 | 0.30 | –.40 |
| Vietnam | 1.99 | 1.70 | na | 0 | 0.4 | | 0.40 | –.40 |
| *East Asia* | | | | | | | | |
| Japan | 0.49 | 0.48 | 4.1 | 0.2 | –0.1 | | 0 | –.10 |
| Taiwan, China | 1.24 | 1.05 | 5.7 | 0.2 | 0.3 | 0.02 | 0 | –.10 |
| Korea, Rep. of | 1.49 | 1.29 | 8.4 | 0.2 | 0.3 | 0.01 | 0 | –.10 |
| China[d] | 1.24 | 1.06 | 2.0 | | | | 0.45 | –.50 |

[a] For the 5-year period beginning in the stated year (UN 1981). [b] Derived as the difference between 1970-79 average annual growth rate of GNP (from World Bank 1981) and projected 980-2000 population growth rate. [c] International Food Policy Research Institute for cereals. Their "high income growth" variant is shown. [d] Includes all provinces except Taiwan.

rates, although there are arguments to be made for expecting divergences from past rates in many circumstances. Available data show that the two big rice countries, India and China, had fairly constant growth rates of GNP during the 1960s and 1970s (World Bank 1981). Growth rates of GNP accelerated during the 1970s in Malaysia, the Philippines, Indonesia, Burma, and the Republic of Korea, while they slowed somewhat in Pakistan, Sri Lanka, Thailand, Japan, and North Korea. The growth rate for the 1970-79 period was used as the basis for projecting demand to the year 2000, so the projections reflect the rates of economic growth prevailing in the 1970s.

*Income and price elasticities.* A comprehensive set of income elasticities was generated separately by country and commodity by the FAO (FAO 1967) for their “Indicative World Plan,” prepared in the late 1960s (Table 7). The US Department of Agriculture (USDA 1971) made a projection of world food demand for which they used a set of price and income elasticities of demand for categories of countries and commodities. That set of parameters included cross elasticities between rice and wheat, which provide some basis for understanding the likelihood of substitution between the two commodities. More recently, the International Food Policy Research Institute (IFPRI 1977) has projected food demand for individual countries using income elasticities for cereals.

The USDA report classifies Asia into three groups of countries — South, Southeast, and East; the income elasticity of demand for rice in South Asia is given as 0.3, for Southeast Asia as zero, and for East Asia as 0.2. The FAO provides separate estimates for each country, with income elasticities ranging from –0.1 for Japan to 0.3 for the Republic of Korea, 0.4 for Burma, and 0.7 for Indonesia. The IFPRI estimates also cover a wide range — from less than 0.1 for Thailand, Malaysia, Korea, and Nepal to about 0.4 for Indonesia, Burma, India, and Sri Lanka.

Reviews of the research studies estimating income and price elasticities of demand for various foods have recently been completed for Indonesia (Dixon 1982), the Philippines (Bennagen 1982), and Thailand (Konjing, unpublished). Bouis (unpublished) conducted a new analysis of a large consumption data set for the Philippines. All these reveal a range of estimates for direct price elasticities of demand as well as income elasticities for rice. For example, in his review for Indonesia, Dixon finds a range in own price elasticities of –0.5 to –1.1 and a range of income elasticities of demand of 0.5 to 0.7, while Bennagen finds a range of price elasticity estimates of –0.3 to –0.5 and income elasticities of 0.1 to 0.2. Bouis finds considerable variation in demand parameters across income and regional groupings, but with average values very similar to those reported by Bennagen.

More importantly, these studies show that income elasticities are, in general, higher where incomes are lower and that they fall as incomes rise. Thus, in countries experiencing rapid economic growth two forces affect the demand for rice — the rising incomes mean that more rice is demanded, but as incomes rise to higher levels, the income elasticities fall. In 1980 only Japan had zero or negative income elasticity, but if incomes continue to increase rapidly in countries like the Republic of Korea and Malaysia, it is likely that their income elasticities for rice will decline to zero. These observations imply that using constant income elasticities to project future

**Table 8. Potential cultivable land compared with present cultivated land, by world regions.**[a]

| Region | Cultivated land 1970 (ha × $10^6$) | Cultivable land (ha × $10^6$) | Cultivated land per capita (ha) | Cultivable land per capita (ha) |
|---|---|---|---|---|
| South Asia | 197 | 195[b] | 0.27 | 0.27 |
| East and Southeast Asia | 72 | 115 | 0.22 | 0.36 |
| China | 111 | 113 | 0.15 | 0.15 |
| Other centrally planned Asia | 5 | 11 | 0.13 | 0.30 |
| South America | 87 | 540 | 0.45 | 2.84 |
| Central Africa | 29 | 169 | 0.80 | 4.69 |
| North America | 236 | 274 | 1.03 | 1.20 |
| Oceania | 45 | 70 | 3.00 | 466 |

[a] Source: Colombo et al (1978). [b] South Asia has extensive multiple cropping so the cultivated land may exceed the cultivable area.

rice demand will overstate that demand. It is especially important to recognize this when making long-term demand projections.

A conventional projections model would use the expected growth rates and income elasticities to compute the quantity demanded at some future date. However, the present model uses them to project the demand function, which together with estimated supply results in equilibrium prices. Table 7 shows the data used in the basic runs of the model for each country. There is a large degree of uncertainty about most of these numbers, but they are judged to be as good as can be obtained at this time.

## Future rice production

In the projections made here, information about the extent of adoption of critical technologies is used to determine the future potential for additional growth from such technologies. Production at any point in time is equal to area harvested times yield per unit area. Area can be increased either by developing new land, substituting rice for other crops, or using land being devoted to rice more intensively. Yields can be increased by improving irrigation and drainage, protecting crops more fully from pests, applying more nutrients, or improving crop husbandry. Potential yields can be raised by improving the genetic potential of the available cultivars.

*Potential for increasing rice area.* The potential for increasing the area planted to crops in Asia is very limited because of high land development costs, particularly where extensive resettlement, irrigation, and erosion control are required. Table 8 shows that by 1970 cultivated land was nearly equal to potentially cultivable land in South Asia and China. Cultivable land per capita is far less in Asia than in other parts of the world.

However, a significant part of the growth in rice output achieved during the 1960s and 1970s has in fact come from increasing area (Table 9). Even in the period from 1972 to 1977 China achieved an annual growth of 1.3% from land, while India obtained 0.9% annually from increasing area planted to rice. Much of this area was gained through multiple cropping, but some was obtained through increases in total arable land. Irrigation contributes importantly to multiple cropping, especially in areas with a distinct dry season. Because of the lack of data it is impossible to separate the cropping intensity effect of irrigation from the increases in cultivated land, but it is clear that both effects may continue, although at a declining rate. Based on the examination of changes in the past sources of output growth and the available data on multiple cropping and arable land, the authors have projected the maximum rates of growth in harvested rice area shown in Table 10.

India and Bangladesh are likely to have, at most, a continued slow expansion of rice area through the 1980s and 1990s. Bangladesh has a very large potential for expanding irrigated area. India has a moderately low average multiple cropping index (115) despite some areas with rather intensive systems. Bangladesh has a considerably higher multiple cropping index (140), but has a more pressing need to intensify further. Both countries are projected to have a slightly lower maximum rate of growth of area in the 1980s than they achieved in the 1970s. Pakistan has achieved a rapid growth in rice output mainly by expanding into areas not previously planted to rice. Its potential for continued expansion is considerable because rice is still a

Table 9. Growth rates of rice output and relative contributions of area and yield to output growth.[a]

| | 1967–1972[b] | | | | | 1972–1977[b] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Rate of output growth from | | | | | Rate of output growth from | | | |
| | Output growth rate | Irrigated land | Non-irrigated land | Fertilizer | Residual | Output growth rate | Irrigated land | Non-irrigated land | Fertilizer | Residual |
| *South Asia* | | | | | | | | | | |
| India | 3.1 | 0.5 | 0.2 | 2.0 | 0.5 | 2.9 | 0.5 | 0.4 | 3.0 | - 1.1 |
| Pakistan | 5.9 | 0.4 | 0.0 | 1.5 | 4.0 | 5.2 | 4.5 | 0.0 | 1.8 | - 1.1 |
| Bangladesh | -0.1 | 0.9 | -0.8 | 0.3 | -0.4 | 2.8 | 0.2 | 0.6 | 0.5 | 1.5 |
| Sri Lanka | 5.3 | 2.5 | -0.1 | 0.7 | 2.2 | 1.5 | 0.4 | -0.2 | 0.6 | 0.7 |
| Nepal | 2.0 | 1.2[c] | – | – | 0.8[d] | -0.4 | 0.8[c] | – | – | -1.2[d] |
| *Southeast Asia* | | | | | | | | | | |
| Malaysia | 7.3 | 5.4 | 0.2 | 0.9 | 1.0 | 1.5 | 0.9[c] | – | – | -0.6[d] |
| Thailand | 2.0 | 0.2 | 1.4 | 0.2 | 0.4 | 3.8 | 3.2[c] | – | 1.0 | -0.5 |
| Philippines | 3.1 | 0.6 | 0.0 | 1.8 | 0.5 | 5.8 | 0.7 | 0.8 | 1.0 | 3.2 |
| Indonesia | 4.8 | 1.9 | -0.5 | 2.2 | 1.2 | 3.3 | -0.9 | 1.7 | 1.5 | 1.0 |
| Burma | 1.1 | 0.4 | -0.1 | 0.2 | 0.6 | 2.7 | 0.3 | 0.4 | 0.8 | 1.2 |
| Vietnam | 3.7 | 0.8[c] | – | – | 2.9[d] | 1.1 | 1.6[c] | – | – | -0.5[d] |
| *East Asia* | | | | | | | | | | |
| Japan | -2.5 | -3.6[c] | – | – | 1.1[d] | 0.9 | -0.4[c] | – | – | 1.3[d] |
| Taiwan, China | -0.1 | -0.3 | -0.5 | -2.6 | 3.3 | 1.4 | 1.8 | 1.5 | 4.4 | 3.4 |
| Korea, Rep. of | 2.4 | 1.4 | -1.7 | 2.0 | 0.7 | 5.4 | 0.5[c] | – | 1.3 | 3.6 |
| Korea, DPR of | 5.0 | 1.8[c] | – | – | 3.2[d] | 6.2 | 1.4[c] | – | – | 4.8[d] |
| China[e] | 4.0 | 2.1[c] | – | – | 1.9[d] | 2.4 | 1.3[c] | – | – | 1.1[d] |

[a] Source: Barker and Herdt, forthcoming. [b] Calculated from 5-year averages centered on year shown. [c] Data not available to separate contribution of irrigated and nonirrigated area. This is contribution of all land. [d] Data not available to separate contribution of fertilizer. This is total contribution of yield. [e] Includes all provinces except Taiwan.

**Table 10. Maximum rates of growth in harvested rice area, 1980s and 1990s, Asia.**

| Area | Historical growth in harvested area[a] (%/yr) | | % of harvested rice area irrigated, 1975-1979 | Cropping intensity[b] | | Max rate of growth of harvested area | |
|---|---|---|---|---|---|---|---|
| | 1967-1972 | 1972-1977 | | Index | Year | 1980s | 1990s |
| *South Asia* | | | | | | | |
| India | 0.7 | 0.9 | 40 | 115 | 1965 | 0.7 | 0.5 |
| Pakistan | 0.4 | 4.5 | 100 | 110 | 1966 | 3.0 | 3.0 |
| Bangladesh | 0 | 0.8 | 12 | 140 | 1966 | 0.6 | 0.4 |
| Sri Lanka | 2.4 | 0.2 | 66 | 120 | * | 0.5 | 0.2 |
| Nepal | 1.2 | 0.8 | n.a. | 140 | * | 0.5 | 0.2 |
| *Southeast Asia* | | | | | | | |
| Malaysia | 6.3 | 3.8 | 67 | 140 | 1968 | 3.0 | 2.0 |
| Thailand | 3.3 | 3.3 | 24 | 100 | * | 3.0 | 2.5 |
| Philippines | 0.6 | 1.6 | 42 | 125 | * | 1.0 | 0.8 |
| Indonesia | 1.4 | 1.6 | 70 | 120 | 1964 | 1.5 | 1.5 |
| Burma | 0.3 | 0.7 | 17 | 111 | 1966 | 3.0 | 2.5 |
| Vietnam | 0.8 | 1.6 | | 130 | * | 1.3 | 1.0 |
| *East Asia* | | | | | | | |
| Japan | –3.6 | –0.4 | 98 | 126 | 1967 | 0 | 0 |
| Taiwan, China | –0.6 | 0.3 | 95 | 190 | 1966 | 0 | 0 |
| Korea, Rep. of | –0.3 | 0.5 | 92 | 153 | 1969 | 1.0 | 0.5 |
| Korea, DPR of | 1.8 | 1.4 | n.a. | 150 | * | 1.0 | 0.5 |
| China[c] | 2.1 | 1.3 | 95 | 147 | 1968 | 1.0 | 0.5 |

[a] Based on 5-year averages centered on years shown. Source: Palacpac 1982. [b] From Dalrymple 1971. For those countries marked *, the cropping intensity estimates have been arrived at by judgments of the authors. [c] Includes all provinces except Taiwan.

minor crop in Pakistan. Both Sri Lanka and Nepal had little growth from land in the 1970s, and it is likely that this will continue, although irrigation development in Sri Lanka could change the picture.

Both Malaysia and Thailand obtained more than a 3% annual increase in rice output from area growth during the 1970s. This relatively rapid rate is projected through the 1980s, but by the 1990s the availability of unused land will slow this source of growth. Thailand, with a rather small proportion of its area irrigated, has much scope for increasing its cropping intensity, but Malaysia exploited much of its irrigation potential during the past 2 decades. The Philippines obtained a 1.3% annual growth from increased land in rice during the 1970s, but the potential for a continuation of that rate of growth in the future is limited, and it will likely fall below 1%/year in the 1990s. Indonesia is having only moderate success with its transmigration program, which is intended to settle people on the extensive areas of unutilized land in the outer islands. Dalrymple (1971) estimated, however, that cropping intensity increased from 105 in 1955 to 120 in 1964 on Java. Therefore, it is possible that through transmigration, irrigation, and cropping intensification, Indonesia may be able to continue to increase rice area harvested at a maximum rate of 1.5%/year.

Based on its historical pattern it is difficult to project rapid increases in harvested rice area in Burma. However, the potential for increased irrigation is large, and the cropping intensity is still only around 110%. Therefore, it is estimated that Burma has the capacity to increase rice area harvested even more rapidly than in the past, given adequate investment in irrigation. Vietnam has a moderately high cropping intensity but achieved a rate of output growth of over 1.5% per year from land in the 1970s. A somewhat lower rate is projected.

Both North and South Korea obtained over 1%/ year increased output from land area increases during the late 1970s. Both have multiple cropping indices of about 150, suggesting that future growth from that source will be limited, especially in the light of the Korean climate. China obtained 2.3% annual output growth from area in the early 1970s and 1.3% during the late 1970s. China also faces a climatic limitation to increasing cropping intensity. In addition, China has effectively irrigated most of her rice land during the past 3 decades and had pushed her multiple cropping index to 150 on a national basis as a result of several mainland provinces having a cropping intensity equal to the 190 reached by Taiwan Province in 1966. Projecting a rate of output growth of l%/ year from land area in China, North Korea, and South Korea may seem too optimistic, but it is likely that these disciplined East Asian countries can achieve this level.

Japan and Taiwan Province of China present somewhat unique cases. Both have achieved a stage of development where rice production more than meets domestic demand and where domestic demand is expected to decline or grow only very slowly over time. Japan has large surpluses that are so burdensome that she has followed policies designed to reduce output; but Japan cannot export the rice because it is produced at a cost far above the world price. Taiwan Province is moving in the same direction. Thus, it seems to make most sense to simply project that Japan and Taiwan Province will be self-sufficient in the future but will not contribute to the rice available for import by deficit countries.

*Potential for increasing rice yields.* The possibility of increasing farmer's yields depends on the present level of yields and the technologically "potential" yield, both of which depend on the quality of the rice production environment, especially the area with irrigation and drainage. The present yield level depends on the extent to which farmers currently use fertilizer and fertilizer-responsive cultivars. Fertilizer and modern cultivar adoption are, in turn, related to the extent and quality of irrigation. The technologically potential yield can be pushed up with research, but there are physiological limits to the process that science has not yet overcome. The present technologically potential yield, represented by yields commonly achieved on experiment stations, is well above average national yields in the South and Southeast Asian countries, leaving an adequate exploitable gap. Only in East Asia do actual national yields approach their potential level, and in China this may be a serious factor limiting future production growth.

Modern cultivars have a significantly higher yield potential than traditional cultivars, and that advantage is most pronounced when they are grown on high-quality (irrigated) land with fertilizer. Traditional cultivars also benefit from irrigation and modest amounts of fertilizer, though. Much of the output growth achieved during the past two decades can be traced to the use of these inputs, and foreseeable continued yield growth will depend, to a large extent, on the remaining potential to exploit these sources.

*Irrigation.* Irrigated rice land is the result of deliberate government decisions to invest in irrigation construction and improvement, but creating irrigated land is expensive, and hence governments and their financiers, the development banks, seek to expand irrigated land no more rapidly than is needed to meet requirements. Irrigation is usually so advantageous for farmers that it is automatically used when made available.[1] Thus, the rate of growth of irrigated land depends on national policy decisions in most countries.

*Fertilizer.* The use of fertilizer is much more dependent on individual farmer decision than irrigation. Governments can encourage fertilizer production or ensure that fertilizer is imported, and governments can set fertilizer prices, but farmers decide how much fertilizer they will use within the limits of availability and its profitability on rice. Fertilizer used on rice in Asia increased substantially during the 1970s, according to the available information (Table 11). Its use has increased especially rapidly where irrigation has been available and modern cultivars have been used.

The increase in fertilizer use reflects a process of adoption — that is, farmers become aware of, learn about, experiment with, and then habitually use fertilizer. When all farmers have gone through the process and have arrived at their equilibrium application level, adoption is complete. Hence one cannot simply project a linear growth rate into the future. Given a technology, once farmers reach an optimum level of use, growth in fertilizer will slow drastically. Better irrigation and more responsive cultivars have the effect of maintaining high response ratios at higher levels of input, but at some level there will be no more response to added

---

[1] A possible explanation to this observation is the situation where the cost of the irrigation exceeds its value and farmers are made to pay the full cost. However, such uneconomic projects are usually screened out during the project selection stage.

**Table 11. Levels of irrigation, modern cultivars, and fertilizer used on rice in Asia, 1960s and 1970s.[a]**

| Location | 1965–69 Irrigation (% area) | 1965–69 Modern cultivars (% area) | 1965–69 Fertilizer[b] on rice (kg/ha) | 1975–79 Irrigation (% area) | 1975–79 Modern cultivars (% area) | 1975–79 Fertilizer[b] on rice (kg/ha) |
|---|---|---|---|---|---|---|
| *South Asia* | | | | | | |
| India | 38 | 7 | 13 | 40 | 37 | 40 |
| Pakistan | 100 | 10 | 13 | 100 | 46 | 43 |
| Bangladesh | 7 | 2 | 3 | 12 | 16 | 8 |
| Sri Lanka | 61 | 1[c] | 36 | 66 | 56[c] | 67 |
| *Southeast Asia* | | | | | | |
| Malaysia | 65 | 3[c] | 57 | 67 | 18[c] | 69 |
| Thailand | 28 | 0 | 6 | 24 | 10 | 11 |
| Philippines | 40 | 22 | 14 | 42 | 70 | 36 |
| Indonesia | 65 | 3 | 11 | 70 | 55 | 41 |
| Burma | 15 | 1 | 3 | 17 | 12[c] | 8 |
| *East Asia* | | | | | | |
| Japan | 100 | 100 | 286 | 100 | 100 | 340 |
| Taiwan, China | 100 | 100 | 218 | 100 | 100 | 246 |
| Korea, Rep. of | 84 | 0 | 143 | 92 | 51[d] | 216 |
| China[e] | 89 | 16 | 24 | 89 | 66 | 49 |

[a] Sources: Modern cultivars data from Herdt and Capule, unpublished. Fertilizer and irrigation data from Palacpac 1982. [b] In nutrients (N + P + K); chemical sources only. [c] Narrow definition of modern cultivars. [d] % in indica-japonica crosses. [e] Includes all provinces except Taiwan; data are assumptions as spelled out in Barker and Herdt (n.d.).

fertilizer (i.e., marginal returns diminish to zero). As a result, fertilizer use may increase very rapidly over an initial period until most farmers are applying the level that provides the initial high yield responses; after that further increases will be slow.

After farmers become familiar with fertilizer use and reach an equilibrium level, the price of fertilizer relative to the price of rice becomes an important factor determining changes in use. Therefore, in the projection model used here, both the process of adoption and the optimum economic level are considered.

The spread of modern cultivars, like initial fertilizer use, is an adoption process. Farmers experiment with and evaluate the new cultivars under their conditions; if found suitable, the new cultivars are adopted. Experience with available modern cultivars has shown that they are more rapidly and widely adopted by farmers who have irrigation, and hence one would expect them to spread as irrigation expands.

To reflect the diminishing marginal returns to fertilizer and the complementarity of modern cultivars, fertilizer, and irrigation, four different fertilizer response curves have been used in projecting future production. These curves define the yield response of modern cultivars with irrigation, modern cultivars without irrigation, traditional cultivars with irrigation, and traditional cultivars without irrigation. Differences in the proportion of area in the four types will result in differences in the total fertilizer used and in the average rice yield in the country. Hence, increases in irrigated area or adoption of modern cultivars will result in greater total use of fertilizer even with constant prices.

The precise fertilizer response curves for each country have been adjusted slightly to reflect the following conditions in each country: average national rice yields, fertilizer application rates on rice, proportion of land of various qualities, and changes in these factors over time. The equations on which the response functions for each country are based are the following ones presented by David and Barker (1978), based on an extensive review of experimental results:

Modern cultivars in irrigated fields:

$$Y = 2100 + 18N - 0.19N^2$$

Modern cultivars in rainfed fields:

$$Y = 1400 + 15N - 0.11N^2$$

Traditional cultivars in irrigated fields:

$$Y = 2100 + 11N - 0.13N^2$$

Traditional cultivars in rainfed fields:

$$Y = 1400 + 9N - 0.16N^2$$

While these fertilizer response functions appear to reflect rather low levels of efficiency, the authors believe they do, in fact, reflect the levels obtained on a nationwide basis, at least in many countries of South and Southeast Asia. Aside from the fact that they were based on examination of a large number of fertilizer response functions, it can be shown that if the response curves were substantially higher than shown, predicted national rice production would have been higher than it was in 1975 and 1980 in all of the countries for which fertilizer-use data are available. Of course, in countries where little is known about how much fertilizer is applied on rice, the estimates may be quite different.

**Table 12. Projected demand for rice (unmilled) in the year 2000 with zero, high, and medium rates of income growth and specified income elasticities.**

| Country | 1980 demand[a] | Projected demand ($t \times 10^3$) with income growth rate[b] | | | % change with medium |
|---|---|---|---|---|---|
| | | Zero | High | Medium | |
| China | 138,007 | 183,367 | 212,432 | 206,478 | 50 |
| India | 79,552 | 110,430 | 129,451 | 125,147 | 57 |
| Indonesia | 33,105 | 43,430 | 68,495 | 59,488 | 114 |
| Bangladesh | 21,455 | 32,513 | 39,488 | 36,988 | 73 |
| Thailand | 14,119 | 20,632 | 21,487 | 22,341 | 39 |
| Burma | 9,166 | 13,353 | 15,228 | 14,578 | 39 |
| Philippines | 7,042 | 10,688 | 12,509 | 12,387 | 58 |
| Sri Lanka | 3,033 | 3,429 | 4,119 | 4,009 | 56 |
| Total of above | 305,389 | 417,842 | 503,099 | 481,526 | 58 |
| Total Asia | 360,765 | 493,609 | 594,326 | 570,008 | 58 |

[a] Production + imports – exports. [b] Income elasticities shown in Table 7 except in the case of Indonesia, where the income elasticity was assumed to decline from 0.5 in 1980 to 0.1 in 2000.

## RESULTS BASED ON SELECTED COUNTRIES

Results have been obtained for eight countries that produced 85% of Asia's rice in 1980 on 88% of Asia's rice land. Table 12 shows the countries, their rice demand in 1980, and selected projections of demand. Although some important countries are omitted from the exercise, the range of conditions included is broad enough to reflect what is likely to happen in Asia as a whole.

If per capita incomes do not grow, population alone will generate an increased demand of about 37% between 1980 and the year 2000. This result is dominated by the rather modest population growth rate expected in China (1.3%/year by 1985). A high rate of per capita income growth will result in about a 65% increase in demand, only slightly higher than the 58% increase in demand expected with a medium income growth rate. The bottom line shows the projected demand if one assumes that demand growth in the other countries of Asia is similar to these. It indicates that the demand for rice in Asia in the year 2000 is likely to be about 570 million t.

Table 13 shows selected variables from the projections made with two sets of assumptions about input availability reflecting medium and fast rates of output growth. In the medium projections, irrigated area is assumed to grow at approximately the historical rate, and fertilizer availability to grow at about 5%/year. The two projections for China are similar because the assumption was made that total rice area could not be expanded any faster than 1%/year during the 1980s and 0.5%/year during the 1990s. Because over 90% of China's land is already irrigated, there can be little increase in cropping intensity from that source. Fertilizer use in China is projected to reach a rather high level in both cases even though in the fast growth case hybrid rice is projected to spread more rapidly, and it has a higher capacity to productively absorb fertilizer.

The medium projection for India reflects the past rate of growth in irrigated area of 1.1%/year and a nearly constant total area of rice. Fertilizer use reaches an average of 67 kg/ha over all land qualities with the medium growth projections. A faster rate of irrigation and fertilizer growth gives a substantially higher level of output with a somewhat higher level of fertilizer use.

The increases in area harvested are obtained because of investment in irrigation which makes possible 2 rice crops/year from a fraction of irrigated area. In most countries 30% of the newly irrigated area is assumed to produce 2 rice crops/year.

The fast rates of growth reflect about a doubling of historical irrigation growth rates except in China, where all the potential area is nearly utilized. More fertilizer is also made available and used in most cases in the fast projections. In the case of Thailand, fertilizer is applied at relatively low average rates, because even with a 3.3% rate of growth of irrigated area about 50% of the area is still rainfed and uses no fertilizer.

Table 14 summarizes the production projections and import requirements needed to maintain a stable real price of output in each country. It is evident that even with the rapid rates of growth implied by the fast projections, most countries in the region will either have to improve their productivity or import or suffer significant price increases despite the rather substantial increases in area planted to modern cultivars, the high proportion of irrigated land, and the increased levels of fertilizer used.

**Table 13. Results of projection on medium and fast rates of rice output growth to the year 2000, rice and fertilizer prices, held constant at 1980 levels through imports.**

| Country | Medium projection | | | | Fast projection | | | |
|---|---|---|---|---|---|---|---|---|
| | Rice output ($t \times 10^6$) | Growth rate (%/yr) | | Fertilizer nutrients (kg/ha) | Rice output ($t \times 10^6$) | Growth rate (%/yr) | | Fertilizer nutrients (kg//ha) |
| | | Area | Irrigated | | | Area | Irrigated | |
| China[a] | 196.1 | 0.2 | 0.2 | 148 | 207.0 | 0.4 | 0.4 | 138 |
| India | 99.5 | 0.2 | 1.1 | 67 | 114.8 | 0.3 | 2.1 | 80 |
| Indonesia | 34.1 | 0.6 | 1.2 | 89 | 46.2 | 1.6 | 2.3 | 108 |
| Bangladesh | 28.7 | 0.4 | 2.5 | 32 | 34.2 | 0.5 | 6.3 | 69 |
| Thailand | 23.8 | 0.9 | 2.3 | 25 | 25.0 | 0.9 | 3.3 | 31 |
| Burma | 14.7 | 1.1 | 2.5 | 71 | 16.5 | 1.2 | 5.0 | 83 |
| Philippines | 9.6 | 1.1 | 1.3 | 61 | 11.5 | 2.0 | 2.5 | 63 |
| Sri Lanka | 3.1 | 0.9 | 2.5 | 102 | 4.3 | 2.3 | 3.0 | 107 |

[a] Fast rate differs in having more fertilizer available and a faster rate of adoption of hybrid rice.

**Table 14. Production and imports of rice and changes in factors affecting production as projected for the year 2000, rice and fertilizer prices constant at their 1980 levels.**

| | Medium projection | | | | Fast projection | | | |
|---|---|---|---|---|---|---|---|---|
| | Output[a] | Imports[b] | % area | | output[a] | Imports[b] | % area | |
| | (t × $10^6$) | | Mod cult | Irrig | (t × $10^6$) | | Mod cult | Irrig |
| China | 196.1 | 9.0 | 65[c] | 94 | 207.0 | 0 | 82 | 94 |
| India | 99.5 | 13.0 | 68 | 51 | 114.8 | 6.4 | 82 | 61 |
| Indonesia | 34.1 | 12.7 | 74 | 84 | 46.2 | 7.4 | 75 | 86 |
| Bangladesh | 28.7 | 5.6 | 63 | 24 | 34.2 | 3.1 | 66 | 47 |
| Thailand | 23.8 | –0.4 | 18 | 41 | 25.0 | –0.9 | 22 | 49 |
| Burma | 14.7 | –1.0 | 65[d] | 21 | 16.5 | –0.2 | 83[d] | 33 |
| Philippines | 9.6 | 1.3 | 89 | 52 | 11.5 | 0.4 | 89 | 57 |
| Sri Lanka | 3.1 | 0.8 | 73 | 66 | 4.3 | 0.3 | 80 | 71 |
| Total/av | 409.5 | 41.1 | 64 | 54 | 459.6 | 17.7 | 72 | 62 |
| Total Asia[e] | 481.8 | 48.4 | – | – | 540.7 | 20.1 | – | – |

[a] Rough rice. [b] Milled rice, negative sign indicates exports. [c] Hybrid rice. [d] Includes modern and improved cultivars. [e] Assuming the countries listed account for 85% of Asia's production and imports.

**Table 15. Impact of a doubling of fertilizer price on projected fertilizer use and rice production in the year 2000, assuming imports to hold real rice price fixed at 1980 level.**

| | 1980 price ratio Fert:Rice | With low price | | | Doubling fertilizer price | | |
|---|---|---|---|---|---|---|---|
| | | Rice produced ($t \times 10^6$) | Fertilizer use ($t \times 10^3$) | Fertilizer use (kg/ha) | Rice produced ($t \times 10^6$) | Fertilizer use ($t \times 10^3$) | Fertilizer use (kg/ha) |
| China | 4.9 [a] | 196.1 | 5519 | 148 | 185.1 | 4219 | 112 |
| India | 3.1 | 99.5 | 2767 | 67 | 96.6 | 2156 | 52 |
| Indonesia | 2.2 | 34.1 | 938 | 89 | 33.1 | 738 | 70 |
| Bangladesh | 2.5 | 28.7 | 552 | 50 | 31.5 | 648 | 57 |
| Thailand | 6.0 | 23.8 | 286 | 25 | 22.1 | 98 | 9 |
| Burma | 1.0 | 14.7 | 444 | 91 | 14.6 | 411 | 87 |
| Philippines | 4.5 | 9.6 | 243 | 61 | 9.0 | 157 | 39 |
| Sri Lanka | 1.7 | 3.1 | 95 | 102 | 4.3 | 119 | 96 |
| Implied total Asia | | 481.8 | 12756 | – | 466.2 | 8631 | – |

[a] From urea, which has a somewhat higher price than the common form of N from ammonium bicarbonate.

Substantial costs are involved in reaching the output levels reflected in these projections. Fertilizer use is projected to expand from 6.13 in 1980 to 12.76 million t (nutrients) by 2000. This figure, of course, represents only the fertilizer used on rice and so cannot be directly compared with total available fertilizer. Investment in irrigation necessary to achieve the "fast" output growth is estimated at over $2 billion year over the period.

The projected rates of fertilizer use in these countries for the year 2000 are rather modest in comparison with the rates used in Japan and Korea in 1980. This is because the fertilizer productivity achievable in the South and Southeast Asian countries is low compared with that in East Asia. If researchers achieve their goal of understanding how to use fertilizer more efficiently in tropical rice production, perhaps the optimal rates of use may be profitably increased and domestic production can move above the levels indicated in Tables 13 and 14.

On the other hand, if real fertilizer prices rise, the rates of application are likely to drop substantially, thereby reducing rice output. Table 15 shows the impact a doubling of the fertilizer price has on the projections. Fertilizer demand is projected at 8.1 million t of nutrients as compared with 12.9 million t with 1980 prices. Rice production is projected to increase to 455.4 million t compared with 464.7 million t with the low fertilizer price. Thus, another 6.2 million t of milled rice in addition to the 54.7 million t shown in Table 14 would have to be imported to hold rice prices at their 1980 levels.

The weight of these projections indicates that it will be difficult to meet demand for rice in the year 2000 with the technology of today, even with very large investments in irrigation and with rapidly increasing availability of fertilizer. In fact, the capacity of the rice crop to effectively utilize high rates of fertilizer in the tropics will limit the growth possible from that source. Unless a way is found to continuously and substantially increase the productivity of land, water, and fertilizer in tropical rice production, the surpluses that a number of countries have in 1982 will disappear by the mid-1980s and will turn into large shortages by the 1990s.

## REFERENCES CITED

Barker, R., and R. W. Herdt. The asian rice economy, manuscript under preparation.

Barr, T. N. 1981. The world food situation and global grain prospects. Science 214:4525, 4 December.

Bennagen, E. C. 1982. Staple food consumption in the Philippines, Working paper no. 5, Rice Policies in Southeast Asia Project, IFPRI, Washington, D.C.

Blouin, G. M., and C. H. Davis. 1975. Energy requirements for the production and distribution of chemical fertilizers in the U.S. Pages 51-67 *in* Energy in agriculture, proceedings of a conference sponsored by the Southern Regional Education Board, 1-3 October 1975, Atlanta, Georgia.

Bouis, H. Rice Policy in the Philippines. Unpublished PhD dissertation, Food Research Institute, Stanford University, 1982.

Colombo, U., D. G. Johnson, and T. Shishido. 1978. Reducing malnutrition in developing countries: increasing rice production in South and Southeast Asia. Triangle Papers 16, Trilateral Commission, Washington, D.C.

Dalrymple, D. 1971. Survey of multiple cropping in less developed nations. US. Department of Agriculture, Foreign Agricultural Economics Report 12, Washington, D. C.

David, C., and R. Barker. 1978. Modern rice varieties and fertilizer consumption. Pages 175-220 *in* Economic consequences of new rice technology, IRRI, Los Baños, Philippines.

Dixon, J. A. 1982. Food consumption patterns and related demand parameters in Indonesia. Working paper no. 6, Rice policies in Southeast Asia project, IFPRI, Washington, D.C.

European Chemical News. 1982. ECN Market Report, European Chemical News. July 1982.

FAO. 1967. Agricultural Commodities — Projections for 1975 and 1985, Vol. II, Rome, Italy.

FAO. 1981a. FAO fertilizer yearbook 1980, Vol. 30, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 1981b. FAO production yearbook 1980, Vol. 34, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 1981c. Current fertilizer situation and outlook, FERT/81/3, Commission on Fertilizers Seventh Session, 70-10 September 1981, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 1982. FAO fertilizer consumption and production statistics. Tennessee Valley Authority Computer Files. Unpublished.

Feng, Yuangi. 1982. The production and application of chemical fertilizer in China. Paper presented at International Workshop and Training Course on Nitrogen Management, Fuzhou, China, 26 April—14 May 1982, International Fertilizer Development Center, Muscle Shoals, Alabama 35660, U.S.A.

Green Markets. 1982. Various issues, McGraw Hill Inc., New York, New York.

Harris, T. G., and E. A. Harre. 1979. World fertilizer situation and outlook — 1978-1985, T-13, International Fertilizer Development Center and Tennessee Valley Authority, Muscle Shoals, Alabama.

IBRD. 1981. World development report 1981, International Bank for Reconstruction and Development, Washington, D. C.

IFDC. 1979. History of chemical fertilizers. *In* Fertilizer manual, International Fertilizer Development Center, Muscle Shoals, Alabama.

IFPRI. 1977. Food needs for developing countries. Research Report no. 3. International Food Policy Research Institute, Washington, D. C.

Konjing, K. Thailand — country consumption paper, forthcoming working paper, Rice Policies in Southeast Asia, IFPRI, Washington, D. C.

More U.S. crude oil prices trimmed by $1-2/barrel, Oil and Gas J. 1982, 80(11):40.

Mudahar, M. S., and T. P. Hignett. 1982. Energy and fertilizer policy implications and options for developing countries, T-20, International Fertilizer Development Center, Muscle Shoals, Alabama.

Patel, A. S., and R. K. Pandey. 1982. Demand for nitrogenous fertilizers in Indian agriculture. Pages 13-16 *in* Fertilizer news, Fertiliser Association of India, New Delhi, India.

Sheldrick, W. W. 1980. Investment and production costs for fertilizers. Paper presented at FAO Commission on Fertilizers, Sixth Session, Food and Agriculture Organization of the United Nations, Rome, Italy.

Tennessee Valley Authority. 1982. Fertilizer capacity files, unpublished statistics, Tennessee Valley Authority, Muscle Shoals, Alabama.

The Fertilizer Institute. 1982. Fertilizer reference manual. The Fertilizer Institute, Washington, D. C.

UN. 1981. World population prospects as assessed in 1980, population studies no. 78. United Nations International Economic and Social Affairs Department, New York.

UNIDO. 1978. Second world wide study of the fertilizer industry: 1975-2000. United Nations Industrial Development Organization, Vienna, Austria.

UNIDO. 1980. Supplement to second world wide study of the fertilizer industry, United Nations Industrial Development Organization, Vienna, Austria.

USDA. 1971. World demand prospects for grain in 1980. United States Department of Agriculture, Foreign Agricultural Economics Report no. 75, Washington, D. C.

World Bank. 1981. World development report 1981. Washington.

## DISCUSSION

SCHARPENSEEL: From the annual requirement of about 300 million t of N for the terrestrial vegetation, about 50 million t (16-20%) are produced as mineral fertilizer. The major part, born by recycling and N-fixation, is input dependent. Since, according to your paper, natural gas useful for urea production is even partly wasted, the question arises as to what extent expensive research on organic N sources is economically useful, unless we give a special allowance for side effects, such as improvement of soil stability, water, and nutrient-holding capacity.

*HERDT:* We can make projections, but we cannot know what the future will be like. Research on organic sources of N has several purposes: to develop technology in case chemical N becomes very much more expensive, to understand how organic sources can be made productive/viable, and to greatly increase the efficiency of production of organic sources so that they can compete with cheap (or not so expensive) chemical sources. Thus, I believe there is a need for research in this area. The question is, of course, how much.

DE DATTA: If energy prices continue to increase, why will the price of urea not go up proportionately?

*HERDT* The cost of energy is only one factor affecting urea prices, but even it does not necessarily have the same impact in all locations.

Natural gas is available almost free of cost in Bangladesh and Indonesia. Until alternative uses for that gas are developed, it can be used to produce fertilizer at a very low price (see Table 4). That low-priced fertilizer will undercut other fertilizer produced at a higher cost.

AGBOOLA: The land area available for rice cultivation will continue to decrease because of competition from other uses. Some land area will be lost because of soil abuse. In light of this, do you think that your assumptions will hold in some of the African countries?

*HERDT:* A large expanse of land is being cleared in that part of the world. Wrong agronomic practices are being used. By soil abuse alone about 20% of the land being used for cultivation now may be out ofproduction because of bad clearing methods, wrong agronomic practices, mining, etc. I therefore feel the assumption about increase in land area for rice cultivation may not work.

MARTINEZ: You mentioned that Asia is the largest user of N. Can you point out why?

*HERDT:* Asia is the largest user of fertilizer N probably because it has the largest area under cultivation. Its needs for fertilizer will continue to grow rapidly because the rates of application are still relatively low. If cheaper biological sources can be developed, then they will fill part of the need.

AMIEN: It seems that you emphasize only investing in huge irrigation projects to overcome the rice shortage in developing countries. Since the investment in that kind of project is quite expensive, don't you think that developing dryland rice with proper management such as applying organic fertilizers, mulching, etc. is a cheaper solution? Some of our experiments showed some promising results.

*HERDT:* I am not aware of dryland rice systems in Asia that could give lower cost production over the millions of hectares planted to wetland rice. It may be possible to develop some such systems for part of the increased production needed, but they will only contribute a small fraction of the needs.

# POTENTIAL OF ORGANIC MATERIALS FOR SOIL IMPROVEMENT

P. R. Hesse

The use of organic materials to improve soil conditions has markedly increased in recent years. However, such increased use has taken place mainly in dryland soils where crops other than rice are grown.

The kinds of organic materials available for cycling or recycling in rice soils are discussed in terms of availability and quality, but the quantities often quoted in the literature are possibly misleading; the potential quantities are, nevertheless, very large.

The effects of organic materials when incorporated into soils are discussed in relation to physical, chemical, and microbiological aspects, and it is concluded that the effects upon physical properties are probably the most important in dryland soils; for flooded soils more research is needed.

Certain known effects of organic materials on the yield and growth of rice and the additional effects of mineral fertilizers are discussed. The best results are from the complementary use of mineral fertilizers and organic manures.

Finally, some management aspects of using organic materials are discussed, and it is concluded that specific investigations into methodologies are needed.

In recent years, worldwide awareness of the need to use renewable forms of energy has revived the use of organic manures. Secondary reasons often given for the increased use of organic materials are the need to improve environmental conditions and public health, and the need to reduce costs of fertilizing crops.

In fact, the greatest benefit from cycling or recycling organic materials in soils is the overall improvement in soil conditions: the development and maintenance of structure, the improvement of physical properties, the decreased susceptibility to erosion, the encouragement of microbial activity, and, possibly of less importance, the provision of potentially available plant nutrients.

However, the increase in organic recycling has taken place predominantly in dryland soils, where crops other than rice are usually grown. On the other hand, the use of mineral fertilizers in irrigated areas has principally benefited rice. Possibly in China has organic recycling in paddy soils been a continuing routine practice.

---

Regional Project Coordinator for Asia and the Pacific for Organic Recycling, Food and Agriculture Organization of the United Nations, P.O. Box 3059, New Delhi 110003, India.

## KINDS OF AVAILABLE ORGANIC MATERIALS

The organic materials most commonly used to improve soil conditions and fertility include farmyard manure, animal wastes, crop residues (either as such or composted), commercial composts of urban origin, green manures, and night soil; less common are sewage, its sludge, and organic wastes from industry.

These available organic materials can be further distinguished as specific kinds of animal waste (pig dung, poultry droppings, bonemeal, etc), specific crop residues, or parts of a crop; green manures can be those specifically grown for a purpose such as *Sesbania* spp. or those that occur naturally such as weeds or water hyacinth. In most cases, but especially for animal materials, the composition of the materials can be extremely variable; there is no such thing, for example, as a standard cow dung.

The value and composition of a compost depend as much upon the composting process as upon the original material. The same quantities of the same vegetable or animal matter, for example, will give composts of different value according to the location of decomposition (in a pit or in a heap), the amount of moisture maintained, the degree of aeration, and the degree of protection from climate. If the material was decomposed anaerobically — as in the case of biogas digester effluents — very different end-products could result.

In rice-growing areas, the most abundant and easily available organic materials are the rice straw itself and, in due course possibly, the rice husks. The next most available materials are probably green manures of various kinds. In China, a large proportion of the rice fields is devoted specifically to cultivation of green manures, mainly milk vetch. Of specific relevance to rice production, especially under flooded conditions, are blue-green algae. These algae are commonly used directly, when their main contribution is N, or in symbiosis with the water fern azolla, when biomass is also contributed.

The literature contains many references to the quantities of organic materials available in the world for recycling and to their vast potential for supplying plant nutrients. For example, Misra (1981) gives a figure of nearly 90 million tons of NPK that could be obtained per year from animal and crop wastes in Asia, another 20 million tons being available from human wastes. The Food and Agriculture Organization (1979) reports that 12,000 t rice straw year is available in the Philippines alone. Such figures, however, can be misleading, as only the very broadest of estimates, involving bold assumptions, can be made, and in any case the materials have other potential value, which may take precedence over their use as manure.

### Organic resources and potential

*Animal wastes.* The excretion of dung and urine from domestic animals such as cattle, sheep, goats, pigs, and poultry provides the potential for enormous quantities of plant nutrients. For example, Gaur (1980) reports that 15 t N and 4 t each of P and K are potentially available from 1,000 t fresh cattle dung. Some countries take full advantage of such potential for recycling plant nutrients, but in other countries alternate uses (e.g., fuel) of the material compete with its agricultural uses.

Apart from animal manure, slaughterhouse wastes such as bones, blood, and skin also have potential for providing plant nutrients.

Human body wastes have greater potential than other animal wastes. An average analysis of sewage has been given as 50 ppm N, 7 ppm P, and 25 ppm K (Gaur 1980), and another calculation indicates that about 2 kg N, 0.2 kg P, and 0.8 kg K (Takahashi 1978) are potentially available per year from one person. As yet this potential is tapped seriously in only a very few countries.

Marine and fresh water animals have a certain potential, and in suitable parts of the world fish meal, prawn dust, etc. are used as manures. Sometimes fish are caught specifically to be used as crop manure, as in Oman, where sardines are netted and used to manure the date palms.

Finally, for those who have access to the more exotic fauna, fresh elephant dung contains 1.3% N, 0.3% P, and 0.1% K, with a C-N ratio of 43; fresh tiger dung has 2.8% N, 3.2% P, and 0.03% K, with a C-N ratio of 10; and fresh lion dung contains 3.6% N, 3.2% P, and 0.04% K, with a C-N ratio of 9 (S. Sein Win, pers. comm.).

*Crop residues.* Crop residues include such materials as straw, stalks, husks, and leaves. Some typical nutrient potential figures are 0.5% N, 0.3% P, and 1.2% K for cereal straw (Gaur 1980); 0.7% N, 0.1% P, and 1.4% K for maize stover; and 0.6% N, 0.1% P, and 0.4% K for rice chaff (Yamamoto and Teramoto 1978). Legume residues have considerably more potential for quality but much less for quantity. In addition to NPK, rice straw is a valuable source of silica. Its potential is widely utilized in the Republic of Korea, where silica has proved to be an essential additive for good rice yield.

Crop residues can be recycled in three ways: after composting, by direct incorporation into the soil, or by mulching. One analysis of rural crop waste compost gave 0.8% N, 0.2% P, and 0.4% K (GOI 1978); another gave 1.9% N, 0.2% P, and 3.1% K; and yet another analysis showed 2.3% N, 0.4% P, and 1.6% K (Kurihara 1978). These figures illustrate the variations that can occur in composts.

*Green manures.* Legume plants are grown for fixing atmospheric N before being incorporated into the soil; it is believed that this beneficial effect is gained by the current crop only and that there is little residual or cumulative benefit. *Crotalaria* spp. contains, on the average, about 4% N, *Sesbania* spp. 3% N, and azolla 4-5% N.

Non-nitrogen-fixing plants are sometimes used as green manure. Examples are water hyacinth, other water plants, numerous species of weeds, and tree leaves. However, it is more usual to compost these materials before use. In the case of water hyacinth, it is important to know the origin, as plants grown on polluted waters can obtain high amounts of elements toxic to food crops. This water plant contains about 0.4% to 0.04% N, 0.03% P, and 0.2% K when fresh. Yields of water hyacinth are approximately 250 t/ha. An application of water hyacinth compost at 10 t/ha has been recommended for rice (Gaur 1980).

*Urban wastes.* The principal organic waste produced in urban areas is sewage, which has already been discussed. The next most prolific organic material is that contained in city garbage. Garbage is treated (usually) by composting and yields products of different quality according to the original material; one analysis shows equal parts (1%) of N, P, and K (GOI 1978). Two more sets of figures are 3.11% N, 0.54% P, 2.60% K, and 1.24% N, 0.26% P, 1.29% K (Kurihara 1978). Thus, as in the case of rural composts, no average analysis can be given. City waste compost is sometimes enriched with plant nutrients, and its quality can be improved by including sewage sludge in the process.

In Indonesia, fresh garbage is used as a mulch and, in due course, nonvegetable matter such as tins, glass, and plastic are removed and the residue is dug into the soil. This procedure, however, is hardly of interest to rice farmers.

## EFFECTS OF ORGANIC MATTER ON SOIL PROPERTIES

### Physical properties

The overall, general effect of organic matter is to improve soil physical properties, most of which are related to soil productivity. Some of these properties have more relevance to dryland soils than to flooded soils and thus are possibly not so important for rice as for other crops.

Organic manures can counteract the deleterious effect upon bulk density that may be caused by the continued use of mineral fertilizers; they can increase the proportion of water-stable aggregates and increase water-holding capacity. Generally, organic materials with high C-N ratios like straw and husks have more effect upon soil physical properties than decomposed or semidecomposed materials such as compost. Thus *in situ* decomposition has been shown to give better results than predecomposition. Although organic matter decomposes over a wide range of soil moisture contents — from wilting point to saturation — in very wet soils the rate of decomposition falls off because of lack of oxygen, and organic matter tends to accumulate. Thus the beneficial effects upon soil physical properties resulting from organic matter decomposition are problematical in flooded soils.

### Chemical and physicochemical effects

Again, the bulk of research into the effects of organic matter upon soil chemical properties has been done on dryland crop soils; relatively little research has been done on flooded rice soils. Most of the research on flooded soils has been done at the International Rice Research Institute.

Addition of organic materials to a flooded soil has several effects upon the chemical properties which, in turn, affect the growth of rice. As the material decomposes, albeit slowly, $CO_2$ is formed, which can liberate certain forms of fixed P, directly influence the photosynthetic process of rice plants, and form complex compounds with Fe and Mn. Other more complex chemical reactions are the formation of $C_2H_4$ (now known to be involved with pathogen control) and of certain growth-promoting substances. An unavoidable effect of decomposing organic matter is a lowering of the oxidation-reduction potential with its numerous associated reactions such as reduction of sulfate and iron.

In most soils the continued use of mineral N fertilizers tends to lower pH values, and organic manures have a buffering effect. Aluminum-induced acidity, if present, can be partially remedied by organic matter complexing with the Al. In very acid soils such as acid-sulfate soils, however, the rate of organic matter decomposition is not sufficient to effectively change the pH values by this process.

Saline soils, too, inhibit certain phases of organic matter decomposition, although the precise mechanisms are yet to be satisfactorily explained. Salts depress the solubility of organic matter, and it is the soluble fraction that is most readily decomposed, Also, an increase in osmotic potential reduces oxidation of carbon.

One positive effect of organic materials added to soil is an increase in cation exchange capacity; an increase in total C is likely to be more noticeable in flooded soils than in dryland soils where, usually, no spectacular buildup of C occurs. Immediate changes in total N and, especially, available N will depend largely upon microbial activity, but an increase in potentially available N could be expected. For nonflooded soils experimental data show that mature compost has longer lasting but less immediate effects upon N availability than animal manures.

The most spectacular effect upon N availability is given by certain N-fixing green manures, particularly azolla and blue-green algae. In parts of China it is the practice to manure the azolla nursery beds with compost made from rice straw and river silt; the benefit is presumably due to nutrients other than N, such as P. Azolla can provide approximately 1.5 kg N/ha per day, which is about 500 kg N/ha per year; blue-green algae can provide up to 30 kg N/ha every season.

Organic manures can increase the availability of P in several ways. The P itself can increase because of mineralization of the organic P added, although the increase is not likely to be rapid in flooded soils; the organic matter can complex Al and Fe from their phosphates and, through $CO_2$ formation, can liberate Ca-bound P, on the other hand, increased microbial action can lead to fixation of available P in organic forms. So far as dryland soils are concerned, it has been found that compost made from city wastes is more effective than farmyard manure for increasing available P.

Organic manures can be a good source of micronutrients, and flooded conditions with low oxidation potentials may be more prone to benefit from them. However, certain organic materials can fix large quantities of micronutrients; the take-up of Cu by peaty materials is a well-known example. In some flooded rice soils rich in peaty material, such as ex-mangrove-bearing soils, the addition of Cu is almost essential for rice production.

### Microbial properties

Organic manures, whatever their origin, have a high microbial population and stimulate general microbial activity in soils. Adding compost to peaty soils appears to be a waste of time but, in fact, is a good practice because it induces microbial activity.

Several experiments have shown that the better effects of the effluents from biogas digesters, compared with those of composts or farmyard manures, are not attributable to nutrient supply; the effect is now thought to be microbial.

Humic substances extracted from manures increase the efficiency of N-fixing organisms like *Rhizobium* and *Azotobacter*.

## EFFECTS OF ORGANIC MATTER ON GROWTH AND YIELD OF RICE

As previously stated, the greatest benefit from recycling or cycling organic materials in soil is the overall improvement of soil conditions. The improved physical condition of the soil alone can result in better crop growth and yield, although such effects are more relevant to dryland rice than to flooded paddy fields. The amended physical conditions and, more important, the enhanced microbial activity, can increase the availability of nutrients. The nutrients, including micronutrients such as Mn, Cu, Zn, and Fe, added as part of the organic matter, eventually become available. Additionally, humic substances and their decomposition products can favorably affect the growth and metabolism of plants and have been reported to control the proliferation of parasitic nematodes and reduce the toxic effects of pesticides. For example, fulvic acid fractions of humus prepared from farmyard manure and applied at 0.03% and 0.05% increased the yield of rice by 56% and 85%, respectively (Gaur 1980).

Fresh organic materials are relatively low in available nutrients, and pretreatment, by composting for example, can give better crop response depending upon the degree of decomposition of the organic matter as well as upon its basic nutrient content. On dryland soils the fresh materials can be used as a mulch before being incorporated into the soil.

In Indonesia it is a common practice to compost the straw of the first rice crop in one corner of the field and incorporate it into the soil for the next crop.

Rice straw has been found to increase the yield of rice in India to the same extent as $(NH_4)_2SO_4$ if applied at equivalent N-containing rates, although a general finding is that the addition of mineral N together with straw is a better practice. Alternatively, repeated recycling of rice straw can result in a significant increase in organic matter, K, and silica. A comparison of rice straw and farmyard manure as rice manures showed increases of yield in both cases but significantly more (nearly double) for the farmyard manure.

In Japan (Shimizu 1978), application of stable manure at 1,100 kg/ha increased wetland rice yield by 10%, and in long-term experiments the more manure used and the longer the period of application, the greater the effect upon yield. The crop response was greatest in years with unfavorable weather conditions such as cold spells. The experiments in Japan were expanded to investigate other organic manures such as compost and fresh cattle dung, with and without mineral fertilizers. As might be expected, complementary use was the most effective.

In Burma (Thant 1978), a long-term experiment showed that farmyard manure had a longer lasting effect upon rice yield than did mineral fertilizers. In Thailand (Jugsujinda et al 1978), a long-term comparison of city waste compost and farmyard manure found that yield increases were proportional to amounts of manure added, but again the best yields were obtained with complementary use of mineral fertilizers.

Data from a long-term experiment on combined application of organic manures (farmyard manure and crop residues) and mineral fertilizers for four seasons in India (Pillai 1978) show the usefulness of at least one application of farmyard manure in a season over a moderate level of mineral N; for crop residues the results were not consistent. Other experiments in India have shown that 12 t manure/ha can save up to 70 kg N/ha and gives a residual effect equivalent to 30 kg N/ha and 13 kg P/ha. Results, however, vary considerably according to location, soil type, climate, and other agroecological factors.

Pillai and Vamadevan (1978) carried out experiments with organo-inorganic combinations of compost and farmyard manure with urea. The granulated compost contained 44% organic material, 25% diammonium phosphate, 22% single superphosphate, 8% KCl, and 1% urea. The farmyard manure mixture was made by treating dry manure with urea solution to give a product containing 5% N. Rice yields were higher with application of manure-fertilizer combinations than with application of separate materials. Similarly Shinde (1975) found that a slow-release N source for rice was effectively formed by blending rice straw, urea, and soil into balls.

Green manures have been found to increase rice yield, and applying green manures such as cowpea can save up to 75 kg N, ha; *Sesbania* has been found to save up to 120 kg N/ha. Increased rice yields have been obtained in Nepal by green manuring after the fields are flooded, but if mineral fertilizers are also used, yields are better (Rajbhandari and Shah 1981).

The use of azolla and blue-green algae is a special case of using organic materials. Popularly, although somewhat inaccurately, referred to as “biofertilizers,” these plants can save considerable amounts of mineral N fertilizer. Some claims have been made that they can completely replace N fertilizers; in one case in Sri Lanka (Uppawansa, pers. comm.) it was said that the azolla had to be frequently harvested from the paddy fields because it was causing the rice crop to suffer from excess N. However, a more general finding is that some mineral N must be used in conjunction with the azolla or algae.

Special mention should be made of anaerobically produced organic manure as a byproduct from biogas production. During aerobic decomposition of organic materials a loss of some plant nutrients is unavoidable because of volatilization and leaching. If anaerobic digestion is used instead of aerobic composting, such losses are much less. Furthermore, anaerobically produced compost is in a better physical condition; when dried it is finely divided and more easily incorporated into the soil. In China, particularly, field experiments have shown the superiority of biogas effluents over ordinary compost (made from identical inputs) with respect to plant nutrient supply and yield response of rice.

It has also been suggested that the best way of using rice straw is to feed it to animals and use the animal waste as manure; such a practice could well be integrated with biogas technology.

## MANAGEMEST ASPECTS

The actual use of organic materials for agriculture is not entirely a straightforward operation. This was clear from the almost universal changeover to mineral fertilizers when they became easily obtainable. As one example, in Japan the use of organic manures on paddy fields dropped from 6.5 t/ ha in 1955 to 2.7 t/ ha in 1975, this being paralleled by an increase from 0.08 t/ha to 0.30 t/ha in use of mineral fertilizers (Shimizu 1978). The greater ease of handling, storage, and application of mineral fertilizers and their quick and dramatic results have led to the abandonment of organic manures in their favor.

Organic materials, especially those thought of as “wastes,” are in general very bulky, requiring time-consuming and labor-intensive collection, storage, transport, and application. They are also usually in a physical state that makes handling and transport difficult and unpleasant.

Another problem is the technical one of how to best use organic manures. At present manuring is an art, and often a very inefficient one. The methodology of applying mineral fertilizers and soil amendments has received and is receiving intensive attention. The untold amounts of data, statistics, and argument produced by laboratory and field experiments have resulted in more efficient use of the materials being investigated. There are very few such results for organic manures; probably the work done on blue-green algae and azolla is the nearest approach so far, but much remains to be done.

A recent World Bank study (1976) estimated that the world is spending $200 billion a year in disposing of its so-called wastes. Replacing the concept of disposal with that of recycling thus has vast economic implications as well as those involving soil and environment improvement.

## REFERENCES CITED

Food and Agriculture Organization (FAO) 1979. Agricultural residues: a quantitative survey. AGS Bulletin.

Gaur, A. C. 1980. Recycling of organic wastes in agriculture. IARI, New Delhi.

Government of India (GOI). 1978. The use of organic fertilizers in India. FAO Soils Bull. 27.

Government of India (GOI). 1979. Recommendations of the task force on water hyacinth.

Jugsujinda, A., S. Glaewiggram, and J. Takahashi. 1978. Usage and production of organic matter in Thailand. FAO Soils Bull. No. 36:239.

Kurihara, K. 1978. The use of industrial and municipal wastes on organic fertilizer. FAO Soils Bull. 36:248-266.

Misra, R. V. 1981. The role of fertilizer industries in organic recycling programmes. Page 35 *in* Field document no. 20 of FAO/UNDP project, Improving Soil Fertility Through Organic Recycling.

Pillai, K. G. 1978. Proc. Symp. Ind/Norway/FAO Complementary use of mineral fertilizers and organic manures, New Delhi.

Pillai, K. G., and V. K. Vamadevan. Studies on an integrated nutrient supply system for rice. 1978. Fert. News 23:11.

Rajbhandari, K. B., and Ranjit Shah. 1981. Country report for Nepal. Field document 20 of FAO Regional Project RAS/75/004.

Shimizu, T. 1978. Country report for Japan. FAO Soils Bull. No. 36:79.

Shinde, J. E. 1975. Use of straw for a potential slow-release nitrogen source for rice. Fert. News 20:25.

Takahashi, J. 1978. Role of nightsoil in Japanese agriculture. FAO Soils Bull. 36:363-364.

Thant, M. 1978. Country report for Burma. FAO Soils Bull. No. 36:15.

World Bank. 1976. Village water supply. World Bank Paper, Washington.

Yamamoto, S., and T. Teramoto. 1978. Present status of organic fertilizers in Japan. FAO Soils Bull. 36:387-393.

## DISCUSSION

PALANIAPPAN: A gradual and small-scale input of human waste or sludge into a river system is probably alright, but an increased dumping as a regular practice is bound to bring about B. O. D. problems. In effect, it will pollute the river system. Are you encouraging such a practice?

*HESSE:* No, naturally we do not advocate such a practice. On the contrary, we recommend that organic wastes should never be discharged into waterways. For example, in Hong Kong it was the practice to rinse pig sties into the streams, causing extreme pollution. We have now introduced a single composting procedure instead.

PALANIAPPAN: If a silty slime is mixed with straw materials, the decomposition my come to a standstill, resulting in the formation of concretions. How do you think they use this as compost?

The effluent that comes out of palm oil mills in Malaysia is nontoxic and, at the same time, very rich in its available plant nutrients, especially N. We have successfully applied it to tin tailings (sand) to raise tomatoes, maize, groundnut, etc. A team of us are involved in various aspects of the research aimed at finding multiple uses of the effluent, the prominent one being toward its use as an organic manure after partial decomposition.

*HESSE:* Experience in China indicates that decomposition is sufficient for the material to be an efficient compost. Possibly waterlogged conditions help.

AGBOOLA: From my own point of view, green manuring in its present form doesn’t seem to have great potential in the humid tropics. Apart from the fact that it only benefits the succeeding crop, it occupies the land without contributing any cash or food; it also increases the rate of organic decomposition and needs inorganic P for maximum production. There are other sources — banana, cassava peelings, cocoa husk, oil palm waste, and city waste. All these have potentials in the humid tropics. Would you comment?

*HESSE:* It is true that, in general, the beneficial effect of a green manure is on the succeeding crop (especially if you are concerned solely with nutrient supply), but that in itself is surely a point in its favor. With regard to the green manure occupying land, this is partly a question of economics. Some green manures can also provide foodstuffs; others can be grown along with another crop, or around the edges of fields, along irrigation ditches, and so on, There is, I am sure, a very great potential for “green manure trees” like the ipil-ipil, which has multifarious advantages.

CHAUDHARY: You have thrown light on organic matter sources and their potentials, but have not mentioned the effect of decomposed and undecomposed sawdust, banana stems/leaves on the yield of crops and soil properties. Would you comment?

*HESSE:* The principal use of sawdust is in composting of wet animal wastes when it acts as an absorbent of excess moisture. Work has been done on the use of banana residues, but I have no data immediately available.

CHAUDHARY: Have you any idea of conserving organic matter in the field on the spot by burying roots and stubble in the field in conjunction with urea *g* S. S. P.?

*HESSE:* Although burying of roots and stubble is widely practiced, few farmers seem to combine this with mineral fertilization, which they do at a later stage. Some research on this is being done in India, Indonesia, and Korea with encouraging results; in some cases a leguminous green manure is added instead of mineral fertilizer, and this has also given promising results.

GAUR: The results of field experiments conducted with organic matter in temperate conditions cannot be immediately applied in tropical or subtropical conditions because specific technologies can be developed for recycling of straw depending on agroclimatic conditions, crop rotation, and so on. Our results showed that 1 week of decomposition of straw in submerged conditions was sufficient for higher yields of rice.

# UTILIZATION OF ORGANIC MATERIALS IN RICE PRODUCTION IN CHINA

Qi-xiao Wen

In the main rice-growing regions of China, the amount of organic manure applied has doubled since 1952. In 1979 organic matter provided about 1/3 of the N, 1/2 of the P, and almost all of the K applied and over 1/2 of the organic materials entering the soils. It is believed that organic manure and chemical fertilizers complement each other in intensive agriculture.

Green manure, straw incorporation, waterlogged compost, farmyard manure, and biogas production are evaluated, and the potentiality of increasing organic manure is indicated.

China has long used organic materials as manures. Historical records from the third century B.C. describe how the ancient Chinese plowed under weeds and processed animal bones as fertilizer. In the third century A.D., a vetch – rice rotation was developed. Using human and animal excreta as fertilizer was practiced even earlier than plowing under weeds (Shi 1957, Wang 1980). These rotation and fertilization methods utilizing organic matter have maintained soil productivity despite several thousand years of continuous farming. In fact, some areas have developed quite high-yielding soils.

Rice is the principal food in China. Over the past 10 years, it has accounted for about 29% of the total harvested area of food crops of the whole country, while its output makes up about 45% of the total grain and tuber production (Editorial Committee of Almanac of China's Agriculture 1981). This paper discusses the utilization of organic materials mainly in the tropical and subtropical zones south of the Huai River, where rice cultivation is centered.

## ROLES OF ORGANIC MATERIALS IN RICE PRODUCTION

### Role in nutrient supply

Although chemical fertilizer was first used in China in the 1930s, its level of utilization was not significant until the 1950s. Side by side with the burgeoning

---

Institute of Soil Science, Academia Sinica, Wuhan, Hubei Province, China.

chemical fertilizer industry, much work has been done to develop organic manure resources and promote recycling in the effort to increase crop yields. By selecting more adaptable varieties of green manure crops, inoculating rhizobium, applying phosphatic fertilizer, and utilizing other cultivation techniques (Gu and Wen 1981), the total area of leguminous green manure crops and azolla in this region was increased from 2.45 million ha in 1952 to 7.82 million ha in 1979, representing 346,000 t N, 88,000 t P, and 236,000 t K in 1979, figures about 2.2 times higher than those of 1952.

With the increasing quantity of crop stubble brought about by the increasing supply of N for crops, and with the development of more fodder sources — including the cultivation of aquatic plants as fodder crops — the number of domestic animals has increased, accompanied by an increase in farmyard manures. Domestic pigs, cattle, and sheep increased by 2.6, 0.2, and 2.7 times, respectively, from 1952 to 1979. Here mention should be made that aquatic plants have the ability to absorb from the water nutrients that are present at very low concentrations (Li et al 1980). Thus, by cultivating aquatic plants, not only can a large amount of organic material be obtained, but also some nutrients that have been leached out of the soil can be recovered.

In addition to leguminous green manure, azolla, and farmyard manure, other major organic wastes are human excreta, straw, and rape seed cake. River mud is also used as fertilizer to a fairly large extent, especially in areas with a network of waterways, as it consists mainly of eroded surface soils and some decomposed aquatic plants and animals. However, it is impossible to estimate the amount of nutrients in the mud contributed by the decomposed aquatic plants and animals. Macronutrients derived from these major organic wastes (except river mud) applied to the soil amounted in 1979 to approximately 7.41 million t, of which 2.15 million t were N, 0.8 million t P, and 2.9 million t K, making up about 1/3 of the N, 1/2 of the P, and almost all of the K applied to the soil that year. This indicates that, although the production and application of chemical fertilizer has increased rapidly in China, organic manures still contribute significantly to the supply of N and P, and especially to the alleviation of the deficiency of K (Table 1).

Besides N, P, and K, organic manures also supply the soil with micronutrients such as B, Zn, Cu, Mo, Ca, and Si, thus preventing micronutrient deficiencies in spite of the long history of cultivation. A micronutrient deficiency that occurs in an area may be due to a) the parent material of the soil being poor in micronutrients; b) a new variety of crops with a greater demand for certain micronutrients having replaced a traditional variety (e.g., Ganlan rape has replaced Shengli rape); c) changes in soil water regime (e.g., poor drainage); or d) antagonism between nutrients (e.g., Zn deficiency resulting from excessive application of phosphatic fertilizer).

Although the total amount of organic manures used in rice produced in China has increased since 1949, their relative contribution to the total need for N has on the average decreased. It appears that the higher the level of intensive agriculture, the lower is the ratio of organic manure N to chemical fertilizer N, and the higher the proportion of farmyard manure N in organic manure N (Huang et al 1981, Hseung et al 1980, Lu 1981, Xi 1981).

**Table 1. Estimated use of organic manures in the main rice-growing region of China, 1979.**[a]

| | Quantity available ($10^6$ t) | Nutrient content (%) | | | Loss of nitrogen (%) | Nutrients ($10^3$ t) | | |
|---|---|---|---|---|---|---|---|---|
| | | N | P | K | | N | P | K |
| Human feces[b] | 34.6 | 1.0 | 0.22 | 0.31 | 40 | 207 | 76.12 | 106.24 |
| Human urine[c] | 84.0 | 0.5 | 0.06 | 0.16 | 50 | 210 | 47.63 | 132.80 |
| Cattle feces[d] | 162 | 0.32 | 0.11 | 0.12 | 35 | 337 | 176.98 | 201.69 |
| Cattle urine[e] | 32.2 | 0.5 | 0.01 | 0.79 | 40 | 97 | 4.37 | 253.98 |
| Pig feces[f] | 148 | 0.5 | 0.18 | 0.42 | 40 | 444 | 259.14 | 615.03 |
| Pig urine[g] | 152 | 0.3 | 0.03 | 0.33 | 50 | 227 | 39.77 | 502.98 |
| Goat and sheep feces[h] | 6.7 | 0.65 | 0.22 | 0.21 | 40 | 26 | 14.86 | 14.11 |
| Goat and sheep urine[i] | 0.6 | 1.40 | 0.01 | 1.74 | 50 | 4 | – | 9.96 |
| Plant residues[j] | 32.6 | 0.6 | 0.09 | 1.08 | – | 195 | 28.40 | 352.75 |
| Straw ash[k] | 70.1 | 0.6 | 0.09 | 1.08 | – | – | 55.06 | 529.54 |
| Green manures[l] | 11.9 | 2.74 | 0.31 | 1.59 | – | 327 | 36.71 | 189.24 |
| Azolla | 8.8 | 0.22 | 0.02 | 0.07 | – | 19 | 1.75 | 6.64 |
| Rape seed cake | 1.3 | 4.6 | 1.10 | 1.16 | – | 60 | 13.98 | 14.94 |
| Total | | | | | | 2153 | 754.77 | 292.99 |

[a] Source: 1980 Almanac of China's Agriculture (Editorial Committee of Almanac of China's Agriculture, 1981). [b] 90 kg per capita, 80% available; population 480 million. [c] 350 kg per capita, 50% available. [d] 5.4 t/head per yr, 70% available; population 42.9 million. [e] 3 t/head per yr, 25% available. [f] 0.95 t/head, 90% available; population 173 million. [g] 1.25 t/head per yr, 70% available. [h] 0.35 t/head per yr, 50% available; population 38 million. [i] 0.15 t/head per yr, 10% available. [j] 825 kg/ha per yr. [k] Assuming 146 kg straw is used as fuel per capita, loss of P = 10%, loss of K = 30%. [l] 15 t/ha, 7.8 million ha.

Opinions on the role of organic manures in intensive agriculture differ (Carter 1980, Okamoto 1975, Tanaka 1975); some scientists favor organic agriculture and others believe that organic manures can be replaced by chemical fertilizers. In China, organic manure and chemical fertilizer complement each other. Without chemical fertilizer, it is impossible to increase food production; on the other hand, relying solely on chemical fertilizer leads not only to the waste of large amounts of natural resources and to environmental pollution, but also to the depletion of soil organic matter content.

## Role in maintaining soil organic matter content

*Soil organic matter and soil fertility.* Soil fertility includes all the physical, chemical, and biological properties of soil that are closely related to the growth of crops. Soil organic matter plays an important role in soil fertility. First of all, organic matter is the major source of nutrients, especially N, in rice nutrition. Experiments have shown that, even in the case of high yields of rice, N derived from the soil still makes up about 76% of the total uptake of N of single-cropped rice and 56% of that of double-cropped early rice (Chu et al 1978). Generally, the higher the organic matter content, the higher the N-supplying capacity of the soil.

Soil organic matter helps give the soil greater buffering capacity with respect to nutrients — the rice growing on those soils neither suffers from starvation caused by inadequate application of fertilizer nor shows luxurious growth when heavily fertilized. In the Chinese farmers' experience, to achieve a higher rice yield (>6 t/ ha) on soil with low organic matter content, it is necessary to apply more chemical fertilizer, but a stable yield will be far from ensured unless the soil has high organic matter content.

Moreover, soil organic matter is favorable to the improvement of the physical properties of soil, which in turn not only helps speed up the growth of roots of dryland crops in rotation with rice, but also facilitates regulation of the soil water regime and thus regulates the uptake of nutrients by rice plants through water management. It has been found (X. L. Yao, and D. F. Yu, Institute of Soil Science, Academia Sinica, unpubl. data) that the mean weight-diameter of soil aggregates increases with an increase in soil organic matter content. Since soils with aggregates of low mean weight-diameter are difficult to drain and show normal shrinkage during dehydration, the air status and the uptake of nutrients by rice plants are hard to regulate by water management.

The content of organic matter in paddy soils varies greatly among different areas. Paddy soils in the areas of Tai Lake, Dongting Lake, and the Pearl River Delta are higher in organic matter content, generally ranging from 2.5 to 3.0%, while those in the Yangtze-Huai River Plain are lower, ranging from 1.0 to 1.5%. According to farmers' experience, under present agricultural systems of China the proper organic matter content of high fertility paddy soils generally ranges from 2 to 4%. In well-drained soils in the same area, the organic matter content, within a certain range, is significantly correlated with soil productivity (Institute of Soils and Fertilizer, Agricultural Academy of Zhejiang 1982; Liu and Zhao 1982).

*Contribution of organic manures.* The content of soil organic matter depends on the relative amounts decomposed and formed annually. So far no method is available for a direct determination of the annual decomposition rate of soil organic matter in the field. Judged from the amount of soil N absorbed yearly by crops (including rice and wheat) and from the N reserves in the 0- to 20-cm soil layer, the mineralization rate of soil organic N, generally being 4-5% per year, varies widely with soil type, texture, pH, etc. Since the soil yearly N uptake by crops is not derived completely from the mineralization of soil organic matter, but also comes from such sources as precipitation, irrigation water, and both nonsymbiotic and symbiotic N fixation, and, moreover, since the mineralization rate between organic N and organic C is not strictly proportional, the figure of 4-5% is at best approximate. It does not correspond exactly to the mineralization rate of soil organic C.

The amount of soil organic matter formed depends upon the amount of organic material and its humification coefficient — the fraction of organic C left after 1 year of decomposition — which varies with chemical composition. As a rule, the higher the lignin content, the higher is the humification coefficient (Lin et al 1980, Cheng et a1 1981). Both soil properties and climatic conditions affect the humification coefficient. In the black soil zone it is significantly higher than that in the yellowish-brown soil zone. However, there is little difference between the humification coefficient in the yellowish-brown soil zone and that in the red soil zone.

There are two ways to introduce organic materials into the soil, i.e., the natural return through roots, stubble, sloughed-off roots, and root exudates, and artificial application in the form of organic manures. For cereal crops the sloughed-off roots and root exudates may amount to 12-18% of the photosynthate (Oades 1978). Based on 1979 data, it is roughly estimated that in this region of China, the organic material (except sloughed-off roots and root exudates) entering into the soil that year in the form of organic manures made up 67% of the total input (Table 2).

In recent years, because of an increase in the rate of application of both organic manure and chemical fertilizer, and also because of an increase in cropping index in some areas, the content of soil organic matter, with a few exceptions, is reported to be on the increase (Xu et al 1980, Xi 1981). Of the increase of soil organic matter content in the Suzhou District, Jiangsu Province, 25% has been estimated to be due to the increasing amount of roots and stubble and 58% to the increasing application of organic manures.

Poor drainage favors the accumulation of soil organic matter. The organic matter content of paddy soils with poor drainage and that of bog soils are commonly higher than that of dry soils, normally ranging from 3.5 to 6%, and sometimes higher than 20%. For these soils, improvements in water regime are of prime importance, as the organic matter content does not reflect soil fertility. Nevertheless, because of the slower mineralization rate of organic matter (Cai and Zhu 1982), organic manures must be applied, even after the water regime has been improved, to form additional active organic matter.

**Table 2. Annual contribution of various organic materials to soil organic matter content**

| Organic material | Dry matter (kg/ha) | C (%) | Humification coefficient | Soil organic matter formed (kg/ha) |
|---|---|---|---|---|
| Naturally returning | | | | |
| Rice root | 557 | 46 | 0.50 | 211 |
| Rice stubble | 452 | 43 | 0.23 | 77 |
| Wheat, barley, and millet root | 82 | 37 | 0.32 | 16 |
| Wheat, barley, and millet stubble | 88 | 52 | 0.31 | 24 |
| Fallen leaves of rape and soybean | 59 | 44 | 0.18 | 8 |
| Roots of green manure | 65 | 47 | 0.40 | 21 |
| Subtotal | 1305 | | | 368.8 |
| Organic manure | | | | |
| Aerial part of green manure | 300 | 49 | 0.20 | 50 |
| Azolla | 12 | 43 | 0.43 | 3 |
| Straw | 825 | 43 | 0.23 | 141 |
| Pig feces | 563 | 44 | 0.52 | 220 |
| Pig urine | 96 | 37 | 0.10 | 6 |
| Cattle feces | 596 | 40 | 0.58 | 238 |
| Cattle urine | 23 | 37 | 0.10 | 1 |
| Goat and sheep feces | 47 | 40 | 0.58 | 19 |
| Goat and sheep urine | 1 | 31 | 0.10 | 0 |
| Human feces | 156 | 42 | 0.50 | 56 |
| Human urine | 56 | 37 | 0.10 | 3 |
| Rape seed cake | 32 | 40 | 0.20 | 4 |
| Subtotal | 2710 | | | 745 |
| Total | 4015 | | | 1114 |

## MANNER OF USING ORGANIC MATERIALS AS FERTILIZER

In China, various methods have been developed to make full use of plant organic materials (Jin 1982). Among such methods are a) direct application as fertilizer, b) initial use as feed, then as fertilizer, and c) initial use as fuel, then as fertilizer.

### Organic materials used directly as manure

In addition to being used partly as domestic animal feed and as raw materials for waterlogged compost and biogas fermentation, most winter green manures are used directly as basal dressing for rice, generally with an application rate of 15-30 t/ha (fresh weight). Excessive application will lead to low efficiency and even to a reduction in grain yield. It is better to plow under the green manure about 15 days before transplanting rice seedlings so that the plants do not suffer damage from the decomposition products of the green manure and so that the growing period of green manure crops might be extended as long as possible for obtaining still more organic material and N. If the rice seedlings are transplanted 10 days after plowing under, it is especially important to regulate the water regime carefully in the early stages of growth.

The effect of winter green manures on rice yield varies with the level of soil fertility, rate of application, and rice cultivar. In general, a ton of green manure (fresh weight) will cause an increase in rice yield by 30-80 kg, with a N utilization rate of 28.0 ± 10.9% (Table 3). Under different methods of utilization, such as green manuring and composting with mud, there are different patterns of N supply, although there is little difference in the effect on rice yield. Using 1.25 t (fresh weight) of milk vetch as pig fodder caused the pig's weight to increase by 26.5 kg, and application of the resultant excreta to the rice plant caused a grain increase of 27 kg. Direct application of the same amount of milk vetch gave a comparable grain increase. It seems that the utilization of green manure crops in this way is more profitable (Gu and Wen 1981).

As a rule, azolla and sesbania may be used not only as basal dressing but also as topdressing. Since the azolla is higher in lignin content, slower in decomposition, and also slower in N liberation (Shi et al 1978), it is important to incorporate it into the soil at the proper time to prevent delayed maturing in the rice plants.

Straw has a rather wide C-N ratio. Although when it is incorporated, a

**Table 3. Plant recovery of nitrogen from different organic manures.**[a]

| | N recovery (%) by | | | |
|---|---|---|---|---|
| | Milk vetch | Azolla | Pig manure | Waterlogged compost |
| Pot experiment | 46.5 ± 16.6<br>(n = 11) | 31.4 ± 12.7<br>(n = 12) | 28.4 ± 4.0<br>(n = 4) | – |
| Field experiment | 28.0 ± 10.9<br>(n = 5) | 28.1 | 13.4 ± 3.1<br>(n = 5) | 15.0 ± 5.1<br>(n = 15) |

[a] Compiled from published and unpublished data obtained by the Institute of Soil Science, Academia Sinica, and provincial and regional Institutes of Soil and Fertilizer, Chinese Academy of Agricultural Sciences.

considerable part of its N may be utilized by late rice (Mo and Qian 1981a), this is possibly only the result of biological interchange. Experimental results indicate that N immobilized during the initial stages of straw decomposition remains incompletely remineralized even after 100 days (Lin et al 1980). To avoid any unfavorable effect of direct application of straw, in addition to increasing the rate of application of N fertilizer slightly, it is better to control the application rate of straw at around 1.5 t early rice straw/ha, to lime before plowing, and to transplant late rice 15 days after plowing.

On most paddy soils, straw incorporation has little effect on the yield of the current rice crop but always has a favorable effect on the succeeding dryland crops. In some K-deficient or Si-deficient paddy soils, however, straw incorporation will raise the grain yield of the current rice crop to a notable extent because of its higher content of both K and Si (Mo and Qian 1981b, Yiyang Institute of Agricultural Science, Hunan Province 1981).

### Waterlogged compost

Waterlogged compost is made from such raw materials as river mud, straw, green manure (or weeds and aquatic plants), farmyard manure, and human excreta and is composted under waterlogged conditions. A traditional practice is to mix damp river mud with straw in winter; after drying up, the mixture is placed in a pit in a corner of the field with a moderate amount of farmyard manure; additional aquatic plants or leguminous green manure are added later; each time materials are added, a thorough mixing and turning is needed. Combinations of raw materials differ widely from place to place; hence there are large variations in the nutrient content of waterlogged compost, e.g., N ranging commonly from 0.18 to 0.40% and P from 0.06 to 0.11%.

The advantages of waterlogged compost are as follows (Research Group of Tsao-Tung-Ni 1959):

- Because it is composted under waterlogged conditions, the mineral N exists as $NH_4^+$-N, and therefore the loss of N through denitrification is greatly reduced after being applied to paddy fields.
- The N-supplying characteristics are steady and lasting, with a N utilization rate of 15 ± 5.7%.
- Waterlogged composting is one way of preventing loss of organic wastes during storage and of avoiding harmful effects on rice plants of organic wastes when they are directly incorporated into the soil.
- Not only does the fertile river mud contain an abundant amount of N, K, etc., but river mud with less organic matter always contains more available K.
- Using river mud helps alleviate the silting up of streams and lakes and raises the field surface level, thus improving soil drainage conditions. For some paddy soils, there is also an improvement of soil texture.
- Since waterlogged composting pits are scattered in various fields and the raw materials are all transported in the slack farming season, the shortage of labor in the busy farming season is alleviated.

Nevertheless, collection of river mud is fairly labor consuming, and it would be better to lower the proportion of river mud in waterlogged compost.

## Farmyard manure

There are two kinds of farmyard manure: liquid manure and “dry” manure. Liquid manure is composed of cattle, pig, and human excreta in various proportions, plus washings; it is used after fermentation as topdressing for rice plants. Most “dry” cattle manure is used as a basal dressing for dryland crops in rotation with rice. Pig manure is generally used as a basal dressing for rice and dryland crops. Its composition varies greatly with the age of the pig, the quality of feed, and the bedding materials used (rice straw or dried mud). The N supply of pig manure is steady and long lasting, with a N utilization rate of 13.4 ± 3.1 % by the current rice crop and a significant residual effect on the succeeding rice crop.

## Sludge and effluent of biogas plants

Biogas fermentation uses rationally and effectively various kinds of organic wastes such as plant residues, green manure crops, aquatic plants, and human and animal excreta. Experiments show that through biogas fermentation every kilogram of organic material will produce about 0.20-0.38 $m^3$ gas, leaving 32-60% organic C, which may serve as a source of soil organic matter (Table 4). Furthermore, biogas fermentation is more advantageous to the preservation of N than composting or waterlogged composting (Table 5). It is roughly estimated that, with biogas widely used as fuel throughout the Suzhou District of Jiangsu Province, there would be an annual increase in N of 8,600 t and in organic matter used as manure of 1.2 million t, i.e., 18 kg N/ha and 2.5 t organic materials/ha. Through biogas fermentation, sizable amounts of N and P become available. The effect of sludge and effluent on crop yield is similar to that of pig manure, having an equivalent amount of N (Research Group of Biogas 1975; Institute of Soils and Fertilizer, Agricultural Academy of Sichuan 1979).

The cost of building a biogas plant and the rate of gas evolution are the keys to the

**Table 4. Gas production of various organic materials during biogas fermentation and the remaining C and N (Wen and Lin 1982).**

| Materials | Proportion | Gas produced ($m^3$/kg) | C remaining (%) | N remaining (%) |
|---|---|---|---|---|
| Pig manure + wheat straw + weeds | 1:0.6:0.7 | 0.23 | 39 | 99 |
| Wheat straw + human excreta | 1:0.26 | 0.31 | 51 | 86 |
| Rice straw + human excreta | 1:0.26 | 0.38 | 60 | 98 |
| Rice straw | – | 0.25 | 38 | |
| Pig manure | – | 0.21 | 56 | 71 |
| Cattle manure | – | 0.11 | 51 | 84 |
| Weeds | – | 0.20 | 36 | 77 |
| Alligator Alternanthera | – | 0.22 | 32 | 86 |

**Table 5. Percentage of C and N in organic materials retained after decomposition under different conditions.**[a]

| | C (%) | N (%) | Gas production ($m^3$/kg) |
|---|---|---|---|
| Biogas fermentation[b] | 38.9 | 94.3 | 0.26 |
| Waterlogged composting[c] | 33.8 | 82.9 | – |
| Composting[b] | 19.4 | 53.0 | – |

[a] Source: Wen and Lin (1982), [b]Rice straw : milk vetch : pig manure = 1:0.2: 0.08. [c] Organic materials used were the same as in [b], and an equal amount in weight of soil was added.

popularization of biogas generation. Biogas plants of various sizes and with different types of digesters have been developed for different conditions (Southwest Designing Institute of Architecture 1979). These plants do not require high technology and are inexpensive, costing generally only $25-$50 for a 10-$m^3$ unit.

Organic materials with different chemical composition vary in the amount of biogas produced and in the evolution pattern. Fresh milk vetch and weeds are rich in easily decomposable components and produce biogas quickly but are not long lasting; about 85% of their total output is produced within 15 days at 30° C. For rice and wheat straw and husks with a composition difficult to decompose, only 9-16% of the total production comes within the same period at the same temperature. With various kinds of farmyard manure, steady production is generally observed during the whole period of fermentation. Only by regulating the proportion of raw materials can a steady and lasting biogas evolution be ensured. To speed the rate of gas production, rice straw and husks should be composted in advance (Sichuan Institute of Biology 1977). However, because of the climatic conditions in the Yangtze River Valley, only 8-10 months/ year are suitable for the operation of biogas plants; how to maintain a normal biogas supply in the severe winter remains a problem.

Compared to manuring, biogas fermentation, although reducing N loss, has the following shortcomings: a) the effluent is low in nutrient concentration ($NH_4^+$-N: 60-600 ppm); b) it is inconvenient to transport to the field; and c) the sludge is inconvenient to distribute in the field.

## CONCLUSION

The maximum reutilization of organic wastes is important to the maintenance and improvement of soil fertility and to the reduction of agricultural costs. The cultivation of leguminous crops, particularly leguminous green manure crops, is the most economical and effective way to increase the soil N content and raise fertility in areas where both fertility and the application rate of manures are low (Deng et al 1981, Xiao 1981). In the region discussed, the hectarage of green manure crops has been increased to a point beyond which it seems impossible to expand on the whole. In the hilly and coastal areas and in the new paddy areas of the Yangtze-Huai Plain, where soil fertility is very low, the hectarage of green manure crops tends to be continuously enlarging; in areas such as central China, where soil fertility is moderate and where climatic conditions are unfavorable to the growth of wheat, the hectarage of green manure crops will possibly remain unchanged; while in areas such as southern Jiangsu and Shanghai, where soil fertility is higher and where livestock husbandry is flourishing, the hectarage of green manure crops will shrink. However, there exists the potential to raise the yield from the 15 t/ha found in some areas to more than 45 t/ha.

At present, livestock husbandry calls for further development. The rapid growth of the chemical fertilizer industry will make it possible to provide even more feed, while it is necessary to increase the use of green manures as fodder. One of the important prerequisites for reducing the hectarage of green manure crops is to raise the absolute amount of farmyard manure in C and nutrient cycling.

The potential of returning more C and N from straw back to the soil by means of biogas fermentation seems to be promising. It is also necessary to seek a solution for the problem of the utilization of biogas manures so as to decrease the use of straw directly as fuel.

## REFERENCES CITED

Cai, G. S., and Z. L. Zhu. 1982. Nitrogen supply of paddy soils in Taihu Lake region [in Chinese]. Paper presented at the Symposium on Taihu Lake Region.

Carter, L. J. 1980. Organic farming becomes “legitimate.” Science 209:254-256.

Cheng, L. L., Q. X. Wen, S. L. Wu, and L. Xu. 1981. The effect of chemical composition and decomposition conditions of plant materials on the newly formed humus [in Chinese, English summary]. Acta Pedol. Sin. 18:360-367.

Chu, C. L., H. L. Hiao, K. S. Tsai, and C. C. Yu. 1978. Soil nutrition status under “rice-rice-wheat” rotation and the response of rice to fertilizers in Suchow district [in Chinese, English summary]. Acta Pedol. Sin. 15:126-137.

Deng, T. J., Y. A. Fan, and X. A. Ding. 1981. The economic benefits of a triple-cropping system composed of two crops of rice and one crop of rape in relation to soil fertility [in Chinese]. Turang Tongbao 6:1-4.

Editorial Committee of Almanac of China’s Agriculture. 1981. Almanac of China’s Agriculture 1980 [in Chinese]. Agriculture Press, Beijing. 508 p.

Gu, R. S., and Q. X. Wen. 1981. Cultivation and application of green manure in paddy fields of China. Pages 207-219 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, Springer-Verlag, Berlin, Heidelberg, New York.

Hseung, Y., Q. Xu, X. L. Yao, and Z. L. Zhu. 1980. Effect of cropping system on the fertility of paddy soils [in Chinese, English summary]. Acta Pedol. Sin. 17:101-119.

Huang, Z. X., X. Y. Liang, and H. Y. Wang. 1981. Nutrient balance and problems unsolved in soils under cultivation in Zhong Shan County, Guangdong Province [in Chinese]. Turang Tongbao 3:24-26.

Institute of Soils and Fertilizers, Agricultural Academy of Sichuan. 1979. On the manurial value of sludge and effluent of biogas plant [in Chinese]. Turang Tongbao 1:37-38.

Institute of Soils and Fertilizers, Agricultural Academy of Zhejiang. 1982. The basic productivity of paddy soils in plain areas in relation to the effectiveness of fertilization [in Chinese]. Turang Tongbao 1:11-13.

Jin, W. X. 1982. Recycling of organic materials — Use of organic wastes and bio-nitrogen as fertilizer in China. Paper presented in the International workshop/ training course on nitrogen management. Fuzhou, China.

Li, Z. S., D. F. Chen, S. X. Zu, D. L. Shen, and L. H. Yu. 1980. Nitrogen cycle in water layer of paddy field as effected by the plantation of aquatic plants [in Chinese, English summary]. Acta Pedol. Sin. 17:245-254.

Lin, X. X., L. L. Cheng, S. L. Shi, and Q. X. Wen. 1980. Characteristics of decomposition of plant residues in soils of southern part in Jiangsu Province [in Chinese, English summary]. Acta Pedol. Sin. 17:319-327.

Liu, Y. W., and S. L. Zhao. 1982. On the regime of soil organic matter of paddy soils derived from red earth [in Chinese]. Hunan Nongye Kexue 2:23-26.

Lu, R. K. 1981. The fertility and fertilizer use of the important paddy soils in China. Pages 160-170 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, Springer-Verlag, Berlin, Heidelberg, New York.

Mo, S. X., and J. F. Qian. 1981a. Uptake of nitrogen by rice plant from straw manure, urea and soil. Pages 800-804 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, Springer-Verlag, Berlin, Heidelberg, New York.

Mo, S. X., and J. F. Qian. 1981b. Effect of ploughing in of rice straw on increasing potassium nutrients for rice crop [in Chinese]. Turang Tongbao 1:20-21.

Oades, J. M. 1978. Mucilages at the root surface. J. Soil Sci. 29: 1-13.

Okamoto, H. 1975. How to keep paddy field in better soil condition for rice cultivation [in Japanese]. J. Sci. Soil and Manure, Jpn. 46:323-327.

Research Group of Biogas. 1975. On the generation of biogas and the use of sludge and effluent [in Chinese]. Turang Tongbao 4: 166-171.

Research Group of Tsao-Tung-Ni. 1959. Investigation on the process of decomposition and nutritive value of Tsao-Tung-Ni, a mixed fertilizer of muds and straw prepared under anaerobic condition [in Chinese, English summary]. Acta Pedol. Sin. 7:190-202.

Shi, S. H. 1957. On agricultural science in ancient China from the book “Qi Min Yao Shu” [in Chinese]. Science Press, Beijing. 87 p.

Shi, S. L., L. L. Cheng, H. H. Lin, C. L. Shu, and C. H. Wen. 1978. Effect of azolla on the fertility of paddy soils [in Chinese, English summary]. Acta Pedol. Sin. 15:54-60.

Sichuan Institute of Biology. 1977. Contradiction between the steady gas supply and the disposal of sludges of bio-gas plants [in Chinese]. Collected Papers on Bio-gas 2:42-45.

Southwest Designing Institute of Architecture. 1979. Design and construction of biogas plant of small scale in rural area [in Chinese]. Science Press, Beijing. 198 p.

Tanaka, A. 1975. Re-utilization of nitrogen and energy of the straw for the rice cultivation [in Japanese]. J. Sci. Soil Manure, Jpn. 46:328-332.

Wang, Y. S. 1980. Soil science in ancient China [in Chinese]. Science Press, Beijing. 217 p.

Wen, Q. X., and X. X. Lin. 1982. On the organic matter of paddy soils in Taihu Lake region [in Chinese]. Paper presented at the Symposium on Taihu Lake region.

Xi, Z. B. 1981. On the tendency of organic matter accumulation in paddy soil under triple cropping system in suburbs of Shanghai. Pages 502-508 *in* Institute of Soil Science, Academia Sinica, Proceedings of symposium on paddy soil. Science Press, Beijing, Springer-Verlag, Berlin, Heidelberg, New York.

Xiao, S. X. 1981. Different rotation systems practiced in double cropping rice fields in winter in relation to increase in soil fertility and crop yield [in Chinese]. Turang Tongbao 2:10-13.

XU, Q., Y. C. Lu, Y. C. Liu, and H. G. Zhu. 1980. The paddy soil of Tai-Hu region in China [in Chinese, English summary]. Shanghai Scientific and Technical Publishers. Shanghai, China. 98 p.

Yiyang Institute of Agricultural Science, Hunan Province. 1981. Turning over of rice straws into soil in relation to soil fertility and increase in crop yield [in Chinese]. Turang Tongbao 2:6-7.

## DISCUSSION

SINGH: Why do you use mud for composting?

*WEN:* As compared with soil, mud generally contains more organic C, N, and other available nutrients. Using mud for composting also has the advantage of alleviating the silting up of streams and lakes.

SINGH: Do you recommend plowing under green manure 15 days before transplanting rice for all kinds of soil conditions?

*WEN:* Plowing under green manure 15 days before transplanting rice may be taken as a general guide. However, it depends on soil conditions and management. In the case of well-drained calcareous soils, rice seedlings can be transplanted less than 15 days after plowing under green manures.

GAUR: What is the time involved in the incorporation of straw in soil and transplantation of rice seedlings to avoid adverse effects on the growth and nutrition of the plants?

*WEN:* For the sake of safety, 15 days after the incorporation of rice straw is considered necessary. However, under assurance of suitable measures, such as incorporation with N-fertilizer, well-drained facilities, etc., the time may be shortened to less than 1 week.

MARGES: Is it true that crops fertilized with organic fertilizer taste better and are more resistant to pests and diseases?

*WEN* In Chinese farmers’ experiences, some fruits such as watermelon fertilized with organic manure taste better, and crops such as rice and wheat fertilized with organic manure are more resistant to pests. But understanding of these facts based on scientific research is still limited.

MORACHAN: Various data comparing individual organic manures with and without chemical N have been indicated for increases in yield. Have any experiments been conducted in China on the combination of farmyard manure or compost + green manure + azolla or BGA to reduce chemical N?

*WEN:* No.

# DEVELOPMENT OF ORGANIC MATTER-BASED AGRICULTURAL SYSTEMS IN SOUTH ASIA

A. Venkataraman

Population growth throughout South Asia continues to press heavily on the food supply. Despite planned efforts to increase production of food, specifically of rice, the available supplies fall short of requirements, demanding renewed efforts. The role of fertilizers in increasing output is significant, but their availability is limited by cost escalation and uncertain supply due to importation problems. However, increased reliance on the production of organic materials abundant in tropical countries offers a possibility for effectively supplementing nutrient requirements. Farmyard manure, compost, green manure, green leaf manures, and use of crop residues open up expanded opportunities for indigenous production and use at much lower cost. Research has clearly validated the manifold beneficial effects of organic matter on soils, crops, and the environment. Biofertilizers are new entrants and possess opportunities for much wider coverage. Clear strategies supported by policy commitments can effectively help to promote organic matter-based rice farming.

Food-population imbalances continue to inhibit economic self-reliance and self-sufficiency in South Asian countries. Historical evidence strongly indicates that prospects for economic security and political stability rest on the strong foundation of an adequate food supply. In most of the South Asian nations, the annual growth rate of agriculture is just precariously keeping pace with the annual growth rate of population (Table 1). In overpopulated countries, marginal inequilibrium is sufficient to set in motion a series of interlinked socioeconomic disturbances manifested by an inflationary wage-price spiral, making hard-won independence meaningless. The obvious and continued need is for vigilance on the food front, especially regarding the production of rice, the staple food.

In countries where agriculture sustains about three-fourths of the population, provision of adequate employment is another factor to be reckoned with. In short, food, employment, security, and equity have to be accommodated within the broad framework of the agricultural sector.

The South Asian countries have made various attempts to increase rice production through the application of modern technology, and in areas where the

---

Vice Chancellor, Tamil Nadu Agricultural University, Coimbatore 641003, India.

Table 1. Growth rate of population and agriculture in South Asia.[a]

| | Bangla-desh | India | Nepal | Pakistan | Sri Lanka |
|---|---|---|---|---|---|
| Population (millions) | | | | | |
| Actual (mid-1979) | 89 | 659 | 14 | 80 | 15 |
| Projected (2000) | 148 | 975 | 21 | 141 | 21 |
| Av annual growth rate of population (%) | | | | | |
| 1960-1970 | 2.4 | 2.3 | 2.0 | 2.8 | 2.4 |
| 1970-1979 | 3.0 | 2.2 | 2.2 | 3.1 | 1.7 |
| Av annual growth rate of agriculture (%) | | | | | |
| 1960-1970 | 2.7 | 1.9 | [b] | 4.9 | 3.0 |
| 1970-1979 | 1.9 | 2.1 | 0.8 | 2.1 | 2.6 |
| Av index of food production per capita (1969-1971 = 100) | | | | | |
| 1977-1979 | 92 | 99 | 88 | 101 | 124 |
| Labor force in agriculture (%) | | | | | |
| 1960 | 87 | 74 | 95 | 61 | 56 |
| 1979 | 74 | 71 | 93 | 57 | 54 |
| Av annual growth rate of labor force (%) | | | | | |
| 1960-1970 | 2.1 | 1.5 | 1.5 | 1.9 | 2.1 |
| 1970-1980 | 3.3 | 1.7 | 2.1 | 2.6 | 2.0 |
| 1980-2000 | 2.6 | 2.0 | 2.1 | 3.0 | 2.0 |

[a] Source: World Development Report (1981), The World Bank, Washington, August 1981. [b] Not known.

new technology has been adopted, production gains have been substantial. But adoption of improved seed-fertilizer-pesticide technology has not been uniform because of a number of physical, biological, and socioeconomic factors. Further expansion is possible, but economic forces, especially the escalating cost of fertilizers caused by the energy crisis, are not conducive to rapid growth.

For example, to meet the food needs of the Indian people in the year 2000, food output will have to be increased to 230 million t from the present level of 134 million t. The Indian National Commission on Agriculture has indicated that the increased crop output can be achieved through expansion and modernization of irrigation facilities, stepping up fertilizer use, and increased adoption of dry farming technology. Over 60% of the augmented production is expected to come through increased fertilizer use alone.

At present 4.1 million t of fertilizers are produced within India and 2.0 million t are imported annually at a cost of $750 million. By 2000, it is estimated that fertilizer consumption will be 21.6 million t, of which a sizable proportion will have to be imported. The price of fertilizers cannot be predicted or controlled since the basic raw materials have to be imported. To maintain parity in prices between internal production and imported fertilizers, the Government is now paying a subsidy. In 1976-77, the subsidy was $75 million, in 1981-82 it was $475 million, and in 2000 it will be a huge sum, disproportionate to the potential gains.

The average size of a farm in India is 2.3 ha (Table 2). The fertilizer-use pattern varies according to available resources; the poor farmer is not in a position to reap the full benefits of modern technology because of his inability to invest in fertilizers. Thus, disparities in growth between and within regions are created.

Is there any alternative to reliance on capital- and enera-intensive, external supply-dependent fertilizer to increase rice production? Can a cheaper, reliable, locally available, effective fertilization technology be recommended to the smaller rice farmers of South Asia? Research evidence and past experiences prove beyond doubt that organic matter-based agricultural systems, if judiciously used in combination with inorganic fertilizers, can help to increase rice production.

## EXPERIMENTAL EVIDENCE

A large number of field experiments have been conducted in South Asia to study the response of rice to organic manures such as farmyard manure, compost, green leaf manure, and green manure. The effectiveness of organic manures depends on several factors, including the kind and degree of decomposition, C-N ratio, time of application, soil characteristics, and soil moisture regimes during crop growth.

The summarized results of 341 experiments on rice from several states of India show that the response to the application of farmyard manure or compost at 12.6 t/ha varied from 100 kg/ ha in Maharashtra and Bihar to 216 kg/ha in Orissa (Garg et al 1971).

Sahu and Nayak (1971) studied the effect of continuous application of $(NH_4)_2SO_4$ alone and in combination with organic manures such as farmyard manure, green manure, and peanut cake on the lateritic sandy loam soil in Bhubaneswar. They observed that the best combination for high yield of indica rice was 45 kg N/ha as inorganic fertilizer with a basal dressing of farmyard manure supplying 45 kg N/ha. The yield was 2.67 t/ha. The yield with green manure and peanut cake at 45 kg N/ha was 2.06 t/ha and 2.35 t/ha, respectively, while that with $(NH_4)_2SO_4$ was 1.93 t/ha. The discrepancy can be explained by the ready availability of N from the two organic manures and the loss of N by leaching from $(NH_4)_2SO_4$.

Sahu and Nayak also reported that studies over a 10-year period indicated an

**Table 2. Land resource status in South Asia.**[a]

| | Bangladesh | India | Nepal | Pakistan | Sri Lanka |
|---|---|---|---|---|---|
| Av size of holding (ha) | [b] | 2.30 | 1.23 | 2.35 | [b] |
| Area per capita (ha) | 0.12 | 0.26 | 0.18 | 0.27 | 0.06 |
| Agricultural population (% of total population) | 84.4 | 64.6 | 92.8 | 54.5 | 54.1 |
| Density (no./km$^2$) | 559 | 190 | 93 | 94 | 215 |
| Irrigated area as % of arable land and land under permanent cropping | 15.6 | 20.5 | 8.2 | 67.0 | 59.2 |

[a] Source: Indian agriculture in brief, 18th edition, 1980, Directorate of Economics and Statistics. [b] Not known.

appreciable increase in total N content of soil with organic manure treatment. Farmyard manure application alone increased the N content from 0.029 to 0.058%; in combination with $(NH_4)_2SO_4$ it increased N content to 0.060%. The study clearly indicated the usefulness of farmyard manure in increasing rice yield in sandy loam soils.

Shinde and Ghosh (1971) reported the effects of continuous cropping and manuring on rice yields in medium black soils of Madhya Pradesh from 1955 to 1966. They concluded that the application of farmyard manure and inorganic fertilizers increased yield from 1.28 to 1.73 t/ha.

In experiments conducted by Gaur and Sadasivam (1981) in sandy loam alluvial soil in India, farmyard manure at 12 t/ha gave 41% more rice yield and 10% higher N uptake than conditions without farmyard manure.

Studies conducted for 2 years on the effect of farmyard manure application at 12 t/ha in rice-wheat rotation indicated that the organic C content increased from 0.23 to 0.30% and the available P content from 7 to 12 kg/ha (Gill and Meelu 1980). The combined application of farmyard manure at 12 t/ha with fertilizer at 80 kg N/ha gave the highest rice yield of 6.74 t/ha — equivalent to the yield with 120 kg N/ha, thus saving 40 kg N/ha (Table 3).

In a rice-wheat rotation study, application of 12 t/ha of farmyard manure to the rice crop produced a residual effect equivalent to that of N and P at 30 kg/ ha each on the succeeding wheat crop (Meelu 1981).

Sarkar et a1 (1973) studied the effect of application of farmyard manure at 15, 30, and 45 t/ha on slightly alkaline, noncalcareous, nonsaline sandy loam soils. They concluded that percentage aggregates of the soil samples analyzed increased significantly up to 104 days and declined thereafter. They also observed increases in organic matter content from 0.66 to 0.79% and in hydraulic conductivity from 0.64 to 1.03 cm/hour. Experiments conducted at the Central Soil Salinity Research Institute, Karnal, India, showed that application of farmyard manure at 50 t/ha supplied plant nutrients in alkali soils and contributed to rice yield increases from 5.4 to 7.7 t/ha (Central Soil Salinity Research Institute 1979).

In field trials at the Central Rice Research Institute at Cuttack the application of compost providing 80 kg N/ha gave a rice yield higher by 408 kg/ ha than did conditions of no fertilizer. An additional yield of 404 kg/ha resulted from the combined application of fertilizer N at 40 kg/ ha and the same level of compost (Central Rice Research Institute 1975).

In field experiments conducted in red loamy soils to determine the influence of

**Table 3. Effect of farmyard manure on nitrogen economy in rice.**[a]

| Farmyard manure (t/ha) | Fertilizer N (kg/ha) | Grain yield (t/ha) |
|---|---|---|
| 0 | 0 | 3.15 |
| 12 | 0 | 3.85 |
| 12 | 40 | 5.16 |
| 12 | 80 | 6.74 |
| 0 | 120 | 6.62 |

[a] Source: Meelu (1981).

**Table 4. Effects of organic and inorganic fertilizer nitrogen on rice yield**[a]

| Treatment[a] (120 kg N/ha as urea) | Grain yield (t/ha) | |
|---|---|---|
| | Summer 1980 | Monsoon 1980 |
| 100% | 5.75 | 5.21 |
| 75% + 25% N (FM) | 5.56 | 5.03 |
| 75% + 25% N (GLM) | 5.81 | 5.27 |
| 50% + 50% N (FM) | 5.33 | 4.77 |
| 50% + 50% N (GLM) | 5.52 | 5.15 |
| 25% + 75% N (FM) | 5.35 | 5.08 |
| 25% + 75% N (GLM) | 5.50 | 5.12 |
| CD[b] (P = 0.05) | 0.06 | 0.07 |

[a] Source: Naidu (1981). FM = farmyard manure, GLM = green leaf manure. [b] Critical difference.

organic manures on rice yield and on the release of P from rock phosphate, Ranjan (1981) found that application of compost at 10 t/ha with rock phosphate supplying 22 kg P/ha gave the highest grain yield of 5.9 t/ha with a common dose of N at 100 kg/ha and K at 374 kg/ha. The uptake of P by the grain increased from 11.5 to 28.1 kg/ha.

Long-term manurial trials at Cuttack from 1948 to 1969 showed that application of compost at 9 t/ha increased the soil organic C from 0.74 to 0.86%, total N from 0.080 to 0.089%, and cation exchange capacity from 21.6 to 22.4 meq/100 g while depressing the exchangeable bases of the soil. No such effect was observed with the application of either $(NH_4)_2SO_4$ or lime (Bandyopadhya et al 1969).

Experiments conducted in Sri Lanka revealed that green leaf manuring with glyricidia combined with the recommended dose of fertilizer increased rice yield by 60% over the control (Amarasiri 1978). In India, Naidu (1981), in a study of the effects of organic and chemical fertilizers on rice, found that application of 75% inorganic N as urea and 25% organic N in the form of green leaf manure gave the highest yield of 5.81 t/ha in summer and 5.27 t/ha during the monsoon (Table 4).

Incorporation of green gram haulms at 4.7 t/ha combined with inorganic N at 120 kg/ha increased the rice yield from 6.9 to 8.6 t/ha in India (Meelu and Rekhi 1981). The available N increased from 69 to 81 kg/ha. Plowing in of 4.7 t green gram haulms/ha, along with the application of 60 kg inorganic N/ha, gave a rice yield of 6.9 t /ha, equivalent to the yield with 120 kg fertilizer N/ha alone, thereby saving 60 kg N/ha.

In a pot experiment, the addition of glyricidia leaves at 20 t/ ha and rice straw at 5 t/ha to flooded soil generated a greater amount of $CO_2$ and higher concentrations of water-soluble $Fe^{++}$, $Mn^{++}$, and other cations than the control conditions. The bad effects of $CO_2$ and reducing products can be avoided if quick-decomposing organic materials are added to soil 3-4 weeks before transplanting of rice (Katyal 1977).

Bhardwaj et al (1981) concluded that green manuring with sunnhemp *(Crotalaria juncea)* saved about 75 kg N/ ha, daincha *(Sesbania aculeata)* 50 kg N/ha, and *Ipomoea carnea* 25 kg N/ ha in rice fields. The additional rice yield over conditions with no green manuring ranged from 225 kg/ ha in the case of *Ipomoea* to 1,966 kg/ ha in the case of sunnhemp. Daincha as a green manure applied to black alkali soils improved the availability of Zn from 0.28 to 0.41 ppm (ICAR 1977).

Sanyasiraju (1952) studied the relative merits of daincha, sunnhemp, pillipesara *(Phaseolus trilobus),* and cowpea *(Vigna unquiculata)* at the Agricultural Station at Coimbatore. The N content of the experimental field was originally 0.079% and the organic matter content 1.58%. The N content increased to 0.141% with daincha, 0.109% with sunnhemp, 0.109% with pillipesara, and 0.101% with cowpea. The organic matter content also increased to 3.18% with pillipesara, 2.42% with daincha, 2.18% with sunnhemp, and 2.02% with cowpea.

Tiwari et al (1980) studied the direct and residual effects of daincha on dryland rice-wheat rotation in a light alluvial soil. They reported that the N content of the rice plant at the tillering stage increased from 1.58 to 1.88%, the P content from 0.45 to 0.69%, and the K content from 2.73 to 3.48% because of green manuring over a fallow plot. The study also showed that green manure plus 40 kg N/ ha compared favorably with 120 kg N/ ha alone in increasing the rice yield (Table 5). The wheat crop following a rice crop with green manure registered a 54% increase in yield compared with the wheat crop that followed rice with no green manuring.

Biswas et a1 (1970) reported the effects of green manure, peanut cake, and farmyard manure alone and in combination with $(NH_4)_2SO_4$ on the physical condition of alluvial soils growing rice. All three treatments improved the aggregate stability, hydraulic conductivity, and water-holding capacity of the soil; of these, green manuring was the best.

Uppal (1955) found an increase in the N content of the rhizosphere soil of daincha, guar *(Cyamopsis tetragonoloba),* and sunnhemp to 0.098, 0.080, and 0.077%, respectively, from 0.059% in the control. The sodic soils were enriched with N and organic matter by green manuring with daincha. Dargan and Chillar (1975) studied the comparative performance of daincha with fertilizer N in alkali soils. They found that the yield of rice following green manuring was equal to the yield obtained with the application of 75 kg/ ha fertilizer N.

The results of permanent manurial experiments on rice in Madurai, Tamil Nadu, indicated that application of farmyard manure, green leaf manure, and compost in combination with NPK (120:60:60 kg/ ha) increased the organic matter content of the soil from 1.45 to 2.61 % with farmyard manure, from 1.46 to 2.70% with green leaf manure, and from 1.45 to 2.58% with compost (Mani et a1 1980).

Amarasiri (1978) conducted experiments in Sri Lanka to study the response of rice to the application of rice husk ash. A rice husk ash application of 0.74 t/ ha with

**Table 5. Effect of green manuring on rice yield.**[a]

| N level (kg/ha) | Yield (t/ha) | |
|---|---|---|
| | Fallow | Green manuring (daincha) |
| 0 | 2.37 | 3.85 |
| 40 | 4.04 | 4.91 |
| 80 | 4.63 | 5.27 |
| 120 | 4.98 | 5.37 |
| Mean | 4.01 | 4.85 |
| CD[b] (P = 0.05) | 0.35 | |

[a] Source: Tiwari et al(1980a). [b] Critical difference.

**Table 6. Effect of rice husk ash on rice yield.**[a]

| Rice husk ash (t/ha) (NPK 69:20:18) | Yield (t/ha) | |
|---|---|---|
| | 1st crop | 2nd crop |
| 0 | 6.7 | 6.8 |
| 0.37 | 6.9 | 7.4 |
| 0.74 | 7.7 | 8.2 |
| 1.10 | 7.2 | 7.6 |
| 1.48 | 7.3 | 7.1 |
| 1.85 | 6.3 | 7.0 |
| CD[b] (P = 0.05) | 0.4 | 0.5 |

[a] Source: Amarasiri (1978). [b] Critical difference.

the recommended level of fertilizers (69:20:18 kg NPK/ ha) yielded an additional 1.0-1.4 t/ha. However, further increase in the application of rice husk ash depressed the rice yield (Table 6). Experiments conducted in farmers' fields showed that application of rice straw ash at 1.0 t/ha gave a grain yield equivalent to that of 36 kg K/ha (Amarasiri and Wickramasinghe 1977).

A study on the addition of residues in different rice-based cropping systems revealed that a substantial quantity of residues could be added to the native soil by following a suitable cropping system (Purushothaman 1979). The rice-rice-finger millet-green gram cropping system added 3.7 t/ha of residues in a year and contributed to increasing the soil organic matter content from 1.33 to 1.58%. The performance of the rice crop after the completion of the cropping system revealed that the rice-rice-finger millet-green gram cropping system gave the highest grain yield of 5.6 t/ha among the rice-based cropping systems tested (Table 7).

Tanaka (1978) stated that addition of organic materials with a high C-N ratio leads to the temporary immobilization of N and the accumulation of substances toxic to rice plants. Cho and Ponnamperuma (1971) observed that the effect of toxins may not be particularly serious at the high temperatures in tropical soils.

Biofertilizer can be used to increase rice yield. Treatment of seed, seedling, and soil with *Azotobacter* helped improve initial plant growth and tillering of the rice crop, although the response of cultivars varied. Co40, Bhavani, IR20, Co37, Prakash, TNAU 4372, and TNAU 8870 responded to *Azotobacter* inoculation. The bacterial inoculant could compensate for 25% of the fertilizer N when applied in combination with 75% of the recommended level of the fertilizer. The yield obtained at the reduced level of N was on a par with that obtained at the recommended level of fertilizer (Oblisami et al 1976). Besides saving in N, the inoculation resulted in yield increases of up to 15.4%. Pig manure and farmyard manure influenced the beneficial activity of the inoculant, while compost deleteriously affected the performance (Rangarajan and Muthukrishnan 1976).

At Coimbatore, two rice cultivars responded positively to *Azospirillum* inoculation (Table 8). The performance of rice inoculated with *Azospirillum* at 75% of the recommended fertilizer N was equivalent to that of the full dose of N application (Natarajan et al 1980).

The use of *Azospirillum* alone with no basal application of N and the application of 30 kg N/ha gave equal rice yields (Lakshmi Kumari et a1 1976).

**Table 7. Residual effect in rice-based cropping systems.**[a]

| Cropping system | | | Yearly addition of residues (t/ha) | Change in organic matter (%) | | Effect of preceding summer crop on yield of succeeding kharif (t/ha) |
|---|---|---|---|---|---|---|
| Kharif (Jun-Sep) | Winter (Sep-Jan) | Summer (Feb-May) | | Initial | After 2 years | |
| Rice | Rice | Rice | 3.1 | 1.29 | 1.51 | 4.6 |
| Rice | Rice | Sorghum + cowpea | 3.3 | 1.26 | 1.59 | 4.5 |
| Rice | Rice | Finger millet + green gram | 3.7 | 1.33 | 1.58 | 5.6 |
| Rice | Rice | Maize + soybean | 3.1 | 1.37 | 1.49 | 4.4 |
| Rice | Rice | Cotton + black gram | 3.3 | 1.23 | 1.52 | 4.8 |

[a] Source: Purushothaman (1979).

**Table 8. Effect of *Azospirillum* on rice cultivars, Coimbatore.**[a]

| Treatment | Yield (t/ha) | | Yield increase (%) | |
|---|---|---|---|---|
| | TNAU 4372 | Co42 | TNAU 4372 | Co42 |
| No *Azospirillum* + 120 kg N/ha (control) | 3.80 | 6.76 | | |
| *Azospirillum* + 120 kg N/ha | 5.00 | 7.54 | 31.6 | 11.5 |
| *Azospirillum* + 90 kg N/ha | 4.24 | 7.14 | 11.5 | 5.6 |
| CD[b] (P = 0.05) | 0.36 | 0.39 | | |

[a]Source: Natarajan et al (1980). [b]Critical difference.

Waterlogged rice fields provide ideal conditions for multiplication of blue-green algae (BGA), which contribute 20-25 kg N ha. Algal inoculations have been found to be effective under different agroclimatic conditions and soil types (De 1939; Venkataraman 1972, 1975). Field trials conducted in India indicated that one-third of the recommended N fertilizer could be saved without affecting crop productivity by the application of BGA (Venkataraman 1982). In a number of field trials, higher levels of fertilizer N complemented with algal inoculation gave significantly higher yields up to 28.9%. Such an effect might be due to release of other growth-promoting substance besides N by the algae (Venkataraman 1979).

Azolla incorporation in rice fields increased grain yields from 13 to 54% (Singh 1979). Studies by Kannaiyan et al (1982) showed that azolla application at Coimbatore increased rice yields up to 16.0% (Table 9). Incorporating azolla basally as a green manure and growing it in dual cropping increased the rice yield to 60 kg N/ha (Kannaiyan et al 1982). Also, the growth of azolla in rice fields suppressed weeds.

The possibility of saving fertilizer N by a judicious combination of heterotrophic bacterial inoculants and BGA was investigated. *Azotobacter* and BGA were compatible and reduced the use of fertilizer N by 37.5% of the recommended level (Oblisarni et al 1977).

Thus, experiments conducted over a period of time in different locations have amply proved that organic matter positively influences the yield of rice by improving

**Table 9. Effect of azolla on yield of Co37.**[a]

| Level of N (kg/ha) | Yield (t/ha) | | Yield increase (%) |
|---|---|---|---|
| | Without azolla | With azolla | |
| 0 | 3.37 | 3.91 | 16.0 |
| 20 | 4.65 | 4.81 | 3.4 |
| 40 | 5.39 | 5.69 | 5.6 |
| 60 | 5.03 | 5.70 | 13.3 |
| 80 | 5.45 | 5.90 | 8.3 |
| 100 | 5.49 | 6.11 | 11.3 |
| 120 | 6.00 | 6.47 | 7.8 |
| CD[b] (P = 0.05) | 0.42 | | |

[a]Source: Kannaiyan et al (1982). [b]Critical difference.

the physical, chemical, and biological properties of soil. High yields of rice can be secured, experiments indicate, by judiciously combining organic matter with inorganic fertilizers. The organic matter required for fertilization can be obtained through recycling of farm wastes and by including a legume crop in the cropping system. The potential of biofertilizers for supplementing fertilizer N to rice crops offers opportunity for further research.

## FARM PRACTICES AND FUTURE APPROACHES

Farmers in South Asia are well aware of the usefulness of organic matter in increasing rice yields. In fact, persuading them to use inorganic fertilizers in the early 1950s was a Herculean job for the extension organizations. Nevertheless, certain problems connected with greater use of organic matter should be overcome to facilitate the judicious use of organic and inorganic fertilizers on a larger scale.

It is often said that farmyard manure should be conserved for use in increasing rice yields. But in most of the South Asian countries. particularly in India, cow dung is one of the main energy sources for cooking. Bits of straw and cow dung are made into thin cakes, dried in the sun, and used as fuel in rural homes. Until cheaper sources of energy are made available to rural people, continued use of cow dung as a fuel cannot be prevented. Biogas technology, which enables securing both cooking gas and manure from cow dung and farm wastes, is slowly becoming popular among farmers. Rapid expansion in the use of this technology in rural areas is likely to enable increased fertilization of rice fields with the enriched effluents of the digesters.

Rural compost is made by farmers with farm wastes. Since the cow dung component is very small, the N content of rural compost is low. There is no public health conservation system in most of the villages, and so the night soil in the rural areas is completely wasted and becomes a health problem. Establishing public health conservation systems in rural areas will improve the health and sanitation of villages and make available cheap but highly useful manure for farming.

In cities, compost with night soil and rubbish is made and sold to farmers, but the quality of compost is poor. Glass and metal pieces are not sieved and removed, and these objects injure the hooves of draft animals while puddling. The quality of urban compost can be enhanced by mechanical composting.

Green manuring and green leaf manuring are practices well known to the farmers. In single-crop areas, kolinji *(Tephrosia purpurea)* is raised as a green manure crop in rotation with rice. This plant withstands drought and gives a high rice yield of 3.5-5.0 t/ha. In double-crop areas, sunnhemp, daincha, pillipesara, etc., are grown as green manure crops during summer and plowed in situ for the succeeding rice crop. In places adjoining forests and large dry tracts, leaves of various plants are cut from the forests and dry lands and applied to the rice crop. But these practices are no longer extensive since the introduction of organic fertilizers. If there is residual moisture in the soil, the farmer now prefers to grow a catch crop of legumes, groundnut, maize, finger millet, onion, etc. and to resort to application of inorganic fertilizers for the next rice crop. The economic advantage is in favor of raising another catch crop instead of a sole green manure crop. In certain areas, indiscriminate cattle grazing due to inadequate social control is yet another reason for the reluctance of the farmer to raise a green manure crop. If these problems are to be overcome. new agronomic techniques to grow green manure crops or plants, without sacrificing an additional catch crop, will have to be developed and popularized. Social organizations to enforce informal social control on the grazing of animals and better utilization of public lands for sylvipasture will have to be established.

Crop residue management as a practice in rice farming is in vogue in certain areas. In the Cauvery River command area of Thanjavur in Tamil Nadu, farmers leave a fairly good amount of straw in the field when cutting the first crop, plow the residue into the soil, and transplant the second crop of rice within 15 days. But in other places, the rice is cut flush with the ground since the straw is a valuable feed for animals. If larger crop residues are to be left in the field for the succeeding rice crop. fodder will have to be separately raised. Selection and introduction of fast-growing, high yielding grasses and legumes in farming systems deserve special consideration.

Growing of legumes as catch crops in summer is yet another practice followed in the river valleys. After pods are collected, the plants are pulled out and incorporated in the soil as green manure. This practice can be extended to larger areas.

The use of biofertilizers including azolla is a relatively new practice for rice farmers. Early experience in popularizing BGA in certain parts of India is encouraging, and these new approaches are likely to be accepted, provided service organizations are established to make efficient strains of microbes available.

Analysis of the existing systems, future needs, and research experiences amply dictates that increased rice production, which is absolutely essential for South Asian countries to meet the growing needs of their increasing populations, can be achieved at a lower cost and with fewer ecological ill effects through judicious use of organic matter and inorganic fertilizers. To bring about this desirable change, attention should be focused on research, education, services, and policy, as follows:

*Research*

- Evolution of drought resistant, more succulent, large biomass-yielding, short-duration green manure plants suited to different agroclimatic environments
- Alternative cheap energy resources for use in rural households
- Selection of virulent thermophilic microorganisms for quick decomposition of organic matter
- Evolution of efficient strains of free-living, N-fixing microorganisms through genetic engineering
- Multiplication and use of azolla in tropical belt
- Agrotechniques to raise green manure crops as companion crops with rice
- Development of efficient implements for incorporating organic materials
- Measures to reduce the ill effects of application of organic matter to ill-drained soils in rice farming
- Indirect use of biological N-fixing organisms through legume catch crops

*Education and service*

- Establishment of laboratories to supply efficient strains of microbes
- Introduction of public health conservation systems in rural areas

- Establishment of mechanical composting facilities in urban areas
- Reorientation of extension services to promote organic matter-based farming systems

*Policy implications*

- Establishing suitable social systems in the rural areas to control grazing, and establishment of wood lots on common lands
- Commitment to development of rural energy systems and promotion of organic matter-based farming systems

## REFERENCES CITED

Amarasiri, S. L. 1978. Organic recycling in Asia — Sri Lanka. FAO Soils Bull. 36: 119-133.

Amarasiri, S. L., and K. Wickramasinghe. 1977. Use of rice straw as a fertilizer material. Trop. Agric. 33:39-49.

Bandyopadhya, A. K., R. Sahoo, A. Bhadrachalam, and S. Patnaik. 1969. Effect of continuous application of compost, ammonium sulphate and lime on some physical and chemical properties of rice soil. J. Indian Soc. Soil Sci. 17:369-374.

Bhardwaj, S. P., S. N. Prasad, and G. Singh. 1981. Economizing N by green manures in rice-wheat rotation. Indian J. Agric. Sci. 51:86-90.

Biswas, T. D., M. R. Roy, and B. N. Sahu. 1970. Effect of different sources of organic manures on the physical properties of the soil growing rice. J. Indian Soc. Soil Sci. 18:233-242.

Central Rice Research Institute. 1975. Annual report, Cuttack, India. 384 p.

Central Soil Salinity Research Institute. 1979. A decade of research. Karnal. India.

Cho, D. Y., and F. N. Ponnamperuma. 1971. Influence of soil temperature on the chemical kinetics of flooded soils and the growth of rice. Soil Sci. 112:184-194.

Dargan, K. S., and R. K. Chillar. 1975. Central Soil Salinity Research Institute. Pages 53-54 *in* Annual report. Karnal, India.

De, P. K. 1939. The role of blue-green algae in nitrogen fixation in rice fields. Proc. Roy. Soc. London 127:121-139.

Directorate of Economics and Statistics. 1980. Indian agriculture in brief. 18th edition. New Delhi. India.

Garg, A. C., M. A. Idnani, and T. P. Abraham. 1971. Organic manures. ICAR Tech. Bull. 32.

Gaur, A. C., and K. V. Sadasivam. 1981. Organic manures in aid of fertilizers. Indian Farming 31:31-37.

Gill, H. S., and O. P. Meelu. 1980. Proc. RRAI Symp. Punjab Agric. University, Ludhiana, India.

Indian Council of Agricultural Research. 1977. Annual report. New Delhi. India.

Kannaiyan, S., M. Thangaraju, and G. Oblisami. 1982. Studies on multiplication and utilization of *Azolla* biofertilizer for rice crop. Abstract. National symposium on biological nitrogen fixation, New Delhi. 50 p.

Katyal, J. C. 1977. Influence of organic matter on the chemical and electrochemical properties of some flooded soils. Soil Biol. Biochem. 9:259-266.

Lakshmi Kumari, M., S. K. Kavimandan, and N. S. Subba Rao. 1976. Occurrence of nitrogen fixing *Spirillum* in roots of rice, sorghum, maize and other plants. Indian J. Exp. Biol. 14:638-639.

Mani, S., G. V. Kothandaraman, and K. K. Krishnamoorthy. 1980. A note on the accumulation of organic matter in rice soil. Madras Agric. J. 67:767-768.

Meelu, O. P. 1981. Integrated use of fertilizers and manures in cropping sequence. Indian Farming 31:75-79.

Meelu, O. P., and R. S. Rekhi. 1981. Mung straw management and nitrogeneconomy in rice culture. Int. Rice Res. Newsl. 6.

Naidu, M. 1981. Studies on the appropriate proportion of organic and chemical fertilizers. MS thesis. Tamil Nadu Agricultural University. Coimbatore.

Natarajan, T., P. Santhanakrishnan, and G. Oblisami. 1980. Response of rice varieties to *Azotobacter* and *Azospirillum* inoculants. Abstract. National symposium on biological nitrogen fixation crop production. Tamil Nadu Agricultural University. Coimbatore. 25 p.

Oblisami, G., T. Natarajan, and K. Balaraman. 1976. Effect of *Azotobacter* on rice crop. Madras Agric. 63:590-594.

Oblisami, G., P. Santhanakrishnan, and T. Natarajan. 1977. Effect of combined inoculants of *Azotobacter* and blue-green algae on rice crop. Pages 104-105 *in* Abstracts, 18th Annual Conference, Madurai.

Purushothaman, S. 1979. Studies on rice-based multiple cropping systems. PhD thesis. Tamil Nadu Agricultural University. Coimbatore.

Rangarajan, M., and P. Muthukrishnan. 1976. Effect of various organic manures and *Azotobacter chroococcum* on the growth and yield of paddy. Madras Agric. J. 63:611-615.

Ranjan, A. S. 1981. Influence of organic matter on the release of phosphorus from rock phosphate and its effect on yield content and uptake of nutrients by rice. MS thesis. Tamil Nadu Agricultural University. Coimbatore.

Sahu, B. N., and B. C. Nayak. 1971. Soil fertilizer investigation under continuous application of ammonium sulphate alone and in combination with the organic sources in Bhubaneswar long-term fertility trials. Proc. Int. Symp. Soil Fert. Eval. 1:873-879.

Sanyasiraju, M. 1952. Role of organic manures and inorganic fertilizers in soil fertility. Madras Agric. J. 39:132-139.

Sarkar, M. C., M. Singh, and Jagan Nath. 1973. Influence of farmyard manure on soil structure and some related soil properties. J. Indian Soc. Soil Sci. 21:227-229.

Shinde, D. A., and A. B. Ghosh. 1971. Effect of continuous cropping and manuring on crop yield and characteristic of a medium black soil. Proc. Int. Symp. Soil Fert. Evaln. 1:905-916.

Singh, P. K. 1979. Use of azolla in rice production in India. Pages 407-417 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Tanaka, A. 1978. Role of organic matter. Pages 605-620 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

Tiwari, K. N., A. N. Pathak, and Hari Ram. 1980. Green manuring in combination with fertilizer nitrogen on rice under double cropping system in an alluvial soil. J. Indian Soc. Soil Sci. 28:162-169.

Tiwari, K. N., A. N. Pathak, and S. P. Tiwari. 1980a. Fertilizer management in cropping system for increased efficiency. Fert. News 25:3-20.

Uppal, H. L. 1955. Green manuring with special reference to *Sesbania aculeata* for treatment of alkaline soil. Indian J. Agric. Sci. 25:211-235.

Venkataraman, G. S. 1972. Algal biofertilizers and rice cultivation. Page 75 *in* Today and tomorrow's printers and publishers. New Delhi.

Venkataraman, G. S. 1975. The role of blue-green algae in tropical rice production. Pages

207-218 *in* W. D. P. Stewart, ed. Nitrogen fixation by free-living organisms. Cambridge University Press, Cambridge, London.

Venkataraman, G. S. 1979. Algal inoculation in rice fields. Pages 311-321 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Venkataraman, G. S. 1982. Nitrogen fixation by blue-green algae and its economic importance in managing soil resources to meet the challenge to mankind. Pages 69-77 *in* 12th International Congress of Soil Science.

World Bank. 1981. World development report. Washington. USA.

## DISCUSSION

BHATTI: Even if they know the benefits of the use of organic matter and its recycling in the system, farmers often do not use the techniques advocated. One of the major constraints is the lack of fuel to cook food in households. What methods and policy procedures could you suggest to help improve the situation?

*VENKATARAMAN:* Suggestions are: a) organize establishment of alternate energy supplies to the rural areas, e.g., biogas, biomass through social forestry, coal, natural gas, etc.; b) technological innovations to use solar energy for rural households. The total energy requirements of the rural areas will have to be worked out; technologies and policies appropriate to the prevailing socioeconomic conditions and natural resources will have to be evolved and implemented,

PALANIAAPAN (comment): I have developed a model for quickening organic matter decomposition, which involves consecutive transfer of inocula from various pits already at different stages of decomposition to fresh composts. By this, one can shorten the time span to a third of the normal duration.

SCHARPENSEEL: One slide indicated highest rice yields with azolla plus lemna application. It seems they go well together. We sometimes found higher Na and P contents in the mixture than in pure azolla. What are your observations or comparisons?

*VENKATARAMAN:* The experimental data indicated that the azolla-lemna combination gave higher rice yields. This needs to be confirmed with further trials.

WOODHEAD: How was the reported greater amount of $CO_2$ measured? Was it by monitoring the surface flux or by measuring the concentration? Treatment of the problem would possibly differ depending on the answer.

*VENKATARAMAN:* The amount of $CO_2$ was measured by measuring the concentration in the soil solution.

# ORGANIC SOURCES OF PLANT NUTRIENTS

# SOIL ORGANIC MATTER AS A SOURCE OF NUTRIENTS

Wolfgang Flaig

Soil organic matter has different functions in plant growth. The liberation of nutrients from the organic materials occurs during the formation and dynamics of soil organic matter by microbial activity.

The enhanced utilization of mineral N fertilizers in the presence of organic matter in soil seems to be due to the function of nitrogenous organic soil constituents as slow-release N sources. Some of the related reactions are reported.

The yield of plants increases when they grow on soils well supplied with organic matter. Laboratory experiments show that low molecular weight substances from humus are taken up by the plants and influence metabolism. Corresponding experiments have been made with lignin degradation products, which are very important intermediates in the formation of humic substances in soil. The uptake of these phenolic compounds through the roots, their transformations in the plants, and possibly their influence on metabolism can be demonstrated.

Quinones, as model substances for oxidized lignin degradation products, decrease urease activity and nitrification.

Under natural conditions, plant nutrients enter the soil through the decomposition of dead plant materials. In agriculture they are added by farmers as residues of the harvest or in the form of stable manure and other organic materials. All these materials and the roots of the harvested plants are transformed during humification, the process by which inorganic plant nutrients become available for the next crop. The amount of nutritive elements in plant materials depends on their composition, which varies from plant to plant, and with the growth conditions of each plant.

Nitrogen is supplied by microbial fixation from the air and by precipitation. In some regions S also enters the soil through precipitation in varying concentrations up to those that can damage plant growth; in industrialized countries S deficiency is seldom observed. The N, P, and S added are mainly constituents of organic compounds. Most of the other elements are present in the form of organic complexes or as ions.

In soil many transformations of organic materials occur through microbial activity. The C skeleton of compounds is changed in most cases by oxidative

---

Retired director of Institute of Soil Biochemistry, Federal Agricultural Research Centre, Braunschweig-Voelkenrode, Braunschweig. Address: Otto-Hahn-Strasse 132, D-8708 Gerbrunn, Federal Republic of Germany.

processes. During humification the N compounds react in most cases as organic amino compounds and, to a lesser extent, as $NH_3$. which is formed from the amino compounds and finally oxidizes to nitrate. Some losses of N occur in gaseous form as $N_2$ or $N_2O$.

Sulfur is bound in the original organic compounds as $S^{2-}$, very seldom as sulfate, and transformed in the soil to sulfate.

Phosphorus occurs in the organic compounds as phosphate esters, which are hydrolyzed.

Cations such as K, Ca, Mg, and the heavy metals are present in plants as complexes. They are transformed during humification into ions by the destruction of the complexing C compounds. Very often they form other complexes with newly formed organic compounds during humification. They interact with the inorganic parts of soil colloids, mainly with silicic acids, sesquioxides, and clay minerals. The rate of formation of the complexes depends on soil properties and environment.

Alkali ions are sorbed by the organic or inorganic sorption complexes of soil at different rates, e.g., K ions form stronger bonds than Na ions. Therefore larger amounts of Na are transported by water to the sea, which contains a relatively high Na content.

The importance of Na for plant metabolism may be seen from the fact that the content of Na in the dry matter of plants is in the same range as that of N (>1%), while the contents of P, S, Ca, and Mg are a tenth of the range and those of micronutrients less than a hundredth.

From the point of view of plant growth under different environmental conditions, the terrestrial N cycle is of great importance. Clark and Rosswall (1981) have provided a detailed description of present knowledge. Therefore the discussion here will be limited to some effects on the N cycle of the constituents of soil organic matter that participate in the processes of plant growth. Plant growth depends mainly on the mode of availability of nutrients, especially N.

## EFFECTS ON PLANT GROWTH

For long it has been known that soil organic matter has a favorable effect on plant growth which cannot be explained by the addition of nutrients alone. The humified organic materials originating from harvested plants or other sources such as stable manure not only supplement N, P, K, and other nutrients, but also have physical or physiological effects.

Even in the mechanized and intensive agriculture in central Europe, N is obtained from diverse sources; Buchner et al (1974) reported that of the 150 kg N/ ha needed by crops, 62% comes from mineral fertilizers (83 kg N) and precipitation (10 kg N) and 38% comes from organic manures (40 kg N), fixation by symbiosis (10 kg N), fixation by asymbiosis (10 kg N), and content of seed (1.5 kg N).

About 60% of the N is added to the fields in the form of mineral fertilizers. When the small portion of 10 kg N/ ha that is contained in precipitation, is added, the total N added in the form of inorganic nitrogenous ions is 62%.

About 38% of the N enters the soil as organic materials (including the N content of seeds) or is fixed by symbiosis and asymbiosis. Not only is the addition of mineral fertilizers necessary for higher yields, but also the dynamics of the humic system in the soil must be considered. The decrease in the C content of soil through the degradation of soil organic matter as a consequence of enhanced microbial activity after the addition of mineral fertilizers year after year causes a continuous decrease of yield. Further increase of mineral fertilizers increases the yield but only to a level determined by local conditions. There must be a balance between fertilizer input and harvest output.

Similar considerations hold for other organic bound nutrients such as P and S. The utilization of inorganic fertilizers is increased in the presence of soil organic matter.

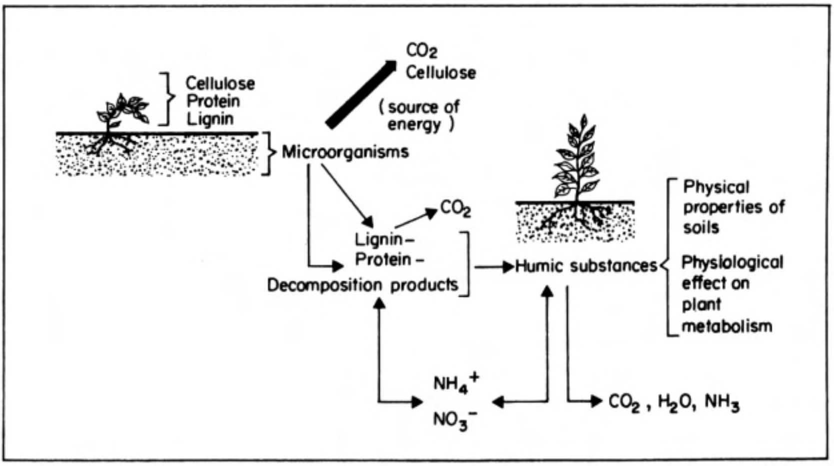
Biochemical investigations of the effects on plant growth of the interactions of some constituents of soil organic matter may create possibilities for regulating processes for the benefit of farmers.

## Humification

Nearly all reactions of organic materials that occur in soil are caused by microbial activity (Haider and Martin 1979, Fig. 1). This means that all the factors that influence microorganisms are important in the transformation of dead plant material. The most important factors are temperature, soil humidity, rate of gas exchange, availability of nutrients, and the structure of colloidal mineral materials.

Under both natural and cultivated conditions the main sources of organic matter are materials derived from plants such as roots, exudates of roots, residues of harvest, and stable manure. The main constituents of plants are cellulose and the hemicelluloses (30-65%), lignin (8–25%), and proteins and amino acids (1–5%).

Cellulose and the hemicelluloses are relatively easily decomposed. They are used by microorganisms mainly as sources of energy for metabolism. For this reason a large part is released from soil as carbon dioxide. Another part is transformed into compounds to build up the body substances of the microorganisms.



**1.** The formation of soil organic matter.

Proteins, peptides, and amino acids decompose relatively fast.

Lignin is more resistant to microbial attack. Degraded lignin and its phenolic decomposition products as well as microbially synthesized phenolic compounds react with proteins, peptides, and amino acids to form humic substances. During these reactions carbon dioxide and ammonia are also formed. Ammonia is oxidized to nitrate.

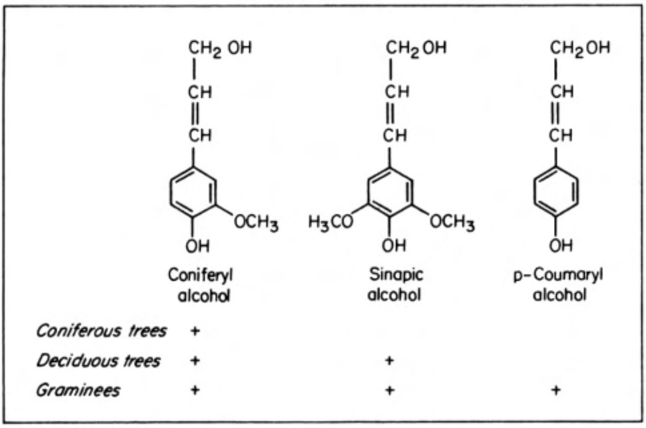
The humic substances are only partially stable. (The dynamics of the humic system will be reported in another paper by Scharpenseel and Neue.) They are finally decomposed to $CO_2$, $H_2O$, and $NH_3$ or $NO_3^-$.

Some fractions of soil organic matter have an effect on the physical properties of soils, e.g., linear or spherical organic colloids affect soil structure. The linear colloids belong mainly to microbially synthesized polysaccharides and the spherical ones to high molecular weight humic fractions. More details are reported by Larson and Clapp, this volume.

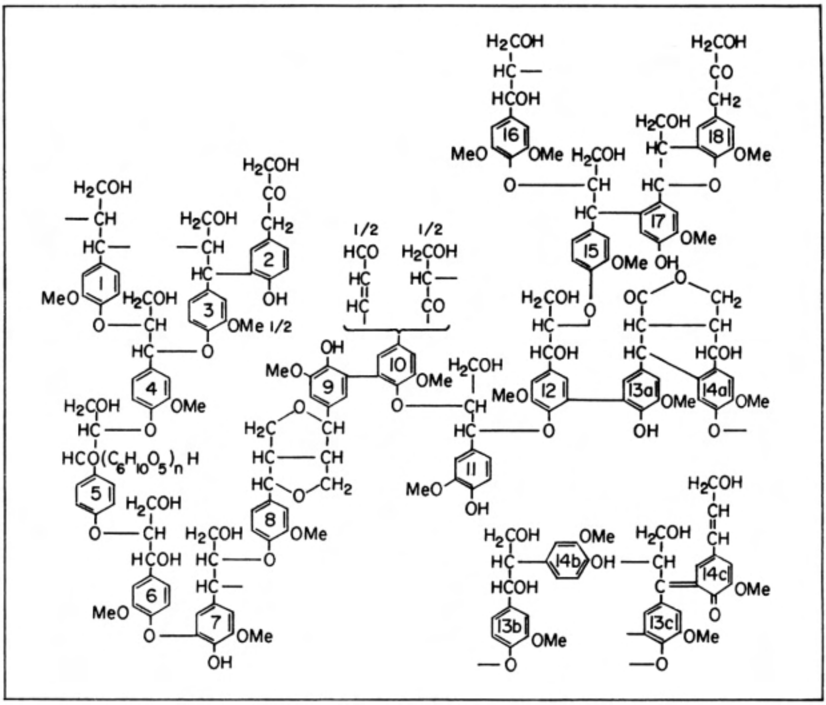
Some of the low molecular weight-constituents of soil organic matter have an influence on plant metabolism, as will be reported later (Flaig 1975).

Lignins are formed by oxidative polymerization of different building blocks, depending on the plant species. The main building block of coniferous lignin is coniferyl alcohol; in the case of deciduous lignin it is a mixture of coniferyl and sinapic alcohol. The lignin of graminaes contains a third building block, p-coumaryl alcohol (Fig. 2).

The structure of lignins is shown in Figure 3 by the simplified scheme of Freudenberg (1964). Further investigations have shown that the structure is much more complicated, especially when several monomers participate in the formation (Glaser and Glaser 1974, Nimz 1974). The monomers are linked by C-C bonds between the side chains and rings as well as by bonds between the phenolic hydroxy groups and the side chains. These linkages differ in stability. The rate of cleavage of the different bonds can be followed by labeling the C atoms in the methoxyl groups, in the ring, or in the side chain. The synthesis of lignins with specifically labeled monomers can be made in vitro or in growing plants.



2. Monomers of different lignins.

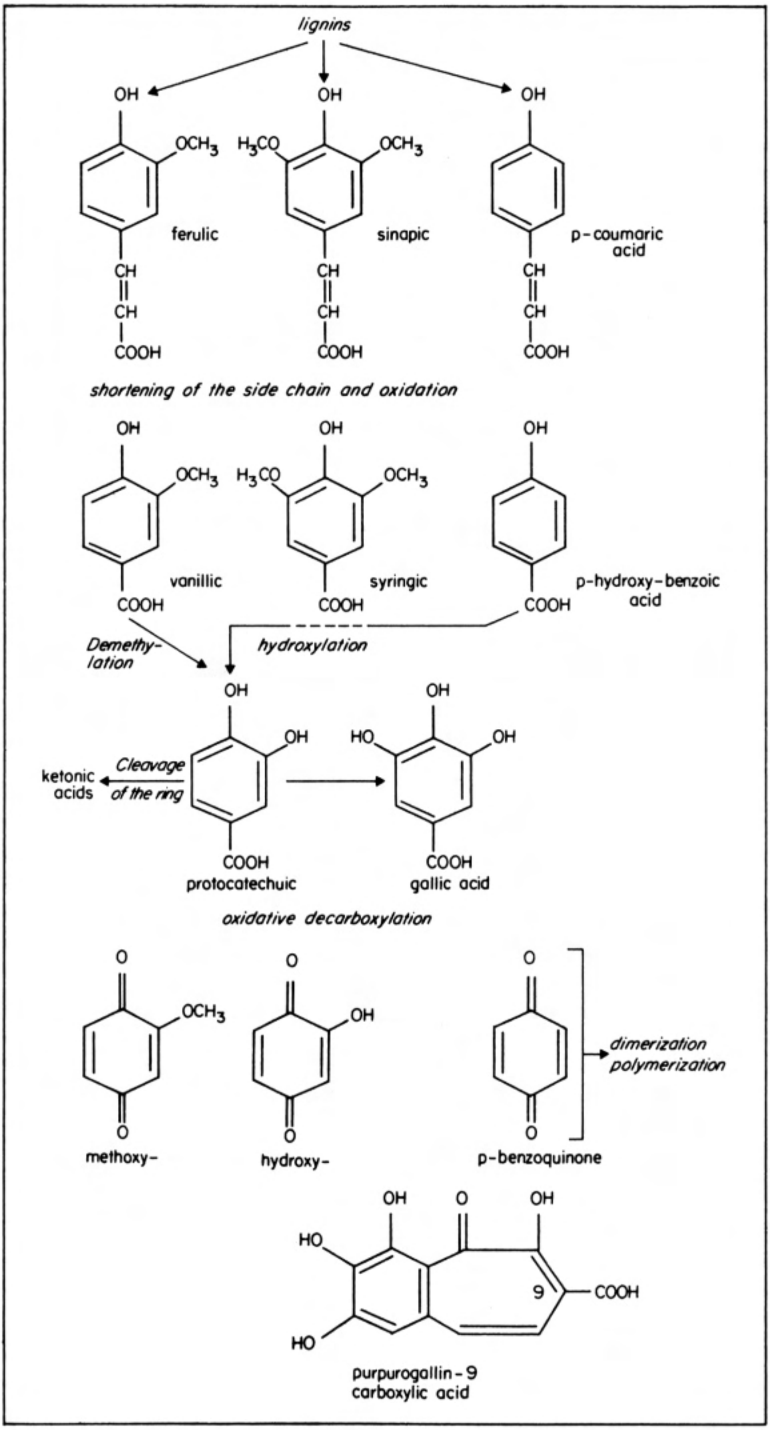


**3.** Simplified structure of coniferous lignin (Freudenberg 1964).

These reactions are important for studies on the formation of humic substances and of low molecular weight phenolic compounds in soil (Flaig 1982). Further chemical details have been published in several books (Flaig et al 1975; Schnitzer and Khan 1972, 1978; Ziechmann 1980). Lignin degradation can be followed in detail (e.g., Martin and Haider 1977, Haider and Martin 1979).

During experiments on rotting of straw it was demonstrated that the addition of an inorganic N source such as 1% $NH_4NO_3$ per dry weight of straw increased not only the rate of decomposition of total straw but also that of the lignin in the straw. In the isolated lignin fractions, the content of methoxyl groups decreased and the N content increased in the course of rotting. The demethylation occurring during the degradation of lignin is a prerequisite for the addition of $\alpha$-amino compounds from rotting plant material or those formed by microorganisms (Flaig et al 1959). This reaction is an important step in the formation of humic substances and also in the N cycle in soil. Some of the newly formed nitrogenous compounds serve as slow-release N fertilizers for plant nutrition because they are more resistant to microbial degradation than the initial materials. Some other phenolic compounds that are formed as metabolic products of soil microorganisms participate in these reactions (Martin and Haider 1971, Haider et al 1975).

During lignin degradation, different phenol acrylic and phenol carboxylic acids are formed (Fig. 4). Nearly all the compounds mentioned in the scheme can also be isolated from humified plant material (Maeder 1960, Flaig 1962) or from soils

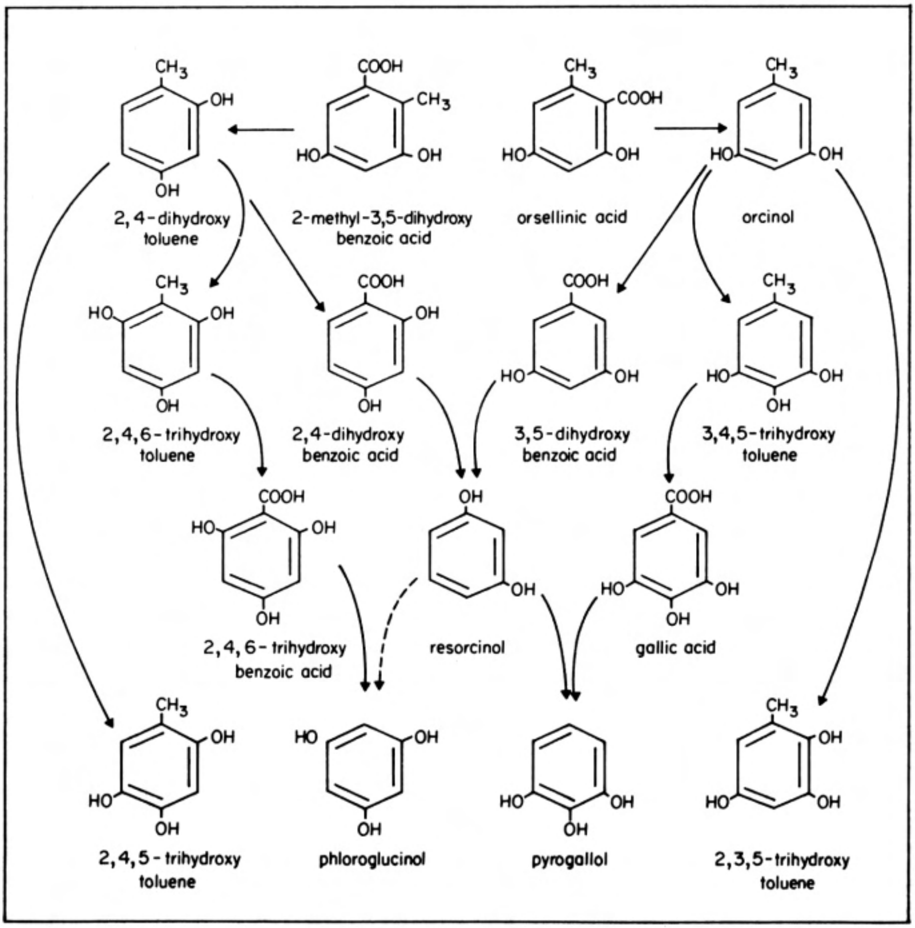


**4.** Transformation of lignin degradation products.

(Bruckert et al 1967, Schnitzer and Khan 1972). They are relatively easily decomposed by soil microorganisms (Martin and Haider 1979), but may be found in rotten straw after 6 months (Maeder 1960).

The main reactions are:

1. Cleavage of the double bond of the cinnamic acids to phenol carboxylic acids.
2. Splitting of the phenol ethers to hydroxy groups — demethylation of vanillic acid to protocatechuic acid and of syringic acid to gallic acid.
3. Oxidative hydroxylation to polyphenolic acids — p-hydroxybenzoic acid to protocatechuic acid and this to gallic acid.
4. Cleavage of the benzene ring occurs in the case of all compounds that have two hydroxy groups in the o-position. The keto carboxylic acids formed serve the microorganisms as carbon sources. In this way some aromatic compounds are eliminated from the formation of humic acids.
5. Oxidative decarboxylation — vanillic acid to methoxy-hydroquinone or



**5.** Synthesis and transformation of phenols by *Epicoccum nigrum.*

methoxy-benzoquinone or syringic acid to 2,6-dimethoxy-hydroquinone. This reaction can also be observed in plants after the uptake of the corresponding phenol carboxylic acids through the roots.

6. Dimerization and polymerization reactions play an important role in the formation of the constituents of the humic system and, together with the addition of amino compounds, lead to higher molecular weight, humic acid-like substances, some with the function of slow-release N fertilizers. Dimerization products such as divanillic acid or purpurogallin can be isolated in addition to others, the chemical constitutions of which are not yet completely known. It can be concluded from some preliminary experiments that they are metabolically active.

The rates of these different reactions were followed with $^{14}$C labeled compounds.

Some fungi such as *Epicoccum nigrum* form orsellinic acid (6-methyl-2,4-dihydroxybenzoic acid) or 2-methyl-3,5-dihydroxybenzoic acid in nutrient solution by acetate or mevalonic acid metabolism (Haider and Martin 1967); all the compounds in the reaction sequence have been identified. Phenolic compounds with hydroxy groups in the ortho-position are formed, and dark-colored, humic acid-like substances can be isolated. The microbially synthesized phenolic acids are transformed by oxidation of the methyl groups to carboxyl compounds and then by decarboxylation or hydroxylation to hydroxy compounds (Fig. 5).

The polymeric substances have been investigated. Their N content — especially α-amino N — is higher than that of the humic acids isolated from soils. This may be explained by the fact that they are not of the same “age” as the soil humic acids. After hydrolysis their properties are similar to those of the natural humic acids in chemical composition and data from gas chromatography and mass spectrometry (Meuzelaar et al 1977). This statement is also a contribution to the properties of humic fractions as slow-release N fertilizers. These fertilizers are acknowledged as favorable N sources for plant production because they deliver N in a steady flow during vegetation. Therefore they have several advantages over ionic mineral fertilizers (Mitscherlich 1948).

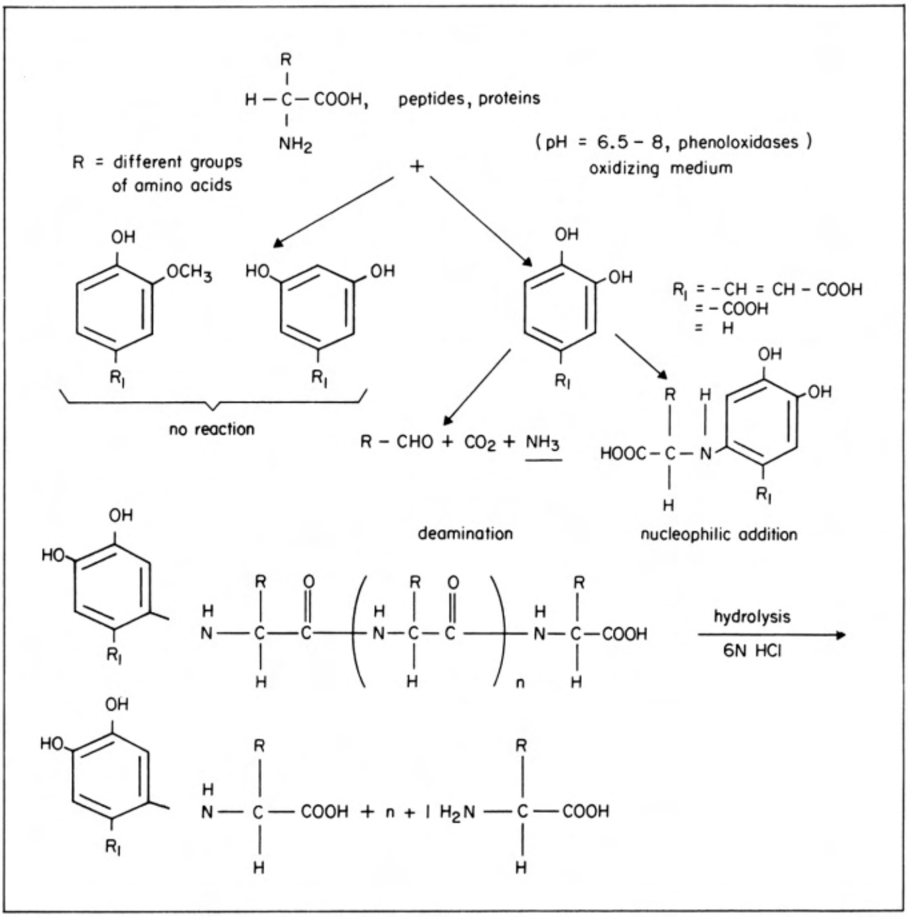
## Slow-release nitrogen source

The main reaction in the formation of humic substances is the condensation of compounds derived from lignin degradation or from microbial synthesis with proteins and their degradation products. The first step is the addition of compounds containing the amino group to phenols through semiquinonoid intermediates in an oxidizing medium, catalyzed by phenoloxydases. The reaction was followed with labeled compounds. The principal reactions for the functions of humic substances as slow-release N fertilizers are depicted in Figure 6 (Haider et al 1965, Flaig 1975).

Partially methylated o-diphenols and diphenols with hydroxy groups in the m-position do not add amino compounds under conditions comparable to those in soils (about 20° and pH values of 6.5-8). Only phenolic compounds that have hydroxyl groups in 1,2- or 1,4-positions react with amino compounds.

Two reactions are chiefly involved in the formation of humic substances:

1. Nucleophilic addition. By means of labeled Compounds it was established that the amino acids are added intact.



**6.** Nucleophilic addition and oxidative deamination

2. Oxidative deamination, whereby the amino acid is transformed to $CO_2$,$NH_3$, and a carbonyl compound in the mentioned case of an aldehyde. The importance of the liberation of $NH_3$ from amino acids in soil during this reaction has not yet been elucidated.

Nucleophilic addition and oxidative deamination often occur simultaneously; the relative reaction rates depend on the chemical constitution of the phenolic compounds. In nucleophilic addition, one molecule of phenolic compound reacts with one amino compound; but one phenolic compound catalyzes the oxidative deamination of several amino acids.

Amino compounds such as proteins, peptides, amino acids, and amino sugars, which are synthesized by soil microorganisms, are partially stabilized against microbial degradation after nucleophilic addition (Bondietti et a1 1972). This means a temporary enrichment of organic nitrogenous substances in soil, which can serve as slow-release N fertilizers for plant nutrition.

In nucleophilic addition of proteins, one amino acid after another can be hydrolyzed with the exception of N-terminal amino acids, in which the amino group reacts with the oxidized phenol (Haider et al 1965, Haider and Martin 1970).

The humic acids, the most stable fraction in the humic system, with an average N content of 1-5%, can be characterized by hydrolysis with 6 N HCl (Bremner 1965).

In the hydrolyzate, the N was determined to be 20-40% $\alpha$-amino N — at least 7-12% in peptide linkage, 1-5% in amino sugar N, and 10-25% in $NH_3$. About 50% of the N remains in the residue after hydrolysis. It is supposed that this part of the N is bound mostly in heterocyclic form. With pyrolysis-mass spectrometry, some heterocyclic compounds can be determined (Haider et al 1977, Saiz-Jimenez et al 1979). But linkages of N exist also that cannot be hydrolyzed and are not heterocyclic bound (compare with Fig. 6.)

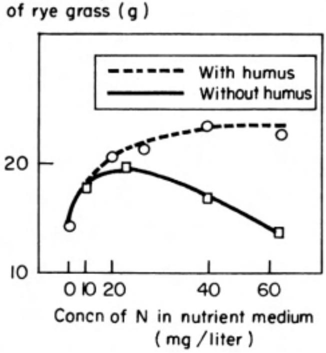
Approximately 50-60% of the N in the harvested plant comes from mineral N fertilizers and 40-50% from the storage of organic bound N in soil. The addition of fertilizers with $NH_4^+$ and nitrate salts to soils not only contributes to plant nutrition, but also increases the microbial activity in the soil. The organic C components in the soil are used as sources of energy. A decrease of C content of soil leads to a deterioration of soil structure, which may result in soil erosion or leaching of nutrients.

### Uptake of low molecular weight organic substances

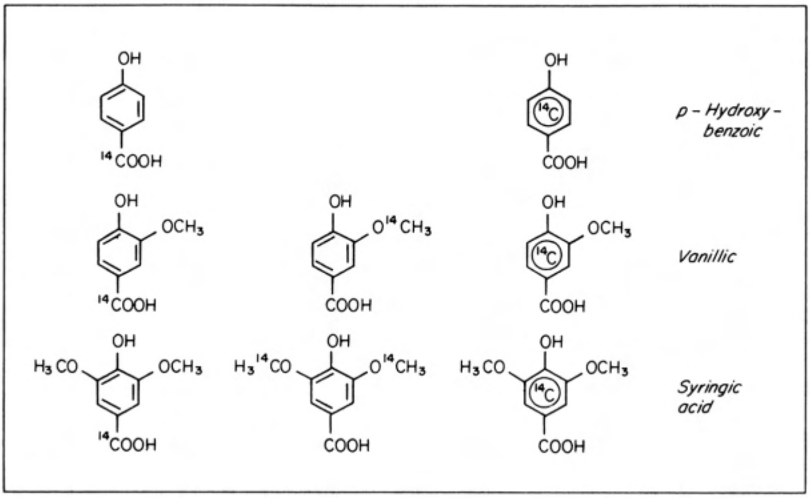
Components of soil organic matter not only affect the physical properties of the soil and act as a source of slow-release N, but also affect plant metabolism (FAO 1978).

Chaminade (1966) was one of the first to find that overdoses of inorganic nitrogenous salts in sand culture increased the yield of rye grass in the presence of humus; without humus yield decreased (Fig. 7). In water cultures as well, adding humic fractions has a favorable effect on yield. In these experiments the effect of the different fractions of humus cannot be explained by alterations of the physical properties of the culture medium. Fractions of soil organic matter may therefore have an effect on plant metabolism after uptake through the roots, but the effect is not yet completely understood.

Because the participation of high molecular weight substances from soil organic



**7.** Influence of humic substances on yield with overdoses of inorganic nitrogenous salts.



**8.** Differently labeled phenol carboxylic acids.

matter can be excluded (Soechtig and Harms 1971), experiments were made with chemically defined model substances of phenolic structure (Soechtig 1964, Flaig 1968, Flaig and Soechtig 1973, Flaig 1975). Alterations were found in sugar metabolism, the citric acid cycle, and oxidative phosphorylation. In sand cultures with nutrient solutions, several pot and field experiments showed that the yield was increased mainly under unfavorable environmental conditions. For instance the treated plants had a higher content of reducing sugars (Saalbach 1957). By having higher osmotic values the treated plants had a higher resistance to drought or frost (Soechtig 1964). Differences in ion uptake have also been observed.

Phenol acrylic and phenol carboxylic acids can be isolated from soils in concentrations of about $10^{-4}$ M. To determine if these substances can be taken up by the roots, and what reactions occur with them in plants, differently labeled phenol carboxylic acids were used (Fig. 8).

The carboxylic acids were labeled with $^{14}C$ in the carboxyl group, in the methoxyl group, or uniformly in the ring. In this way the rate of uptake, the transport, and the transformation of the phenolic acids added to the plant could be followed. The labeling of different C atoms on one compound allowed investigation of certain questions, e.g., whether vanillic and syringic acid are oxidatively decarboxylated to the corresponding methoxy-hydroquinones in the plant to about 1% of the activity of the added compound (Harms et al 1971).

Numerous experiments with wheat seedlings were made in a sterile water culture (Harms et al 1969 a,b). After 6 days of incubation the seedlings had taken up 1-3% of the added activity. Five to fifteen percent of the activity in the sprouts was in the form of the free acids. About 60-80% of the activity was determined to be glucose esters or glucosides of the glucose esters of the respective added acids — the alcoholic monomers of lignins are transported in plants in the form of glucosides (Freudenberg 1962). After the splitting of the glucosides in the cells by a ß-glucosidase, lignin formation starts. At the moment there is no explanation for the importance of the glucosides of the phenol carboxylic acids and their possible cleavage to the acids again in the plant. Potato plants with a higher content of phenol carboxylicacids are more resistant to phsophthera (Olteanu and Brad 1969) and wheat plants more resistant to stem rot (Chigrin et a1 1973). The same may be true for fungal infections of rice (Purushothaman 1974).

Another interesting result of these investigations is that up to 10% of the added activity was determined to be labeled $CO_2$. The quantity in each experiment depended on the substitution in the benzene ring of the added phenyl carboxylic acids. This reaction must occur in the plant, because at the end of the experiment only the original added compound and the added activity minus the one taken up could be determined in the culture solution. Hydroquinones or corresponding quinones, which are very reactive, must have been formed in the plant by oxidative decarboxylation. The dependence of the reactivity of the phenolic acids on their substitution was additionally investigated with cell suspension cultures (Fig. 4; Harms 1972, 1973; Harms et a1 1972).

It was found with sand cultures and some pot experiments that the phenolic compounds at lower concentrations had a favorable effect on plant growth and grain or straw yield under special environmental conditions (Saalbach 1958).

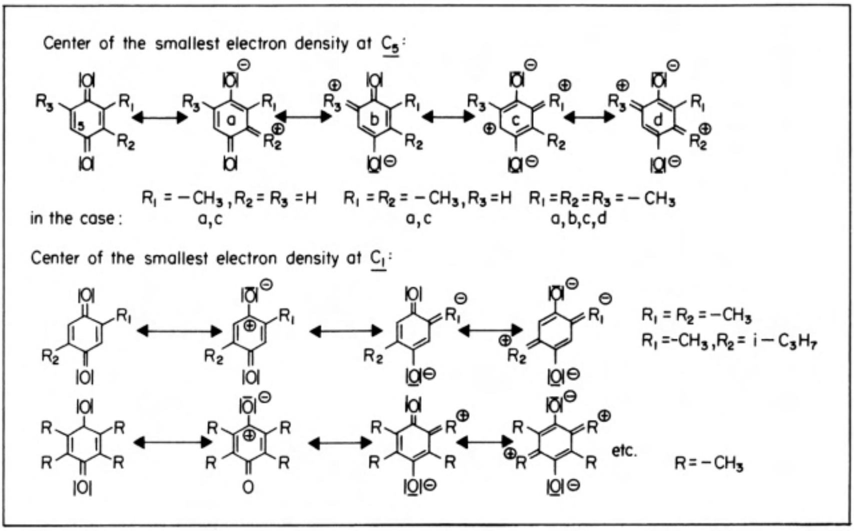
## Alterations of plant metabolism

One of the factors that have a favorable effect on plant growth, then, may be the presence of lignin degradation and its transformation products in soil. Therefore the author's group studied model substances of decarboxylated phenol carboxylic acids such as methylsubstituted quinones, which have varying effects on the growth of seedlings of rye in sand culture with nutrient solution in concentrations of $10^{-3}$ to $10^{-4}$ *M* (15-150 mg/1). Some have been more effective and some less.

On the basis of physical measurements (e.g., UV and IR spectra, redox potential) the distribution of electron density on the ring, and thus the favored center for reactions, was determined (Riemer 1970, Flaig and Riemer 1971, see Fig. 9). There are two groups of quinones. One has the smallest electron density at $C_5$; this C has a positive charge compared with the others. This group is less effective in the experiments with the seedlings. The other group has the smallest electron density at the $C_1$; the carbonyl group is strongly polarized. It has a stronger effect in the plant experiments.

According to the chemiosmotic theory of Mitchell (1966), the effect of physiologically active substances can be explained by their complex formation with alkali ions, causing an increase in the permeability of lipid membranes, as do other growth substances. The effect of the methyl-substituted benzoquinones-1,4 on the increase in dry weight of the seedlings could therefore also depend on this tendency toward complex formation, whereby the distribution of the electron density in the ring system of the quinones plays an important role.

Quinones form strong complexes with alkali ions in water-free media depending upon the molecular structure (Peover and Davies 1963). The lipid phase of the cell membrane can also be considered as a water-free medium in which the quinones are transported.



**9.** Distribution of electron density in differently methyl substituted benzoquinones – 1, 4.

The tendency of quinones for complex formation with alkali ions decreases as follows:

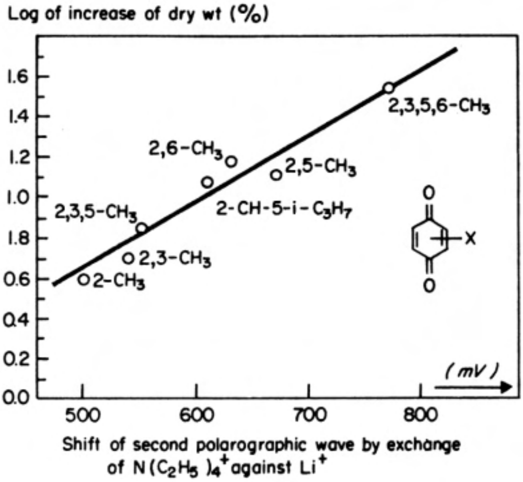
$$Li^+ > Na^+ > K^+ > N\,(C_2H_5)_4{}^+$$

The tendency of complex formation can be measured by the shift of the second polarographic wave of the quinones; this means the reduction of the dependence of the semiquinone radical ($Q^- + e^- \rightarrow Q^{2-}$; Q= quinone) on the added ions. Radicals have also been shown in fractions of humic substances (Schnitzer 1982).

It was hypothesized that the tendency of complex formation of quinones with alkali ions may be the reason for the increase in dry weight of seedlings. This was tested by determining the shift of the second polarographic wave of the methyl-substituted quinones in acetonitrile (water-free medium) in 0.1 *M* $LiClO_4$ solution against a solution of 0.1 *M* $N(C_2H_5)_4ClO_4$. The correlation of the log of the increase of dry weight, in percent, and the shift of the second polarographic wave gave a linear slope (Fig. 10). The reason may be an increase in the permeability of the cell membrane for protons and cations by a partial breakdown of the electrochemical potential between the inside and outside of the membrane. The theory of Mitchell is generally valuable for compounds of different chemical constitution such as indol-3-acetic acid, gramicidin, and valinomycin. Bielawski et a1 (1966) found that 2,4-dinitrophenol, a compound that readily uncouples oxidative phosphorylation, increases electrical conductivity of artificial lipid membranes more than a hundred-fold.

## Inhibition of soil enzymes in the nitrogen cycle

The use of urea, with its relatively high N content of more than 40%, as fertilizer is increasing. The decomposition of urea to $CO_2$ and $NH_3$ is often too fast in the soil,

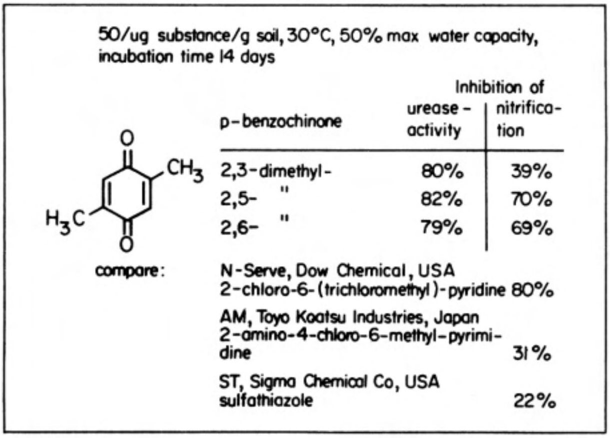


**10.** Shift of the second polarographic wave by exchange of $N(C_2H_5)_4^+$ $Li^+$ vs dry weight of rye seedlings.

so that losses of N occur. Quinones inactivate urease, which is the enzyme responsible for the decomposition (Bundy and Bremner 1973, 1974; see Fig. 11).

Nitrification is also inhibited by quinones. In this case 2,3-dimethyl-benzoquinone-1,4 is less effective than 2,5-dimethyl- and 2,6-dimethyl- derivatives, as in the transport of ions through the cell membranes. The effectivity of the quinones is comparable with that of substances produced industrially.

The usual lignin degradation products such as 2-methoxy- and 2,6-dimethoxy-benzoquinone-1,4, which are formed by oxidative decarboxylation of vanillic or syringic acid, inhibit urease activity (Bundy and Bremner 1973), while 2,5-dimethoxy-benzoquinone-1,4 has no effect (Mishra and Flaig 1979, see Fig. 12). The latter compound cannot be considered either as a lignin degradation product or as a compound of microbial metabolism.



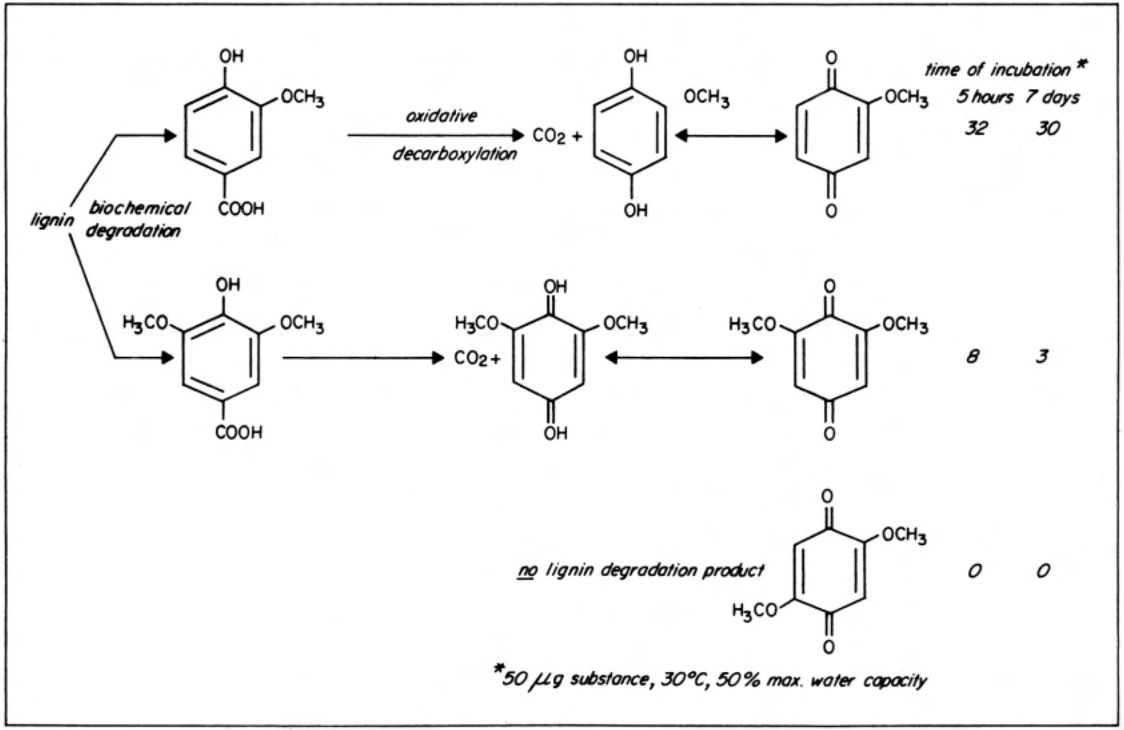
50/ug substance/g soil, 30°C, 50% max water capacity, incubation time 14 days

| p-benzochinone | Inhibition of urease-activity | Inhibition of nitrification |
|---|---|---|
| 2,3-dimethyl- | 80% | 39% |
| 2,5- " | 82% | 70% |
| 2,6- " | 79% | 69% |

compare:

| | |
|---|---|
| N-Serve, Dow Chemical, USA<br>2-chloro-6-(trichloromethyl)-pyridine | 80% |
| AM, Toyo Koatsu Industries, Japan<br>2-amino-4-chloro-6-methyl-pyrimidine | 31% |
| ST, Sigma Chemical Co, USA<br>sulfathiazole | 22% |

**11.** Inhibition of urease activity and of nitrification by quinones.



**12.** Inhibition of urease activity by lignin degradation products.

## DISCUSSION

Much basic research work has been reported in this paper, and the results have potential for practical utilization.

Literature summarizing related problems has been published by FAO (1975, 1978) and the International Atomic Energy Agency (1963, 1968, 1977). The most recent summary of research in this field is the excellent contribution of Stevenson (1982).

The principal views in this paper and in Stevenson's are in agreement. Stevenson refers in more detail to the dynamics and to the possibilities of release of N, P, S, and micronutrients, which are influenced by components of soil organic matter. He reports corresponding experiments and discusses the results. According to several publications he mentions, the proportion of C:N:P:S in soil humus is 140: 10: 1.3: 1.3. The degree of availability depends on mineralization and immobilization; the rates of these processes are regulated by biological systems, wherein the activities of microorganisms play an important role.

In this paper the subject is treated more from a biochemical point of view to find possible explanations for the course of the processes related to soil organic matter as a source of nutrients. Considering the world food situation, it is clear that every possible measure must be used to increase plant production. The use of mineral fertilizers, plant breeding, soil cultivation, and plant protection have succeeded in increasing yields in the last decades. But these measures also involve relatively high costs, and their success depends on local climate and soil conditions. Soil organic matter not only serves as a source of nutrients but also stabilizes to a great extent the yield potential of the soil by permitting intensified utilization of mineral fertilizers and by interacting with the plant in physical and biochemical ways. Also, use of residual organic materials shifts the costs partly from capital to labor.

In this paper, attention has been called to some of the trends in biochemical research in the field of soil organic matter and plant growth. Nutrient supplies from soil organic matter cannot be treated separately from their additional effects on plant mass production. Basic knowledge about the dynamics of the humic system in soils and about the biochemical reactivity of its components may allow discovery of cause-and-effect relationships that may affect agricultural practices.

## REFERENCES CITED

Bielawski, J., T. E. Thompson, and A. L. Lehninger. 1966. The effect of 2,4-dinitrophenol on the electrical resistance of phospholipid bilayer membranes. Biochem. Biophys. Res. Comm. 24:948-954.

Bondietti, E., J. P. Martiland, and K. Haider. 1972. Stabilization of amino sugar units into humic type polymers. Proc. Soil Sci. Soc. Am. 36:597-602.

Bremner, J. M. 1965. Organic forms of nitrogen. *In* C. A. Black(ed.) Methods of soil analysis. Agron. Monogr. 9, ASA, Madison.

Bruckert. S. F., F. Jacquin, and M. Metche. 1967. Contibution a l'etude des acides phenols presents dans les sols. Bull. E Nat. Super. Agron. Nancy, 9:73-92.

Bundy, L. G., and J. M. Bremner. 1973. Effects of substituted p-benzoquinones on urease activity in soils. Soil Biol. Biochem. 5:847-853.

Bundy, L. G., and J. M. Bremner. 1974. Effects of urease inhibitors of nitrification in soils. Soil Biol. Biochem. 6:27-30.

Chaminade, R. 1966. Effect physiologique des constituants de la matiere organique des sols sur le metabolism des plantes, la croissance et le rendement. Pages 35-47 *in* The use of isotopes in soil organic matter studies. Report of the FAO/IAEA Technical Meeting. Pergamon Press Ltd. Oxford.

Chigrin, V. V., L. V. Rozum, and M. N. Zaprometov. 1973. Phenol-carboxylic acids and lignin in the leaves of wheat varieties resistant and sensitive to stem rust infection. Fiziol Rast 20:942-948. (Russ.)

Clark, F. E., and T. Rosswall (eds.). 1981. Terrestrial nitrogen cycles. Ecol. Bull. (Stockholm) 33, Printed in Sweden by Berlings, Arlov. 714 p.

FAO (Food and Agriculture Organization of the United Nations). 1975. Organic materials as fertilizers. Soils Bull. 27. Rome. 393 p.

FAO (Food and Agriculture Organization of the United Nations). 1978. Organic materials and soil productivity. Soils Bull. 35. Rome. 199 p.

Flaig, W. 1962. Unwandlung von Lignin in Huminstoffe. Freiberg. Forschungsh. A 254:39-56.

Flaig, W. 1968. Uptake of organic substances from soil organic matter and their influence on metabolism. In Pontif. Accad. Sci. Scr. Varia 32:723-770.

Flaig, W. 1975. Specific effects of soil organic matter on the potential of soil productivity. Pages 31-69 *in* FAO Soil Bull. 27. Rome.

Flaig, W. 1982. Dynamics of organic matter decomposition in soils. Pages 115-124 *in* Transactions of the 12th International Congress of Soil Science Indian Society of Soil Science. New Delhi. Vol. 2.

Flaig, W., U. Schobvinger, and H. Deuel. 1959. Umwandlung von Lignin in Huminsauren bei der Verrottung von Weizenstroh. Chem. Ber. 92:1973-1982.

Flaig, W., and H. Riemer. 1971. Contribution to the mechanism of the influence of substances from soil organic matter on plant growth. Pages 519-526 *in* Studies about humus, Transaction of International Symposium "Humus et Planta V", Prague, Czechoslovakia.

Flaig, W., and H. Soechtig. 1973. Wirkung organischer Bodensubstanzen und Ertragssicherung. Landbauforsch. Voelkenrode 23:19-28.

Flaig, W., H. Beutelspacher, and E. Rietz. 1975. Chemical composition and physical properties of humic substances. Pages 1-211 *in* J. E. Gieseking (ed). Soil Components *1*, Springer-Verlag New York, Inc.

Freudenberg, K. 1962. Forschung am Lignin. Fortschr. Chem. Org. Naturst. 20:41.

Freudenberg, K. 1964. Erganzung des Konstitutionsschemas fur das Lignin der Fichte Holzforschung 18:166.

Glaser, G., and H. R: Glaser. 1974. Simulation of reactions with lignin by computer (Simrel) II. A model of softwood lignin. Holzforschung 28:5-11.

Haider, K., L. R. Frederick, and W. Flaig. 1965. Reactions between amino acid compounds and phenols during oxidation. Plant Soil 22:49-64.

Haider, K., and J. P. Martin. 1967. Synthesis and transformation of phenolic compounds by *Epicoccum nigrum* in relation to humic acid formation. Proc. Soil Sci. Am. 31:766-772.

Haider, K., and J. P. Martin. 1970. Humic acid-type phenolic polymers from *Aspergillus sydowi* culture medium, *Stachybotrys* spp. cells and autoxidized phenol mixtures. Soil Biol. Biochem. 2:145-156.

Haider, K., J. P. Martin, Z. Filip, and E. Fustec-Mathon. 1975. Contribution of soil microbes to the formation of humic compounds. Pages 71-85 *in* Proceedings International Meeting on Humic Substances, Nieuwersluis, Centre for Agric. Publ. and Documentation, Wageningen, Netherlands.

Haider, K., B. R. Nagar, C. Saiz, H. L. C. Meuzelaar, and J. P. Martin. 1977. Studies on soil humic compounds, fungal melanins and model polymers by pyrolysis mass spectrometry. Pages 213-220 *in* Proceedings Symposium IAEA-FAO, Vienna, Vol. II.

Haider, K., and J. P. Martin. 1979. Abbau und Umwandlung von Pflanzenruckstanden und ihren Inhaltsstoffen durch die Mikroflora des Bodens (Engl. summary). Z. Pflanzenernaehr Bodenkd. 142:456-475.

Harms, H. 1972. Positionsspezifische O-demethylierung von Benzoesauren in Zellsuspensionskulturen sowie in Weizenkeimpflanzen. Hoppe Seyler's Z. Physiol. Chem. 353:1523.

Harms, H. 1973. Pflanzliche Zellsuspensionskulturen — ihr Leistungsvermogen fur Stoffwechseluntersuchungen. Landbauforsch. Voelkenrode 23:127-132.

Harms, H., H. Soechtig, and K. Haider. 1969a. Untersuchungen zur Aufnahme und Umwandlung $C^{14}$-markierter Phenole durch die Pflanze. I. Aufnahme von C14-carboxyl-markierter p-hydroxy-benzoe-, Vanillin- und Syringasaure durch die Wurzeln von Weizenkeim-pflanzen und Verteilung der Aktivitat uber die Pflanze. Plant Soil 31(1):129-142.

Harms, H., H. Soechtig, and K. Haider. 1969b. Untersuchungen zur Aufnahme und Umwandlung $C^{14}$-markierter Phenole durch die Pflanze. II. Die Umwandlung von p-hydroxy-benzoesaure, Vanillinsaure sowie Syringasaure nach der Aufnahme durch die Wurzeln von Weizen-keimpflanzen. Plant Soil 31(2):2:257-272.

Harms, H., H. Soechtig, and K. Haider. 1971. Aufnahme und Umwandlung von in unterschiedlicher Stellung $C^{14}$-markierter Phenolcarbonsauren in Weizenkeimpflanzen. (English summary). Z. Pflanzenphysiol. 64:437-445.

Harms, H., K. Haider, J. Berlin, P. Kiss, and W Barz. 1972. Uber O-demethylierung und Decarboxylierung von Benzoesauren in pflanzlichen Zellsuspensionskulturen. (English summary). Planta 105:342-351.

International Atomic Energy Agency, IAEA-FAO, Vienna, Austria 1963. Proc. Symp. The use of isotopes in soil organic matter studies. 505 p.

International Atomic Energy Agency, IAEA-FAO, Vienna, Austria 1968. Proc. Symp. Isotopes and radiation in soil organic matter studies. 584 p.

International Atomic Energy Agency, IAEA-FAO, Vienna, Austria 1977. Proceedings of Symposium on soil organic matter studies. Vol. 1. 424 p; vol. 2, 388 p. (in cooperation with Agrochimica).

Larson, E. W., and C. E. Clapp. 1983. Effects of organic matter on soil physical properties. Pages 367-389 *in* International Rice Research Institute. Organic matter and rice. Los Baños, Laguna, Philippines.

Maeder, H. 1960. Chemisch und pflanzenphysiologische Untersuchungen mit Rottestroh. Diss. Justus-Leibig-Universitat, Giessen, Fed. Rep. of Germany, 104 p.

Martin, J. P., and K. Haider. 1971. Microbial activity in relation to soil humus formation. Soil Sci. 111:54-63.

Martin, J. P., and K. Haider. 1977. Decomposition in soil of specifically carbon-14-labeled DHP and corn stalk lignins, model humic acid-type polymers and coniferyl alcohols. Pages 23-32 *in* Proceedings of Symposium on soil organic matter studies, Vol. II, IAEA, Vienna.

Martin, J. P., and K. Haider. 1979. Effect of concentration on decomposition of some $^{14}$C-labeled phenolic compounds, benzoic acid, glucose, cellulose, wheat straw and Chlorella protein in soil. Soil Sci. Soc. Am. J. 43:917-920.

Meuzelaar, H. L. C., K. Haider, B. R. Nagar, and J. P. Martin. 1977. Comparative studies of pyrolysis mass spectra from melanins of soil fungi, model phenolic polymers and humic acids from soil, peat and composted straw. Geoderma 17:239-252.

Mishra, M. M. and W. Flaig. 1979. Inhibition of urea nitrogen in soils. Plant Soil 5:301.

Mitchell, L. P. 1966. Chemiosmotic coupling in oxidative photosynthetic phosphorylation. Biol. Rev. Cambridge Philos. Soc. 41:445-502.

Mitscherlich, E. A. 1948. An der Grenze der Ertragsteigerung. Z.Pflanzenernaehr. Dung. Bodenkd. 40:193-200.

Nimz, H. 1974. Das Lignin der Buche. Entwurfeines Konstitutionsschemas. Angew. Chemie 86:336-344.

Olteanu, G. H., and J. Brad. 1969. Contributii privind continutul in a minoa cizi, za haruru, acizi organic si sustante aroma tice la soiuri de cartof cu rezistenta diferita fata de mana. Cartoful Annalele, L. C. C. A. 1:177-184. (Roumanian)

Peover, M. E., and J. D. Davies. 1963. Einfluss der Jonenassoziation auf die Polarographie der Chinone in Dimethyl-formamid. J. Electroanalyt. Chem. (Amsterdam) 6:46.

Purushotaman, D. 1974. Phenolics changes in rice varieties infected by *Xanthomonas oryzae.* Acta Phytopathologica Acad. Sci. Hung. 9:65-69.

Riemer, H. 1970. Polarographische Untersuchungen uber Beziehungen zwischen Structur und Reactivitat bei Benzoichinonen. Diss. Univ. Braunschweig, Fed. Rep. of Germany 109 p.

Saalbach, E. 1957. Zur Kenntnis der Huminsauren, XIV. Mitt. Einfluss von Modelsubstanzen von Huminstoffen auf den Stoffwechsel von Getreide. Landwirtsch Forsch. Sonderh. 9:95-100.

Saalbach, E. 1958. Beitrag der Grundlagenforschung zum Problem der Strohdungung. Landwirtsch Forsch. 8:83-84.

Saiz-Jimenez, C., K. Haider, and H. L. C. Meuzelaar. 1979. Comparison of soil organic matter and its fractions by pyrolysis mass spectrometry. Geoderma 22:25-37.

Schnitzer, M., and S. U. Khan. 1972. Humic substances in the environment. M. Dekker, New York. 327 p.

Schnitzer, M., and S. U. Khan, eds. 1978. Soil Organic Matter. Elsevier, Amsterdam. 319 p.

Schnitzer, M. 1982. Quo vadis soil organic matter research? Pages 67-78 *in* Transactions of the 12th International Congress of Soil Sci., Ind. Soc. of Soil Sci., New Delhi, Vol. 5.

Soechtig, H. 1964. Beeinflussung des Stoffwechsels der Pflansen durch Humus and seine Bestandteile und die Auswirkung auf Wachstum and Ertrag. Landbauforsc. Voelkenrode 14:9-16.

Soechtig, H., and H. Harms. 1971. Uber den Einfluss von Torfauf Keimung und Anfangswachstum von Pflanzen. Landwirtsch Forsch. 26(2): 168-174.

Stevenson, F.J. 1982. Organic matter and nutrient availability. Pages 137-151 *in* Transactions of the 12th International Congress of Soil Sci., Indian Society of Soil Science, New Delhi, Vol. 2.

Ziechmann, W. 1980. Huminstoffe, Probleme, Methoden, Ergebnisse. Verlag Chemie, Weinheim, Deerfield, Florida, Basel. 408 p.

## DISCUSSION

YOSHIDA: Are there any differences in the N content of grasses with and without the addition of organic molecules?

*FLAIG:* Nitrogen content is nearly the same in both cases but content is increased less.

WAIN (comments): Your suggestion that phenolic and other compounds produced in the decomposition of soil organic matter may enter the plant and confer protection against certain fungal diseases is certainly of interest. However, all plants are totally resistant to most of the fungi to which they are exposed — and this appears when they are growing with their roots in nutrient solution in the absence of soil. Recent research has shown that one of the main reasons for the natural resistance of plants to diseases arises from the presence of defensive chemicals in their tissues. Thin film chromatograms of leaf extracts sprayed with fungal spores in a dilute nutrient medium, when incubated, can often reveal the presence of these defensive chemicals. A number of these chemicals have been isolated and identified in my laboratory.

It is soluble phosphate that enters the roots of plants, but soluble phosphate in fertilizer such as superphosphate becomes fixed and unavailable both in acid and alkaline soils. While many nutrient carbon compounds can enter plants through their leaves, phosphate cannot readily be utilized when provided in this way. It might be worthwhile to determine whether the phosphate esters that, you say, arise from organic matter decomposition in soils can enter the plant through the leaves to become hydrolyzed and nutritionally available at the cell level as a source of phosphate. If we could find a form of P that could be utilized following absorption through leaves, there would be an enormous saving of fertilizer phosphate, and soil fixation of phosphate would no longer be a serious problem.

# STRUCTURES OF HUMIC SUBSTANCES

M. H. B. Hayes

A better awareness of the structures of humic substances is needed for a fuller understanding of the mechanisms of interactions involving these polymers in a variety of soil processes. The availability of modern instrumentation, such as gas liquid chromatography mass spectrometry with computerized libraries of organic structures, microinfrared spectroscopy equipment, cross polarization magic-angle spinning nuclear magnetic resonance, as well as the renewed interest by coal scientists and the new involvement of water scientists in this area of research, has greatly advanced our concepts of humic structures during the past decade.

Analyses of the evidence from the identification of degradation products and interpretations of spectra indicate that humic materials have varying amounts of single-ring aromatic compounds and considerable quantities of aliphatic hydrocarbon, carbohydrate, and peptide structures. The aromatic rings are invariably disubstituted to polysubstituted, and the ring attachments include hydroxy (phenol), methoxy, and possibly phenoxy, carboxyl, and hydrocarbon groups. The polymers are polydisperse with respect to charge and size, and appear to take up random coil solution conformations. In the field the component strands in the coils are held together by H bonding or by linkages through divalent and polyvalent cations. Such linking gives rise to a shrinking of the dimensions of the polymers in space, which leads to a partial exclusion of water from the matrix and a resulting loss in solubility. Considerations of these structural concepts are helpful when attempting to explain the role of humic substances in stabilizing soil aggregates and in reacting with chemicals added to the soil.

Humic substances are amorphous, polymeric, brown-colored components of soil organic matter. They are composed of fulvic acids, soluble in aqueous acid and base; humic acids, which are precipitated when the alkali soluble components are acidified to pH 1; and humins, or components which are insoluble in aqueous acid and base.

Humic acids are the most abundant of the humic substances and, together with fulvic acids, are found in all soils and waters. Flaig (1983) has discussed the origins of humus materials. They are thought to be formed by microbial, enzymatic, and chemical transformations of plant and animal residues (Flaig et al 1975).

Few reliable data indicate the global abundance of humic substances. However, the humus contents of a soil are likely to be less abundant than the aboveground

---

Chemistry Department. University of Birmingham, Edgbaston, Birmingham B15 2TT, England.

phytomass only in forests (Kovda 1974); they are likely to be several times greater than the annual production of grasses, cereals, and other crops in most soils. Bazilevich (1974) has estimated that humus reserves on land amount to about 2.4 × $10^{12}$ t, but this figure is likely to be low if Kovda's (1974) estimate of 3.2 × $10^{12}$ t for the organic C in terrestrial environments is correct.

Despite growing attention to the importance of humus substances for the formation and maintenance of good soil structure, for aiding water entry and enhancing its retention by soils, for the holding of plant nutrients, and for the release through mineralization of N, P, S, and some trace elements, much is not known about the detailed structures of humic substances.

Studies of humic structures have always lacked direction. It is partly for this reason that the International Humic Substances Society (IHSS) was formed in 1981. The Society intends to make available standard samples of humic and fulvic acids, and has planned conferences for August 1983 (at Estes Park, Colorado) and August 1984 (in Birmingham, England), which will consider details of the genesis, extraction, fractionation, structure, complexation, etc. of, or by, humic substances.

Soil scientists who have worked with organic soils have long since documented how Cu and other trace elements are immobilized in such soils. More recently research on sewage sludges and soil-pesticide interactions has focused attention on the extent and mechanisms of binding of heavy metals and organic chemicals by humic substances. The swelling and shrinking of these substances on wetting and drying influence their binding properties and the extent and rates at which they undergo biological oxidation. It will not be possible to understand fully the mechanisms involved in these and other soil processes influenced by humic materials until there is a better understanding of their component molecules, structures, shapes, and sizes. Fortunately, during the past 15 years or so, new instrumentation that makes the formidable task of studying humic structures more feasible has become available.

To carry out meaningful studies of the structures of humic substances, it is first necessary to extract the components and to fractionate them into reasonably representative entities. This paper reviews some of the methods used to extract and to fractionate humic materials; outlines some of the procedures used to degrade the polymers; indicates the types of information obtainable from the degradation reactions and the products of degradation; refers to modern spectroscopic techniques expected to provide much useful structural information without giving rise to artifacts produced in degradation processes; and refers to current views about the shapes and sizes of humic polymers.

## EXTRACTION OF HUMIC SUBSTANCES

Hayes and Swift (1978) reviewed procedures used up to the time of their writing for the extraction of humic substances from soils and discussed some of the principles of relevant extraction processes. They emphasized how humic polyelectrolytes are insoluble at the pH values of most fertile soils because of the contribution of divalent and polyvalent cations to the neutralization of the negative charges originating largely from the carboxyl groups in the polymer. Such cations give a pseudo cross-linking effect, causing the polymer to shrink and to be difficult to hydrate. Effective solvation of humic molecules requires the replacement of these cations. For that reason, humic substances are $H^+$-ion exchanged by treatment with dilute acid before extraction. (Treatment with some $H^+$-exchanged resins should, in principle, be effective also.) Low-molecular-weight, polar, and highly charged $H^+$-exchanged humic substances (fulvic acids) are soluble in water, but the less highly charged materials are not. The insoluble molecules are associated into moderately compact structures through intermolecular and intramolecular H bonding.

Because the acid groups of $H^+$-exchanged humic substances are largely undissociated, such polymers will have some of the solubility properties of neutral polymers, especially those that are capable of H bonding. Thus dipolar aprotic solvents such as N-methylformamide (NMF), N,N-dimethylformamide (DMF), and dimethylsulphoxide (DMSO) have been used as extractants, but yields were on the order of 25% of the total organic matter (Hayes and Swift 1978). The polymers can swell to an extent in these solvents at room temperature, but this swelling is not sufficient to overcome the polymer-to-polymer interactions in most instances. Recently Sinclair and Tinsley (1981) have obtained significantly better results by extracting under reflux in sequence with formic acid:water (85:15 vol/vol) and formic acid:60% wt/wt HF (70:30 vol/vol). However, this procedure needs further investigation to establish the extent to which artifacts are produced during the extraction.

Aqueous sodium pyrophosphate ($Na_4P_2O_7$; 0.1 M), neutralized to pH 7 with phosphoric acid (Bremner and Lees 1949), is a good solvent for highly oxidized components of humic substances. $H^+$-exchanging should not be necessary when this solvent is used, because the major function of the pyrophosphate is to complex the divalent and polyvalent cations held on the humic exchange sites. However, it would appear that enough exchange of N does not take place to allow sufficient dissociation to promote solubilization of the polymers having lower charge densities. A more complete extraction would be achieved by using non-neutralized pyrophosphate solution; all of the carboxyls and many of the phenolic hydroxyl groups would be dissociated in the pH range of 9-10. When the ionized groups are sufficiently close to repel each other, the polymers expand, and solvent molecules can solvate the charged and polar groups in the polymer matrix.

Aqueous solutions of hydroxides of monovalent cations with high hydration energies such as $Li^+$, $NH_4^+$, and $Na^+$ form the best solvents for humic substances. Dilute solutions (0.1-0.5 M) of these hydroxides are strongly alkaline ($pH > 12$), and even the very weak acid groups in humic polymers are dissociated under these media. However, some oxidation of the polymers takes place under alkaline conditions (Bremner 1950), giving rise to the formation of artifacts. These undesirable effects can be partially controlled by carrying out the extractions in an atmosphere of N and adding reducing substances such as $SnCl_2$ (Choudhri and Stevenson 1957).

From the principles referred to when describing extraction processes, it is clear that fulvic acids are the most highly charged and polar of the three major components of humic substances. Humin materials are the least charged; their lack of solubility in alkaline solutions can be attributed to a low charge density, to a low content of polar groups, and/ or to a higher degree of covalent cross linking than in the humic and fulvic materials. Humins may be solubilized in concentrated $H_2SO_4$, and some recovery can be achieved by diluting the acids under controlled-temperature conditions.

## FRACTIONATION OF HUMIC SUBSTANCES

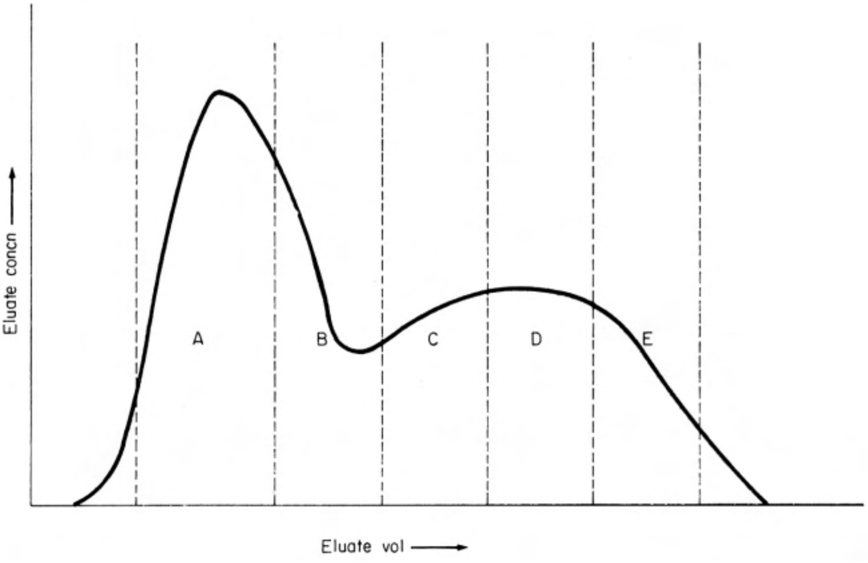
The use of resin materials, such as Polyclar-AT, and the XAD range can give useful separations of humic and fulvic acids from the other components of humus such as polysaccharides. However, the isolation of reasonably homogeneous fractions from humic mixtures still presents a major challenge, although some success has been achieved by the use of gels and of graded porosity membranes.

Fischer (1969) has provided an appropriate review of the structures and properties of gels and of their applications to the isolation from mixtures of polymers that are reasonably homogeneous with regard to size. The Sephades (from Pharmacia) and Biogel (from Biorad) ranges of gels have been extensively used for the fractionation of humic substances.

To obtain valid results, the gel should not adsorb the solute molecules. Where adsorption occurs, the separation cannot be attributed solely to inclusion in the gel pores; hence the fractionation cannot be attributed solely to molecular size differences. Humic substances may be adsorbed particularly by the dextran gels. A second problem arises from repulsion between charges in the solute molecules and the residual charges in the solute molecules and the residual charges in the gels. When these residual charges are not suppressed, molecules which would normally enter the pores are repelled and eluted at or close to the column void volume. Inclusion of salts in the elution medium helps to control these problems. The use of polyacrylamide gels and of a buffer containing a large organic cation such as tris [2-amino-2 (hydroxymethyl) propane-1,3-diol] can lessen these effects considerably.

Elution patterns of the type shown in Figure 1 would indicate that the components of the separation mixture were highly polydisperse. To isolate compounds with a degree of molecular weight homogeneity where an elution pattern of the type illustrated is obtained, it would be necessary to combine fractions with similar elution volumes (represented by areas A, B, C, etc.. Fig. 1) and to reduce the volumes of these before passing the mixture again through the same column. The second elution pattern would give a distribution similar to the first, but the concentration of organic substances would be greatest in the elution volume from which the sample was obtained originally. By recombining samples from this volume and repeating the process a number of times, it should be possible to isolate components of similar sizes.

Gel filtration procedures for fractionating humus substances are slow and tedious. An alternative technique, used by Cameron et al (1972a), uses membranes with pore sizes of known and discrete dimensions. The pores act as sieves; they retain molecules with cross-sectional areas greater than those of the pores, and they allow the smaller molecules to pass through. Pressure is applied to speed up the filtration. For this technique to be effective, it is important that there not be interactions between the solutes and the membranes.



**1.** Diagramatic representation of the elution pattern obtained when humic substances are fractionated on gel columns.

The work of Cameron et al (1972a) provides the most comprehensive study of the fractionation of soil humic acids. They isolated reasonably homogeneous fractions by repeatedly refractionating components eluted in similar volumes of tris buffer [2-amino-2 (hydroxymethyl) propane- l, 3-diol] from gel columns, as described above. Pressure filtration through graded porosity membranes also provided fractions that were moderately homogeneous on the basis of molecular size. The 11 components isolated had molecular weight values ranging from $2 \times 10^3$ to $1.5 \times 10^6$.

Humic acids are also polydisperse with respect to charge. In theory, at least, separations on the basis of charge differences can be made by electrophoresis and by ion-exchange chromatography techniques. Stevenson et al (1952) used moving boundary electrophoresis to show that some separation of components with different charge densities was possible. Continuous-flow (paper curtain) electrophoresis, used by Chahal et a1 (1966) and Waldron and Mortensen (1961), also indicated that humic substances contain materials with a spread of charges. However, no discrete fractions have yet been isolated. Any appropriate approach to isolate fractions having such homogeneity should use materials that were previously fractionated on the basis of molecular size differences, and, as suggested by MacCarthy et a1 (1979), the use of a pH gradient might help desorb differently charged components held by a resin material.

## DETERMINATION OF STRUCTURES OF HUMIC SUBSTANCES

To assign fully a structure to any organic polymer, it is necessary to identify the repeating units (primary structures), to know the order in which such units are linked together (secondary structure), and to determine its shape, size, and the arrangement in space of the components (tertiary structure). Homogeneous biological polymers, whose synthesis is genetically controlled, have invariant primary structures, linked in invariant sequences. This almost certainly applies to homogeneous soil polysaccharides, but it is doubtful that it does so for humic materials.

It is highly likely that the primary structures of humic polymers are single molecules randomly linked together. Thus it is essential, in order to get useful information about the polymer structures, to establish what the primary structural components are; it would be pointless, however, to try to determine secondary structures accurately if the polymer synthesis is not genetically controlled. A knowledge of the shapes and sizes, or tertiary structures, is important because these properties can affect the reactivities of the polymer, and can, for instance, determine the extent to which adsorptive molecules penetrate the polymer matrix for adsorption by the primary structural components in the interior of the polymer.

## Determination of primary structures of humic substances

The classical procedures for determination of primary structures in polymers have degraded the macromolecules to identifiable components that could be assigned to structures within the polymer. Such procedures work well where labile bonds, such as the peptide bonds of proteins and the glycosidic linkages of polysaccharides, hold the component molecules together. Because of the high energy input required to cleave some of the linkages in humic substances, it will be shown below that in many instances the products identified in degradation reaction digests are not the same as those released from the polymer, but are in fact derivatives of these. Progress is being made in applications of spectroscopy, which is nondegradative, to studies of polymer structures, and some promising results have already been obtained from applications of these procedures to humic acids research.

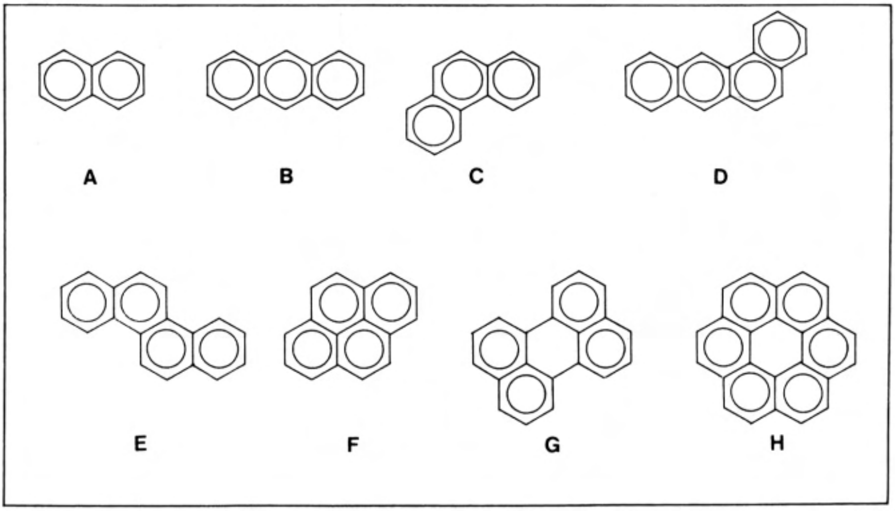
*Degradative procedures.* Some who have worked on reactions for degrading humic substances have regarded the identified digest products as primary structures from the polymers. Hayes and Swift (1978) have argued that in many instances the compounds identified only resemble components in the polymers from which they were derived. A publication by Maxinov et al (1977), which appeared when Hayes and Swift had finalized their views, also put forward this point of view, and both sets of authors shared the opinion that the uses of highly energetic degradative procedures are likely to alter the structures of the components even before they are released from their linkages in the polymers. Furthermore, and in many instances drastic alterations may be expected in the released molecules during their residence in the highly reactive conditions prevailing in the digest during the course of the reactions. For these reasons it is important to carry out model studies to investigate the types, extent, and rates of alterations to structures when organic compounds of the types that might be present in humic structures are reacted under the digest conditions used for the degradation of humic substances.

An interesting and often quoted impression of humic acid structures was put forward by Haworth and his colleagues (see Atherton et al 1967; Cheshire et al 1967, 1968). Their degradation procedures used zinc dust distillation of previously acid boiled (6 M HCl) humic acids in a stream of $H_2$ gas and at a temperature of

500-550° C. Yields of oily compounds corresponding to about 3% of the starting materials were obtained. This is a drastic procedure in which yields of identifiable organic products are always low, regardless of what the starting materials are; hence the isolation of products amounting to 3% of the starting materials can be regarded as highly satisfactory. By combining data for the degradation reactions with their information from hydrolysis (which gave high yields of sugars and amino acids) and estimations of free radical contents (from electron spin resonance or ESR data, Atherton et al 1967), the Haworth group concluded that humic substances contain a polycyclic aromatic core of compounds such as those in Figure 2, with appendages of polysaccharides, simple phenols, proteins or peptides, and metals.

In their latest publication in this research area, the Haworth group (Cheshire et al 1968) showed that 3,4- and 3,5-dihydroxybenzoic acids (which could come from oxidation and demethylation of lignin materials and from products of microbial metabolism), furfural (from dehydration of pentoses), and polymers from quinones gave polycyclic aromatic structures from zinc dust distillation reactions at 500°-550° C. Whereas humic acids gave the same yields of fused aromatic structures when the zinc dust distillation reactions were carried out at 400° C, no aromatic compounds were detected in the digests when furfural and polymers from *o*- and *p*-benzoquinone were reacted in the same way at this temperature. Only small yields of anthracene (compound B, Fig. 2) were detected when the hydroxybenzenes were reacted at the lower temperatures.

These model studies by Cheshire et al (1968) inevitably cast some doubts concerning the origins of the polycyclic aromatic structures identified in the zinc dust distillation of humic substances. There is general agreement that such structures are



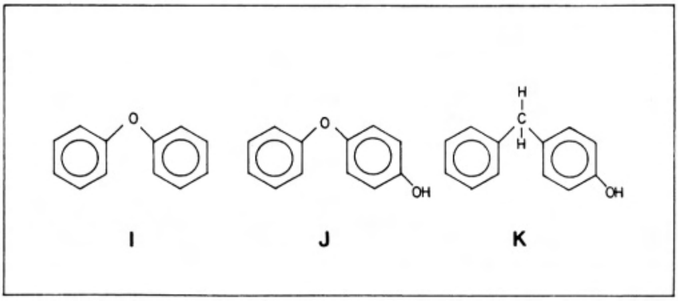
**2.** Some of the fused aromatic structures identified in zinc dust distillation digests of humic substances. The compounds are naphthalene (A), anthracene (B), phenanthrene (C), 1,2-benzanthracene (D), chrysene (E), pyrene (F), perylene (G), and coronene (H).

contained in coals, especially in those of high rank. Further model studies are required, however, to establish whether or not these are important components of soil humic substances.

Since the *sodium amalgam* (Na/Hg) technique was introduced by Burgest et al (1964) for the degradation of humic materials, it has been used by several workers interested in natural and in laboratory-synthesized humic acids (Hayes and Swift 1978). Piper and Posner (1972) were first to investigate the mechanism of the reaction using structures and bonds which might be relevant to humic structures. These model studies showed, for instance, that compound I degraded to benzene and benzenol, that compound J gave only benzenol, and that no cleavage took place in the case of compound K (Fig. 3). Such evidence led them to conclude that atomic hydrogen (H) released in the process acted as an electrophile, and could equally attack the linkages on either side of the oxygen atom in compound 1. It attacked the bond *para* to the –OH substituent, exclusively, in the case of compound J. No cleavage of compound K took place because the excess electron density could not reside on the ring-bridging $CH_2$ group.

The products isolated from the sodium amalgam degradation of humic substances are of the types represented by compounds **24-33, 38, 39,** and **41-44** in Figure 4. Piper and Posner did not observe degradation in the digests using model substances of the types isolated in the degradation reactions. However, Martin et al (1974) observed some degradations in their digests of model substances with structures represented by **24** and **25** in which –OH is substituted in the ring for $-OCH_3$, and by **43** and **44.** Decarboxylation of dihydroxybenzenecarboxylic and trihydroxybenzenecarboxylic acids can be expected under reflux conditions, and the presence of even traces of $O_2$ in the medium would lower the yields of dihydroxybenzenes and trihydroxybenzenes released into the digests. Degradation would be significantly lessened where strictly anaerobic conditions were observed.

It is reasonable to accept, on the basis of the model studies that have been carried out, that most of the structures isolated from cleavage with sodium amalgam represent some of the primary structures of humic substances. The degradation procedure is relatively mild, and further alterations of the structures released into the digest should be small. It is possible that many of the compounds identified were present in ether linkages in the polymer or as biphenyl-type structures where



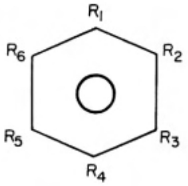
**3.** Model compounds reacted with sodium amalgam.

$CH_3(CH_2)_nCH_3(n = 12 \text{ to } 28)$

**1**

$HO_2C(CH_2)_nCO_2H(n = 2 \text{ to } 8)$

**3**



$CH_3CH(R')(CH_2)_nCO_2H$

**2**

$HO_2CCH_2\,CH(R'')\text{-}_nCH_2CO_2H$

**4**

**6** $R_1 = R_2 = CO_2H; R_3 = R_4 = R_5 = R_6 = H$
**8** $R_1 = R_4 = CO_2H; R_2 = R_3 = R_5 = R_6 = H$
**10** $R_1 = R_2 = R_4 = CO_2H; R_3 = R_5 = R_6 = H$
**12** $R_1 = R_3 = R_5 = CO_2H; R_2 = R_4 = R_6 = H$
**14** $R_1 = R_2 = R_3 = R_5 = CO_2H; R_4 = R_6 = H$
**16** $R_1 = R_2 = R_3 = R_4 = R_5 = CO_2; R_6 = H$
**18** $R_1 = R_3 = CO_2H; R_2 = R_5 = R_6 = H; R_4 = OH$
**20** $R_1 = R_2 = R_4 = CO_2H; R_5 = R_6 = H; R_3 = OH$
**22** $R_1 = R_2 = R_3 = R_4 = CO_2H; R_5 = OH; R_6 = H$
**24** $R_1 = CO_2H, R_2 = R_6 = H, R_3 = R_4 = R_5 = OH$
**26** $R_1 = CO_2H, R_2 = R_6 = H, R_3 = R_5 = OCH_3, R_4 = OH$
**28** $R_1 = COCH_3, R_2 = R_6 = H, R_3 = R_4 = R_5 = OCH_3$
**30** $R_1 = CHO, R_2 = R_5 = R_6 = H, R_3 = R_4 = OCH_3$
**32** $R_1 = CH_3$, 2 to 3 OH's variously in ring, other substituents H
**34** $R_1 = CH_2CO_2H, R_2 = CO_2H, R_3 = R_5 = R_6 = H, R_4 = OCH_3$
**36** $R_1 = CH_2CO_2H, R_2 = R_3 = R_4 = R_5 = R_6 = CO_2H$
**38** $R_1 = CH_2CH_2CO_2H, R_2 = R_5 = R_6 = H, R_3 = OCH_3, R_4 = OH$
**40** $R_1 = CH_2CH_2CO_2H, R_2 = R_6 = H, R_3 = R_4 = OCH_3, R_5 = CH_3$
**42** $R_1 = R_3 = OH, R_2 = R_4 = R_5 = R_6 = H$
**44** $R_1 = R_3 = R_5 = OH, R_2 = R_4 = R_6 = H$

**7** $R_1 = R_3 = CO_2H; R_2 = R_4 = R_5 = R_6 = H$
**9** $R_1 = R_2 = R_3 = CO_2H; R_4 = R_5 = R_6 = H$
**11** $R_1 = R_2 = R_5 = CO_2H; R_3 = R_4 = R_6 = H$
**13** $R_1 = R_2 = R_3 = R_4 = CO_2H; R_5 = R_6 = H$
**15** $R_1 = R_2 = R_4 = R_5 = CO_2H; R_3 = R_6 = H$
**17** $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = CO_2H$
**19** $R_1 = R_3 = R_5 = CO_2H; R_4 = R_6 = H; R_2 = OH$
**21** $R_1 = R_3 = R_4 = R_5 = CO_2H; R_2 = OH; R_6 = H$
**23** $R_1 = R_2 = R_3 = R_4 = R_5 = CO_2H; R_6 = OH$
**25** $R_1 = CO_2H, R_2 = R_5 = R_6 = H, R_3 = OCH_3, R_4 = OH$
**27** $R_1 = COCH_3, R_2 = R_5 = R_6 = H, R_3 = R_4 = OCH_3$
**29** $R_1 = COCH_3, R_2 = R_3 = R_4 = OCH_3, R_5 = R_6 = H$
**31** $R_1 = CHO, R_2 = R_6 = H, R_3 = R_4 = R_5 = OCH_3$
**33** $R_1 = CH_3, CH_3$ and 2 OH's variously in ring, other substituents H
**35** $R_1 = CH_2CO_2H, R_2 = R_5 = R_6 = H, R_3 = R_4 = CO_2H$
**37** $R_1 = CH_2CO_2H, R_2 = R_6 = H, R_3 = R_4 = OCH_3, R_5 = CH_2CH_3$
**39** $R_1 = CH_2CH_2CO_2H, R_2 = R_6 = H, R_3 = R_5 = OCH_3, R_4 = OH$
**41** $R_1 = R_2 = OH, R_3 = R_4 = R_5 = R_6 = H$
**43** $R_1 = R_2 = R_3 = OH, R_4 = R_5 = R_6 = H$
**45** $R_1 = OH$, n $C_3H_7$ or n $C_4H_9$ variously in ring, other substituents H

**4.** Compilation of the types of organic structures identified in the digests from various degradation reactions of humic substances.

activating ($CH_3$— or — OH) substituents were *ortho* or *para,* or both, to the linking bond.

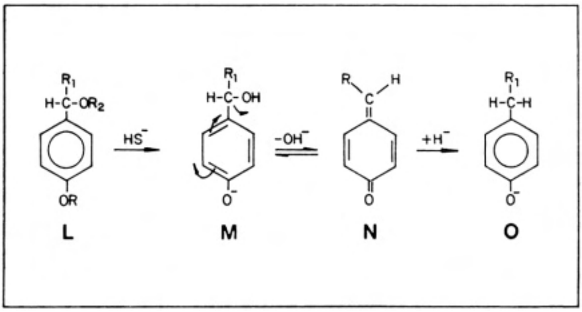
The presence of aldehyde and of keto substituents in humic substances is well recognized, and results from sodium amalgam degradation indicate that some of them are present in phenolic structures. This degradation procedure also provides evidence of the presence of methyl substituents in the aromatic structures (compounds of types **32** and **33**), and the propanoic acid groups in structures **38** and **39** provide evidence for longer chain aliphatic substituents in the aromatic nuclei.

Not more than one carboxyl substituent was present in any of the aromatic structures identified in digests of sodium amalgam degradation reactions. It is possible, of course, that decarboxylation had taken place in some instances. However, it can be stated with confidence that at least one carboxyl group is present in some of the aromatic structures in humic polymers, because carboxylic acids would not be generated as artifacts under the reducing conditions that prevail in sodium amalgam degradation reactions.

Coal scientists have reported considerable success in depolymerizing coals by reactions with *phenol* and *boron trifluoride* or *para-toluenesulphonic acid* (PTS) catalysts. Jackson et al (1972) have applied this technique to the degradation of soil humic acids, and more recently Colclough (1980) has used similar procedures in the author’s laboratory. Hayes and Swift (1978) have summarized suggestions about the reaction mechanisms thought to be involved in the degradation reactions. This procedure helps to identify interaromatic linkages in the humic polymers. Up to 60% of the mass of starting materials has been isolated as ether-soluble components, and several of the digest materials still await identification by gas liquid chromatography mass spectrometry (GLCMS) procedures. From the results obtained, it would appear that this degradation provides good evidence of the presence of substantial amounts of aliphatic groups linking aromatic structures in the polymer. It is probable that these linkages carry hydroxyl, carboxyl, and possibly carbonyl functional groups. Long-chain aliphatic hydrocarbons contributed substantially to the composition of Colclough's digest products. These were not artifacts, but as yet no plausible explanation can be given for their origins, although it is likely that they arose from microbial synthesis and were adsorbed by the humic acids.

*Sodium sulfide* and sodium hydroxide mixtures have been used in the pulping industry to delignify wood since the end of the last century. Swift (1968) recognized the value of the procedure for the depolymerization of soil humic acids, obtaining yields of 50-60% of the mass of the starting substances as solvent soluble digest products. Later Craggs (1972) and O'Callaghan (1980) carried out model studies that have helped our understanding of the degradation mechanisms involved, and O'Callaghan was able to take advantage of GLCMS techniques to identify more than 30 of the digest products. The degradation procedure involved heating humic acids in saturated (10%) aqueous solutions of $Na_2S$ under autoclave conditions at 250°C. All compounds were methylated for separation by GLC. It is difficult, however, to obtain complete methylation of phenols, and thus mixtures of –OH- and of $-OCH_3$-substituted benzenes were detected. Because reaction with $Na_2S$ demethylates methoxy substituents, it is most likely that the compounds isolated as methoxybenzenes were present as phenols in the digests, but these might have been present as phenols or as methoxybenzene compounds in the polymer. Compounds of type 3 (Fig. 4), where n =2-5, were considerably in evidence, as were *n* alkanols $[CH_3(CH_2)_nOH$, where $n = 1\text{-}4]$. Among the aromatic compounds identified were structures of types **6, 25, 27, 32, 37, 41, 43,** and **45** (Fig. 4).

Several compounds, of types that can be represented by structures such as **32, 37,** and **45,** having one- to four-carbon aliphatic substituents on aromatic nuclei, were identified. On the basis of model studies carried out by O'Callaghan, it can be concluded that such structures would arise where quinone methide intermediates could form, as indicated in the reaction scheme in Figure 5. In saturated solutions of sodium sulfide, where the pH is 12.5, equal amounts of $SH^-$ and $OH^-$ species are present at elevated temperatures. $OH^-$ is more basic (or has a greater ability to bind a proton) than $SH^-$, but the latter species is the stronger nucleophile because the larger ionic species is polarized more readily. Thus an $SN_2$ reaction involving $SH^-$ will cause cleavage of the ethers and the formation of the quinone methide (structure N), as indicated by the sequence L, M, and N of the reaction scheme. Addition of a hydride ion gives rise to structure O, and this completes a reaction sequence in which a hydrocarbon substituent is derived from an ether functional group on the side chain carbon alpha to the aromatic nucleus. It can readily be deduced how *p*-hydroxyphenylethane, -phenylpropane, and -phenylbutane derivatives, which can form the appropriate quinone-methide structures, would give rise to the substituted aromatic compounds identified by O'Callaghan.



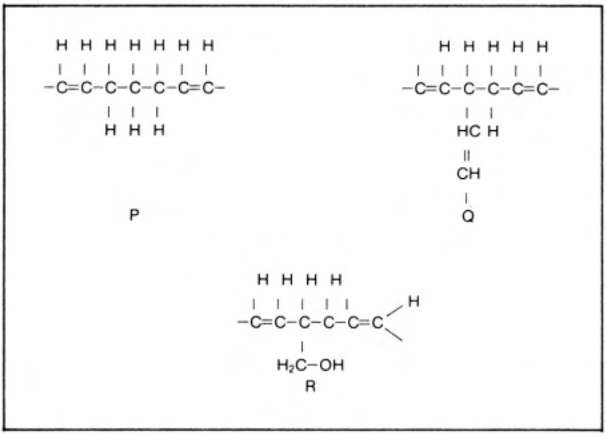
**5.** Reaction scheme involving quinone methide intermediates indegradation in $Na_2S$ solution at elevated temperatures.

*Alkaline permanganate* has been used extensively by Schnitzer and his colleagues (Schnitzer 1978, Schnitzer and Khan 1972) to degrade methylated humic substances. By GLCMS and microinfrared spectroscopy they identified about 34 compounds in the methylated digest products. Methylation of the humic substances before reaction was necessary to prevent degradation of the phenolic components in the polymers.

When the methylated humic and fulvic acids were refluxed for about 8 hours in *ca.* 0.25 M aqueous $KMnO_4$ at pH 10, about 30-35% of the masses of the starting materials were recovered as solvent-soluble (diethylether or ethylethanoate) components of the digest mixture. Compounds that could be assigned to structure types **3, 4, 6-25,** and **34-36** (Fig. 4) were identified. It is highly unlikely, however, that these identified products were components of the polymers, and it is probable that for the most part they were oxidized derivatives of some of the primary structures or were artifacts formed during the reaction. Because much is known about the mechanisms of permanganate oxidation of organic compounds, some general conclusions can be reached about the possible origins of the structures identified. For instance, naphthalene, anthracene, phenanthrene, 1,2-benz-anthracene, and chrysine (compounds A-I; Fig. 2) could all give 1,2-benzenedicarboxylic acid. Compounds B and D could also give 1,2,4,5-benzenetetracarboxylic acid, and compounds C and D could give 1, 2, 3, 4-benzenetetracarboxylic acid. On the basis of the foregoing information it can readily be deduced that compounds F and G could give rise to benzenetetracarboxylic or tricarboxylic acid structures, and that compound H could lead to benzenehexacarboxylic acid. However, the presence of benzenecarboxylic acids in the digests cannot be regarded as conclusive evidence for the presence of fused aromatic structures in the polymers because aliphatic substituents on the aromatic nuclei would also be oxidized in permanganate solutions to benzenecarboxylic acid structures.

The identification of aliphatic dicarboxylic and tricarboxylic acid structures in humic acid digests might be regarded as evidence for the presence of aliphatic hydrocarbons with some unsaturated (especially olefins) or oxidizable groups in the chains. For instance, structure P (Fig. 6) would degrade to give pentanedioic acid, and compounds Q and R would give the same appropriate trioic acid.

*Alkaline cupric oxide* reactions have also been extensively used by Schnitzer and his colleagues for the degradation of humic substances (Schnitzer 1974, 1978; Griffith and Schnitzer 1976). About 65 compounds have been identified by



**6.** Aliphatic structures that could give rise to dibasic and tribasic acids on treatment with alkaline permanganate.

Schnitzer's group and by others in alkaline (2 M NaOH) and in alkaline CuO digests of humic and fulvic acids, and about 25 of these have also been shown to be present in permanganate digests. Products found common to both sets of digests include several aliphatic dicarboxylic and tricarboxylic acids, and all of the benzenedicarboxylic and polycarboxylic acids. Compounds which occurred only in the alkaline CuO digests included a number of straight-chain aliphatic hydrocarbons (structure **1,** Fig. 4), a series of straight-chain and branched aliphatic carboxylic acids (structures of type **2,** Fig. 4), as well as aromatic keto (**27-29**) and aldehyde (**30** and **31**) structures. (These aromatic aldehyde and ketone structures had methoxy group substituents, but these might well have been present as phenolic hydroxyls in the parent molecules; it was necessary to methylate the digest products to confer volatility so that they could be separated by GLC techniques.) A number of dimethoxy (possible hydroxy in the original structures), benzenedicarboxylic, and benzenetricarboxylic acids were identified.

Hayes and Swift (1978) have discussed in some detail the kind of information that the digest products from alkaline CuO oxidation reactions can provide about primary structures in humic substances. Schnitzer and his colleagues rightly suggested that the aliphatic hydrocarbons could have come from microbially synthesized hydrocarbons adsorbed by the humic substances and the fatty acids from the saponification of phenolic esters. Hayes and Swift showed how these might also be released from long-chain unsaturated hydrocarbons, or even from saturated hydrocarbons containing carbonyl groups. They attached special significance to the fact that all the benzenecarboxylic acids found in the permanganate digests were also present in those from the CuO degradations. Alkaline CuO would not degrade fused aromatic structures to benzenepolycarboxylic acids. The most plausible explanation for the presence of such acids in the digests might be their formation from oxidation of aliphatic substituents on aromatic primary structures. However, they could have been formed by carbonylation of aromatic structures under the alkaline conditions, and careful model studies will be needed to establish whether or not such artifacts might have been formed. There was evidence also of the presence of methanol and ethanoic acid substituents on the aromatic nuclei. These might have been present as parts of the primary structures, or they could have been released from hydrolysis of esters, or from the degradation of longer chains bearing appropriate substituents or olefinic groups.

*Nondegradative procedures.* A variety of spectroscopic procedures has been used in studies of structures of and functional groups in humic substances. Phenolic and some other substituted aromatic components, as well as olefinic and variously substituted aliphatic substances, can be expected to provide chromophores that absorb in the *visible* and *ultraviolet* regions of the electromagnetic spectrum. However, the spectra recorded for these regions for humic substances have been featureless, and they generally show an increase in absorption with decreasing wavelength. A probable explanation for this is that the absorption bands of the numerous chromophores overlap throughout the spectrum. Better defined spectra might be obtained from humic materials carefully fractionated on the basis of molecular weight and charge density differences.

The $E_4$:$E_6$, or the ratio of optical density values measured at 400 and at 600 nm, is frequently used as an index of the extent of humification of soil organic matter. It is suggested, though not generally accepted, that the lower the value for this ratio, the greater is the extent of humification. In general, the more highly condensed or the higher the molecular weight of the humic substances, or both, the lower is the $E_4$:$E_6$. In contrast, the components that are more highly oxidized or of lower molecular weight, or both, tend to have higher ratios.

The *infrared spectra* of humic substances are also largely featureless because of overlapping of absorption bands from the numerous groups capable of absorbing electromagnetic radiation. However, some absorption bands appear as reasonably well-defined peaks. These include the broad — OH stretch at around 3,400/cm, the C-H stretch with sharper peaks at 2,920 and 2,850/cm, the carbonyl stretch at 1,720/cm, and there is generally evidence for carboxylate groups in peaks at 1,610 and 1,380/cm.

Infrared spectroscopy is especially useful for investigations of changes in the absorption frequencies of functional groups on the polymer that result from their interactions with adsorptive species. However, the technique is limited by the problems of resolution, although it is possible that recent developments in fourier transform infrared spectroscopy will allow resolution for humic suspensions to be improved over a greater expanse of the spectrum.

Hayes and Swift (1978) have summarized data for *electron spin resonance* (ESR) spectroscopy measurements of free radical contents of humic substances. Contents in the range of $10^{16}$-$10^{18}$ spins/g have been reported, and in general the numbers decrease in the order humins > humic acids > fulvic acids. ESR measurements provide evidence which indicates that the solvent used for extraction can significantly influence the free radical contents of the humic fractions isolated (e.g., Hayes et al 1975).

*Electron nuclear double resonance* (ENDOR) spectroscopy provides a further advance in resonance spectroscopy, and this procedure has been used by Retcofsky et al (1981) for investigations of the nature of free radicals in coals.

*Nuclear magnetic resonance* (NMR) is the most promising of the spectroscopy procedures for studies of the structures of humic substances. Some of the data from measurements with advanced NMR instrumentation indicate that humic materials are less aromatic than previously thought from degradation studies, although recent data by Schnitzer (1982), referred to below, suggest that such might not always be the case.

Grant (1977) extracted soils successively by soxhlet procedures or in the cold using various sequences of acetone, formic acid, and hydrochloric acid, and he subjected the extracts to analysis by proton ($^1$H) and carbon-13 ($^{13}$C) NMR. The $^1$H-NMR spectra, run in deutero-dimethylsulfoxide and in deutero-pyridine solutions, indicated various environments of $CH_2(CO)$, $CH_2$-NH-, carbohydrate H-C-O, and only minor amounts of aromatic components.

Recent developments in $^{13}$C-NMR instrumentation have incorporated facilities for cross polarization and magic angle spinning (CPMAS) to allow meaningful spectra to be obtained for solid samples. Substantial data have been accumulated using this technique for solid coal (e.g., Van der Hart and Retcofsky 1976; Maciel et al 1979, 1982; Barron and Witson 1981; Havens et al 1982), and some are now available for solid soil organic matter and for soil humic structures (e.g., Barron et al 1980, Hatcher et al 1981, Worobey and Webster 1981, Wilson 1981, Wilson et al 1981, Schnitzer 1982).

The major advantage of the cross-polarization (CP) technique over conventional $^{13}$C-NMR is that it reduces the time required to obtain identifiable spectra and it provides better resolution of spectra as the result of elimination of heteronuclear dipolar broadening. Increased sensitivity is brought about by transfer of polarization from $^1$H to $^{13}$C spins, and by the occurrence of the $^{13}$C spin-lattice relaxation at the relaxation rate of the proton population, which is about an order of magnitude faster than the conventional $^{13}$C rate. The resulting reduction in line widths is sufficient to allow assignments in the spectra of some functional groups in amorphous solids. Line broadening due to chemical shift anisotropy is not removed by the CP technique, but it can be eliminated by rapidly spinning the sample about an axis at the “magic angle” (MAS) of 54° 44’ with respect to the axis of the static magnetic field.

Data of Wilson et al (1981) show the very considerable improvement in resolution which the CPMAS procedure provides compared with the CP technique alone for analysis of organic components of soils. The latter provided questionable evidence for alkyl, O-alkyl, aromatic, and carboxyl carbons. With CPMAS, however, line widths in the spectra were on the order of 1-2 ppm, and the authors claimed that the broad signals observed were attributable to overlap from the large variety of C types present, and not to chemical shift anisotropy. Interpretation of the data suggested the presence of methyl groups terminal to alkyl chains (there was separate evidence for methylene chains), of polysaccharide-type structures, of aromatic carbons, and of carboxyl groups, although interference from polymethylmethacrylate used in the rotor prevented unambiguous assignment to carboxyl.

Schnitzer (1982) has provided CPMAS spectra for humic acids extracted from Spodosol 0 and $B_h$ horizons, and for a fulvic acid from the $B_h$ horizon. He interpreted the spectra to indicate the presence of unsubstituted aliphatic C, ether and carbohydrate C, aromatic C, C substituents on O of phenols, carboxyl C, and carbonyl C. Aromatic carbons were estimated to compose 59% of the humic acids in the 0 horizon and 57 and 68%, respectively, of the humic and fulvic acids in the $B_h$ horizon. These contents were considerably higher than those quoted for NMR studies by other workers. However, Schnitzer included the carbonyl and carboxyl groups in the aromatic structures, but it is certain that these functional groups also contribute significantly to the aliphatic components.

From CPMAS $^{13}$C-NMR data, Hatcher et a1 (1981) estimated the aromaticity in the Armadale Spodosol (Prince Edward Island) to be 25%, whereas that for a North Carolina Spodosol was 45% — similar to the 46% aromaticity found in Florida and Minnesota peats. Some of the scientists involved in NMR studies of humic structures have expressed surprise at the relatively low aromaticities of some of the samples. However, up to 50% of the weight of the humic acids may be lost on hydrolysis with 6 M HCl, and the hydrolysates can be expected to be composed largely of carbohydrate- and peptide-type materials. NMR studies are providing confirmatory evidence for the presence of substantial amounts of aliphatic hydrocarbon (recognized in digests of degradation reactions by Colclough and by Schnitzer and colleagues) components in humic acid materials.

There is no doubt that, as instrumentation and handling techniques continue to improve, nondegradative procedures will provide increasing amounts of the data and information needed to determine the structures of humic substances. It is likely that the first reliable indications of humic primary structures will be deduced from combinations of data from degradative procedures and from nondegradative spectroscopic techniques. Spectroscopy will be especially useful for indicating the types of linkages in the structures, and it will allow better predictions of plausible secondary structures in the polymers.

### Determinations of tertiary structures of humic substances

The ultracentrifuge provides a versatile tool for determinations of the sizes and shapes of macromolecules in solution. Molecular weight values ($M$) can be calculated from the Svedberg equation:

$$M = \frac{RTs}{(1-\nu\rho)D} \tag{1}$$

where $R$ is the gas content, $T$ the temperature (K), $v$ the partial specific volume of the solute, $p$ the solution density, $D$ the diffusion coefficient,

$$s = \frac{1}{x\,\omega^2}\cdot\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{\mathrm{d}\log_e x}{\omega^2 \mathrm{d}t} \tag{2}$$

representing the velocity of solute molecules divided by the centrifugal field; $x$ is the distance of the solute/solution boundary from the axis of rotation, $w$ the angular velocity, and t the time.

The equilibrium centrifugation procedure does not require measurements of the diffusion coefficient to calculate molecular weight from the relationships

$$M = \frac{2\,RT\,\mathrm{d}\log_e c}{(1-\nu\rho)\omega^2\mathrm{d}x^2} = \frac{RT}{(1-\nu\rho)}\cdot\frac{\mathrm{d}c/\mathrm{d}x}{\omega^2 xc} \tag{3}$$

where $c$ is the solute concentration at distance $x$ from the axis of rotation.

Because humic acids behave as polyelectrolytes in solution, it is necessary to add electrolyte (such as 0.1-0.2 M KCl) to suppress the charge and avoid anomalous results from the highly expanded polymer molecules. The problems of polydispersity are more difficult to overcome because numerous molecules of different sizes and diffusion coefficients and sedimenting at different velocities make it difficult to obtain well-defined sedimenting boundaries. Mention was previously made of the manner in which Cameron et al (1972a) tackled this problem by using gel filtration and pressure filtration procedures to isolate fractions with moderately small spreads of molecular weight values. Diffusion coefficients were measured for each fraction, and molecular weight values were calculated. Hayes and Swift (1978) have given an extended treatment of the use of ultracentrifugation for studies of humic substances, and they refer to the uses of osmometry, viscometry, and light scattering in this area. They have also indicated how molecular weight values can be obtained by means of gel filtration where gel columns are calibrated using humic materials of known molecular weights (Cameron et al 1972b).

Ultracentrifugation and viscosity measurements are useful also for determinations of the shapes and sizes of polymers because they allow determinations to be made of frictional forces acting on solute molecules as they move through solvent media. Determinations of frictional ratios $f{:}f_0$ are especially useful, where $f$ is the frictional coefficient of the molecule being studied and $f_0$ is that for a condensed sphere occupying the same volume. Tightly coiled globular proteins would give $f{:}f_o$ values close to 1, whereas highly solvated molecules, or those that are significantly more extensive in one direction than in another, give much higher values.

Cameron et al (1972a) obtained reliable frictional ratio data from their ultracentrifugation studies on fractionated humic acid samples. When they plotted frictional ratios against molecular weight values, a linear relationship was observed for samples with molecular weights up to $2 \times 10^5$. From their data, the authors concluded that humic molecules assumed random coil solution conformations. Hayes and Swift ( 1978) discussed how a randomly coiled humic molecule in solution could be regarded as a strand, with charges distributed along its length, which coils randomly with respect to both time and space. This would give a molecule that is roughly spherical and with a Gaussian distribution of mass (i.e., greatest at the center and decreasing to zero at its outer limits). Branching would give rise to higher mass density within the sphere and create a more compact structure. Such branching was thought to be responsible for the lower-than-theoretrial $f{:}f_o$ values for humic acids of molecular weight values greater than $2 \times 10^5$ in the studies by Cameron et al (1972a).

## GENERAL CONCLUSIONS FROM STRUCTURAL STUDIES OF HUMIC SUBSTANCES

There is strong evidence, based on the structures identified in the digests from the degradation of humic substances, to indicate that single ring aromatic compounds are components of humic structures. Additional evidence of aromaticity is being provided in NMR spectra of solid humic materials. The available data suggest that many of the aromatic structures are disubstituted or polysubstituted.

It is possible that the fused aromatic structures identified in zinc dust distillation digests of humic substances were artifacts of these highly energetic reactions. It is possible also that the benzenecarboxylic acids identified in the digests of permanganate-oxidized humic materials originated in fused aromatic components in the polymer structures. However, this is not highly likely because similar structures were isolated in digests from degradations with alkaline CuO, a procedure that would not oxidize the fused structures to benzenecarboxylic acids. Thus it is more likely that the aromatic acid structures in the digests were derived from the oxidation of aliphatic or carbonyl substituents on benzene-type structures, or both. Degradations with phenol plus *p*-toluenesulphonic acid and with sodium sulfide provide further evidence for the presence of aliphatic substituents on the aromatic nuclei. However, further model studies are required to prove conclusively that some of the carbonyl group substituents did not arise from carbonylation reactions in the alkaline conditions in the digests.

Many of the benzene structures also contain hydroxy and methoxy substituents, and the positioning of these substituents in the rings suggests possible lignin-type precursors for some of the humic structures. Others of the phenolic structures could arise also from products of microbial metabolism.

Sugars and amino acids released during the hydrolysis of humic materials could arise from polysaccharides and peptides physically sorbed on these materials. It is possible that some of these sugars and amino acids might be integral parts of the humic structures because they are released in hydrolysates even after humic substances are carefully fractionated by procedures that would remove physisorbed components. Phenolic glycoside structures could link sugars, oligosaccharides, or even polysaccharides in the humic polymer structures. Peptide bonds could attack amino acids and peptides in the polymer, and additionally free amino groups could form covalent links with carbons *ortho* to the carbonyl group of quinone structures. It is generally agreed that humic substances contain some heterocyclic N, but little is known about these types of structures in the polymer.

The types of linkages that bind together the primary structures in humic polymers are poorly understood. Interpretations of data from sodium amalgam cleavage reactions suggest that phenolic ether links could be important. For the most part, though, it would seem that linkages in the humic “backbone” or core are through C-C bonds. However, the activation energies for the cleavage of such bonds is lowered where polar substituents are present on the C atoms. Therefore, on the basis of what is known from degradation and from spectroscopic studies, it is plausible to propose that humic polymers contain saccharide and amino acid or peptide components, which may be peripheral to the major structural unit or “backbone.” These major structural units could involve single-ring aromatic structures, which in many instances are substituted with carboxyl, phenolic hydroxyl, and phenolic ether groups, and with hydrocarbon substituents. Quinone structures inevitably arise from the oxidation of phenols. Some of the linking hydrocarbons could be expected to be substantially unsaturated, and to be substituted with acidic and with polar functional groups. The saturated hydrocarbons isolated could also have come from cleavage of interaromatic links, or they might merely be products of microbial skeletons or metabolism that were sorbed by humic substances.

Modern spectroscopic instrumentation, especially CPMAS $^{13}$C-NMR, provide useful tools for studying the composition of dry humic substances in the solid state. However, no suitable instrumentation available will allow the size, shape, branching, etc. of such amorphous polymers to be observed directly in the solid or gel phases that are relevant to soil conditions. Concepts that we have of the tertiary structures of humic substances in the field must be derived from studies of the polymers in solution. The data from which Cameron et al (1972a) concluded that humic acids have random coil solution conformations are excellent, but were obtained only for fractions that dissolved in tris buffer at a pH of about 9. From the results obtained, Cameron et al were able to predict that polymer branching increased as the molecular weight increased. Because substantial amounts of the humic acids were insoluble in the buffer, it is plausible to assume that the residual materials contained the components that had higher molecular weights, were more highly branched, cross linked, or had lower charge densities than those that dissolved. The random coil concept for humic acid solutions is used here as a basis for predictions of the arrangements of the polymer molecules in the solid or gel phases in the soil.

Humic substances can have an independent existence associated with the organic matter of the soil, and they can be bound to the clay and hydroxide inorganic colloids (Burchill et al 1981, Hayes and Swift 1981). It is highly unlikely that these substances would be exchanged with $NH_4^+$, $K^+$, or $Na^+$ ions because the resulting soluble polyelectrolytes would be lost in the drainage. It is most likely that the predominant exchangeable cations would be $Ca^{2+}$, $Mg^{2+}$, and, depending on the environmental conditions, $H^+$, $Al^{3+}$, and iron cations. $H^+$-exchanged fulvic acids are, of course, water soluble, and so it is necessary to have these substances partially exchanged with divalent and polyvalent cations to retain them in the soil.

$H^+$-exchanged humic acids are insoluble in water because the carboxyl groups are largely undissociated and hence lack the impetus to solvate which is provided by charged groups. Equally important is the fact that intermolecular and intramolecular H bonding will pull together the strands in the random coils and in this way exclude $H_2O$ from the polymer matrix. Similarly, divalent and polyvalent cations, which bridge two or more charged groups within or between the polymer strands, render humic and some fulvic acids insoluble by shrinking the structures and driving out water. The divalent and polyvalent cations also form bridges between the negative charges on the polymers and those on the inorganic colloids, and this can form the basis of some of the inorganic-organic “conglomerate” colloids in the soils (Hayes and Swift 1981). (It is possible that some associations between humic materials and soil inorganic components merely involve precipitation of the organic polymers in the presence of metal ions.)

As drying of humic substances proceeds, further shrinkage of the structures will occur, and the contribution of the bridging cations to the shrinkage will be enhanced by van der Waal’s forces, particularly those between the hydrophobic groups on adjacent polymer strands. Thus, what was a random coil when in solution is likely to be a condensed, close-packed, though amorphous, structure when dried. These concepts explain why humic materials dried in the laboratory or soil organic matter subjected to drought conditions in the field are difficult to rewet.

The nature of the humic materials, as well as the cations with which they are associated will, of course, determine their reactivities in the soil. Turchenek and

Oades (1979) have provided extensive data that indicate the extents to which organic matter and elements such as Al, Ca, Fe, Mg, P, Si, and Ti are present in the different density fractions of soils. They have shown that the trends are not the same for all soils, and that there are differences in the properties of the organic materials associated with the different clay-size fractions; for instance, their data suggest that the heavier fine clays contain the more aliphatic humic and fulvic acid materials, and that these might be adsorbed through physical adsorption forces, whereas the more highly humified and aromatic humic components appear to associate preferentially with the lighter, coarser soil clays. It is very likely that the affinities of the different humic components for various adsorptive species will not be the same, and these differences might be explained in terms of shapes, charge, polarity, etc. The observations of Turchenek and Oades (1979) have focused attention on the probable importance, in terms of soil reactivities, of differences among humic materials associated with soil clays; and CPMAS NMR spectroscopy can be expected to play an important role in resolving differences between the types of organic materials associated with the various inorganic soil colloids.

## REFERENCES CITED

Atherton, N. M., P. A. Cranwell, A. J. Floyd, and R. D. Haworth. 1967. Humic acid — 1. ESR spectra of humic acids. Tetrahedron 23: 1653-1667.

Barron, P. F., M. A. Wilson, J. F. Stephens, B. A. Cornell, and K. R. Tate. 1980. Cross-polarization $^{13}$C-NMR spectroscopy of whole soils. Nature 286:585-587.

Barron, P. F., and M. A. Wilson. 1981. Humic soil and coal structure study with magic-angle spinning $^{13}$C CP-NMR. Nature 289:275-276.

Bazilevich, N. I. 1974. Soil-forming role of substance and energy exchange in the soil-plant system. Trans. 10th Intern. Congr. Soil Sci. (Moscow) 6:17-27.

Bremner, J. M. 1950. Some observations on the oxidation of soil organic matter in the presence of alkali. J. Soil Sci. 1:198-204.

Bremner, J. M., and H. Lees. 1949. Studies on soil organic matter. II. The extraction of organic matter from soil by neutral reagents. J. Agric. Soil. 39:274-279.

Burchill, S., M. H. B. Hayes, and D. J. Greenland. 1981. Adsorption. Pages 221-400 *in* D. J. Greenland and M. H. B. Hayes (eds.). The chemistry of soil processes. Wiley, Chichester and New York.

Burges, N. A., H. M. Hurst, B. Walkden. 1964. The phenolic constituents of humic acid and their relation to the lignin of plant cover. Geochim. Cosmochim. Acta 28: 1547-1554.

Cameron, R. S., B. K. Thornton, R. S. Swift, and A. M. Posner. 1972a. Molecular weight and shape of humic acid from sedimentation and diffusion measurements on fractionated extracts. J. Soil Sci. 23:394-408.

Cameron, R. S., R. S. Swift, B. K. Thornton, and A. M. Posner. 1972b. Calibration of gel permeation chromatography materials for use with humic acid. J. Soil Sci. 23:342-349.

Chahal, K. S., J. L. Mortensen, and F. L. Himes. 1966. Decomposition products of carbon-14 labeled rye tissue in a peat profile. Soil Sci. Soc. Am. Proc. 30:217-220.

Cheshire, M. V., P. A. Cranwell, C. P. Falshaw, A. J. Floyd, and R. D. Haworth. 1967. Humic acid — II. Structure of humic acids. Tetrahedron 23:1669-1682.

Cheshire, M. C., P. A. Cranwell, and R. D. Haworth. 1968. Humic acid — III. Tetrahedron 24:5155-5167.

Choudhri, M. B., and F. J. Stevenson. 1957. Chemical and physicochemical properties of soil colloids. III. Extraction of organic matter from soils. Soil Sci. Soc. Am. Proc. 21:508-513.

Colclough, P. 1980. Degradation of humic acids with phenol and *p*-toluenesulphonic acid. Unpublished results, Chemistry Department, University of Birmingham.

Craggs, J. D. 1972. Sodium sulphide reactions with humic acid and model compounds. Ph D thesis, University of Birmingham.

Fischer, L. 1969. An introduction to gel chromatography. Pages 157-390 *in* T. S. Work and E. Work (eds.). Laboratory Techniques in Biochemistry and Molecular Biology, Vol. 1, Part II. North Holland Publishing Company, Amsterdam.

Flaig, W. 1983. Soil organic matter as a source of nutrients. Pages 73-92 *in* International Rice Research Institute. Organic matter and rice. Los Baños, Laguna, Philippines.

Flaig, W., H. Beutelspacher, and E. Rietz. 1975. Chemical composition and physical properties of humic substances. Pages 1-219 *in* J. E. Gieseking (ed.). Soil components, Vol. I. Springer-Verlag, Berlin, New York.

Grant, D. 1977. Chemical structure of humic substances. Nature 270:709-710.

Griffith, S. M., and M. Schnitzer. 1976. The alkaline cupric oxide oxidation of humic and fulvic acids extracted from tropical volcanic soils. Soil Sci. 122: 191-201.

Hatcher, P. G., G. E. Maciel, and L. W. Dennis. 1981. Alipathic structure of humic acids; a clue to their origin. Org. Geochem. 3:43-48.

Havens, J. R., J. L. Koenig, and P. C. Painter. 1982. Chemical characterization of solid coals through magic-angle $^{13}C$ nuclear magnetic resonance. Fuel 61:393-396.

Hayes, M. H. B., R. S. Swift, R. E. Wardle, and J. K. Brown. 1975. Humic materials from an organic soil: A comparison of extractants and of properties of extracts. Geoderma 13:231-245.

Hayes, M. H. B., and R. S. Swift. 1978. The chemistry of soil organic colloids. Pages 179-320 *in* D. J. Greenland and M. H. B. Hayes (eds.). The chemistry of soil constituents. Wiley, Chichester and New York.

Hayes, M. H. B., and R. S. Swift. 1981. Organic colloids and organo-mineral associations. Int. Soc. Soil Sci. Bull. 60:67-74.

International Society of Humic Substances (ISHS). 1981. Agronomy news, Appendix IV, Nov-Dec.

Jackson, M. P., R. S. Swift, A. M. Posner, and J. R. Knox. 1972. Pholic degradation of humic acid. Soil Sci. 114:75-78.

Kovda, V. A. 1974. Biosphere, soils and their utilization. Report of the president of the ISSS, 10th International Congress Soil Sci. (Moscow).

MacCarthy, P., M. J. Peterson, R. L. Malcolm, and E. M. Thurman. 1979. Separation of humic substances by pH gradient desorption from a hydrophobic resin. Anal. Chem. 51:2041-2043.

Maciel, G. E., V. J. Bartuska, and P. Miknis. 1979. Characterization of organic material in coal by proton-decoupled $^{13}C$ nuclear magnetic resonance with magic-angle spinning. Fuel 58:391-394.

Maciel, E. G., M. J. Sullivan, L. Petrakis, and D. W. Grandy. 1982. $^{13}C$ nuclear magnetic resonance characterization of coal macerals by magic-angle spinning. Fuel 61:411-414.

Malcolm, R. L. 1981. International standard collection of humic and fulvic acids. Int. Soc. Soil Sci. Bull. 60:30-31.

Martin, J. P., K. Haider, and C. Saiz-Jimenez. 1974. Sodium amalgam reductive degradation of fungal and model phenolic polymers, soil humic acids and simple phenolic compounds. Soil Sci. Soc. Am. Proc. 38:760-765.

Maxinov, O. B., T. V. Shvets, and Yu. N. Elkin. 1977. On permanganate oxidation of humic acids. Geoderma 19:63-78.

O'Callaghan, M. R. 1980. Some studies in soil chemistry. Ph D thesis, University of Birmingham.

Piper, T. J., and A. M. Posner. 1972. Sodium amalgam reduction of humic acid — I. Evaluation of the method; II. Application of the method. Soil Biol. Biochem. 4:513-531.

Retcofsky, H. L., M. R. Hough, M. M. Maguire, and R. B. Clarkson. 1981. Nature of free radicals in coals, pyrolized coals, solvent-refined coal, and coal lignification products. Pages 37-58 *in* M. L. Gorbaty and K. Ouchi (eds.). Coal structure. Advances in Chemistry Series, 192, American Chemical Society.

Schnitzer, M. 1974. Alkaline cupric oxide oxidation of a methylated fulvic acid. Soil Biol. Biochem. 6:1-6.

Schnitzer, M. 1978. Humic substances: chemistry and reactions. Pages 1-64 *in* M. Schnitzer and S. U. Khan (eds.). Soil organic matter. Elsevier, Amsterdam, and New York.

Schnitzer, M. 1982. Quo vadis soil organic matter research. Trans. 12th Int. Congr. Soil Sci. 5:67-68.

Schnitzer, M., and S. U. Khan. 1972. Humic substances in the environment. Marcel Dekker, New York.

Sinclair, A. H., and J. Tinsley. 1981. Studies of soil organic matter using foric acid solvents: Factors affecting composition and degree of formylation of organic isolates. J. Soil Sci. 32:103-117.

Stevenson, F. J., J. D. Marks, J. W. Varner, and W. P. Martin. 1952. Electrophoretic and chromatographic investigations of clay adsorbed organic colloids. 1. Preliminary investigations. Soil Sci. Soc. Am. Proc. 16:69-73.

Swift, R. S. 1968. Physicochemical studies on soil organic matter. Ph D thesis, University of Birmingham.

Swift, R. S., B. K. Thornton, and A. M. Posner. 1970. Spectral characteristics of a humic acid fractionated with respect to molecular weight using an agar gel. Soil Sci. 110:93-99.

Turchenek, L. W., and J. M. Oades. 1979. Fractionation of organomineral complexes by sedimentation and density techniques. Geoderma 21:311-343.

Van der Hart, D. L., and H. L. Retcofsky. 1976. Estimation of coal aromaticities by proton-decoupled carbon-13 magnetic resonance spectra of whole coals. Fuel 55:202-204.

Waldron, A. C., and J. L. Mortensen. 1961. Soil nitrogen complexes: II. Electrophoretic separation of organic components. Soil Sci. Soc. Am. Proc. 25:29-32.

Wilson, M. A. 1981. Applications of nuclear magnetic resonance spectroscopy to the study of the structure of soil organic matter. J. Soil Sci. 32:167-186.

Wilson, M. A., P. F. Barron, and K. M. Goh. 1981. Differences in structure of organic matter in two soils as demonstrated by $^{13}C$ cross polarization nuclear magnetic resonance spectroscopy with magic-angle spinning. Geoderma 26:323-327.

Worobey, B. L., and G. R. B. Webster. 1981. Indigenous $^{13}C$-NMR structural features of soil humic substances. Nature 292-526-529.

## DISCUSSION

SCHARPENSEEL: Grant Taylor, at the 8th International Radiocarbon Congress in Lower Hutt, New Zealand, presented data that indicate that organic solvent extracts of humic substances isolate materials that are older (based on radiocarbon dating) than the rest of the humus components. Might the hydrophobic materials be the oldest components of humus? Does your model, which suggests that the more hydrophobic components of humus orientate to the outside on drying, suggest that gradient elution with mild solvents could effectively extract humus materials?

*HAYES:* Humins, the most hydrophobic of the three major gross fractions of humic substances, are likely also to be the oldest. Humins, however, are insoluble in aqueous and in nonaqueous solvents. A plausible model for humic structures suggests that the polymers contain hydrophobic and hydrophylic components in the molecules. As drying occurs, the hydrophylic groups associate and, possibly predominantly, orientate toward the interior of the polymeric structures and give rise to a predominance of hydrophobic components on the outside. Effective solvation will depend on the relative abundance of the hydrophylic groups (especially carboxyl) and on the abilities of the solvents to penetrate the polymer matrix (where these reside) through the more hydrophobic exterior. Our experience suggests that hydrophobic solvents extract little of the humic materials. Hayes and Swift (1978, referenced in text) have discussed the application of sequences of solvents such as dipolar aprotics, neutral pyrophosphate, and NaOH. They indicate that there are differences between the materials isolated when the humics are exhaustively extracted with one solvent system before proceeding to the next. Gradient elution might not prove effective because of the intimate mixing required to obtain maximum solvation. There is much that can be learned from uses of solvent mixtures, especially if it can be established that certain mixtures are efficient extractants giving good yields of polymers with a minimum of artifact formation.

NAGAR: In my view, it is possible to obtain primary structures of humic substances by use of Curie point pyrolysis - gas chromatography - mass spectrometry (CPPGCMS) computerized systems. Applications of this technique would allow us to differentiate between humus formed under aerobic and under submerged conditions. What is your view?

*HAYES:* We define as primary structures the different small chemical entities that are combined to form the polymeric structures. Although CPPGCMS represents a considerable advance in pyrolysis techniques, the procedure cannot be relied upon to release chemically unaltered fragments from the polymeric structures. Nevertheless, the procedure can be relied upon to allow the “fingerprinting” of humic substances of different origins, as your work (see references in Hayes and Swift 1978, quoted in text) shows. In my view, additional studies using model substances are needed before it will be possible to assign with confidence the compounds identified in the pyrograms to structures in the polymers. I hope that you will continue to direct your experience in this area to investigations of primary structures of humic substances.

TSUTSUKI: It is difficult to obtain absolute values for the molecular weights of humic substances. For instance, applications of osmotic pressure procedures are limited because of the problems which the membranes used can provide, and light scattering is not practical because of the high absorption of light by the dark polymers. Results from gel permeation procedures are greatly influenced by properties of the buffers used (such as pH, salt content, etc.). Do you consider that there is any reliable procedure available at this time for the determination of molecular weights of humic substances?

*HAYES:* Ultracentrifugation is the best of the procedures for molecular weight determinations of humic substances based on data available at this time. Any procedure used must take account of the fact that humic materials are polyelectrolytes; hence the dimensions of the polymers will be influenced by their extents of ionization (influenced by pH) and by electrical double-layer properties (influenced by the addition of salt).

Cameron et al (1972, referenced in text) have, in my view provided the most reliable and useful data on molecular weights of humic materials. These values were obtained for materials that had been carefully fractionated into components with reasonably homogeneous molecular weight sizes (see text) and had been subjected to ultracentrifugation. Cameron et al used tris buffer with a pH of about 9, and their work was limited to the materials solubilized in the buffer. We need an appropriate buffer system that can operate at a high enough pH to solubilize most of the humic acid materials in order to get more representative molecular weight values for these components of humic substances. Fulvic acids do not present a problem in this regard. Addition of an appropriate amount of salt is essential, although some experimentation is needed to determine the optimum ionic strength for a medium of known pH containing a known concentration of humic material.

TSUTSUKI: Humic materials are components of the very heterogeneous mixture that is soil organic matter. Would it be appropriate to separate the mixture into various fractions before isolating the humic components?

*HAYES:* A simple classification would regard soil organic matter as a mixture of humic and of nonhumic substances. The nonhumic materials could contain unaltered and partially transformed plant and animal residues as well as soluble polysaccharides and peptide materials, etc. Some of the plant and animal residues could be removed by hand, by sieving, or by flotation procedures. However, such procedures are generally not practical and largely unnecessary, because the components that are removed by such means are in general not soluble in the extractants used for humic substances. The soluble nonhumic components extracted with the humic materials can present problems when attempting to purify the humic materials. Gel filtration procedures provide useful tools for separating humic from coextracted nonhumic compounds. Hayes and Swift (1978, referenced in text) have described the uses of gels for the separation of components in extracts of humus. Thus I would suggest that any attempts to subdivide the soil organic components before extracting the humic materials would be impractical. Instead, efforts should be focused on better methods of separating humic from nonhumic substances in extracts, and for fractionation of the humic materials on the basis of molecular weight and charge density differences.

WEN: Your paper suggests that fused aromatic compounds may not be present as components of humic substances. If so, can you explain why more benzenehexacarboxylic and benzenepentacarboxylic acids are found in permanganate digests than in alkaline cupric oxide digests of humic substances?

*HAYES:* Permanganate will cleave to benzenecarboxylic acids any sidechains containing one or more H atoms on the carbon attached to the ring. It will also of course cleave fused aromatic substances as indicated in the text. Alkaline CuO is more selective in its cleavage of aliphatic substituents (see reference to Hayes and Swift in the text) and it will not cleave (to carboxyls) fused aromatic structures. Differences in amounts of the polycarboxylic acids in the two digests could represent differences in the structures attached to the aromatic nuclei. We cannot, of course, on the basis of such evidence rule out the possibility that fused aromatic structures exist. The possibility that the polysubstituted benzenecarboxylic acids might be artifacts arising from carboxylation of the aromatic structures in the alkaline digests should also be considered. It is unusual to find highly substituted aromatic structures in abundance in polymers having origins in biological processes, and so it is necessary to exercise caution when interpreting the origins of the benzenepolycarboxylic acids identified in alkaline degradation digests of humic substances.

# STRAW AS A SOURCE OF NUTRIENTS FOR WETLAND RICE

F. N. Ponnamperuma

Rice straw contains about 0.6% N, 0.1% each of P and S, 1.5% K, 5% Si, and 40% C. Because it is available on the spot in amounts varying from 2 to 10 t/ha, it is a convenient source of plant nutrients.

Long-term experiments indicate that straw incorporation in wetland rice fields causes an increase in the content of organic C, N, and available P, K, and Si.

In the tropics, all the straw produced in situ can be incorporated into wetland soils, and rice can be planted almost immediately without adverse effects.

The yield advantage due to straw incorporation over straw burning or removal is about 0.4 t/ha per season, and it increases with time as soil fertility builds up. The benefits stem from an increased supply of nutrients and a favorable N release pattern.

The value of nutrients in 5 t straw is about $35. The extra paddy is worth about $70 at Philippine prices. Incorporating straw may benefit the farmer to the extent of about $100 per season.

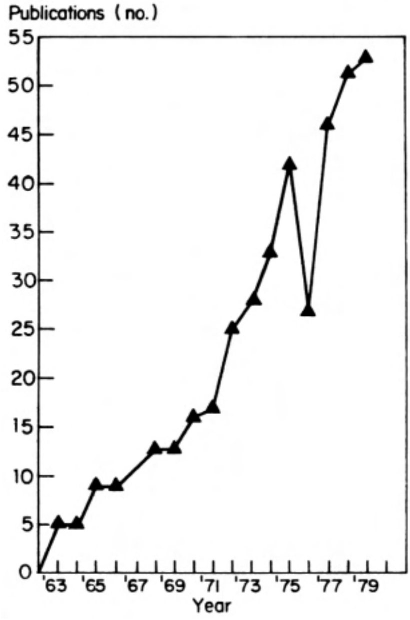
The rising cost of fertilizers and the need to conserve plant nutrients by recycling them focus attention on organic materials as sources of fertilizer elements. Of farm organic substances, rice straw is the most suited to wetland rice. The increasing number of publications on rice straw in recent years (Fig. 1) indicates a growing interest in this resource.

A 5-t crop of paddy (rice in the husk) removes from the soil, in the paddy and straw, about 150 kg N, 20 kg P, 150 kg K, and 20 kg S. Almost all the K and about a third of the N, P, and S remain in the straw. Rice straw is thus a good source of those macro nutrients. Besides, 5 t straw contain about 2 t C, which in wetlands can be an indirect source of N. Other factors that favor the use of rice straw as a manure are its on-the-spot availability in amounts varying from 2 to 10 t/ha per season and elimination of disposal problems.

In 1981 the world produced 408 million t paddy (Palacpac 1982). Assuming a grain-straw ratio of 2:3, the mass of straw produced was over 600 million t. This straw contained about 3.6 million t N, 0.6 million t P, and 9 million t K, valued at about $4.2 billion at 1981 international spot prices. The total nutrient content of the straw produced in three Asian countries (for which figures are available) was more than twice the amount used on rice as chemical fertilizers in those countries (Table 1).

---

The International Rice Research Institute, P. O. Box 933, Manila, Philippines.



**1.** Number of publications on rice straw.

## NUTRIENT CONTRIBUTION BY RICE STRAW

The contribution of nutrients by a rice straw crop to a soil depends on the mass and composition of the straw, its management, and the soil's water regime.

### Mass

The mass of straw produced is a function of water regime, season, cultivar, soil fertility, and the grain-straw ratio.

*Water regime.* The average yield of dryland rice, computed from Palacpac (1982), is about 1.4 t/ ha, compared with 2.8 t/ ha for wetland rice. If the grain:straw is assumed to be the same for both rice types, on the average, the mass of wetland rice straw per hectare is twice that of the dryland.

*Season and cultivar.* Table 2 shows the effects of season and variety on straw yield under good management. But, as with most reports, the moisture content of the straw is not stated. Tall Meeung Naung 62 M produced 15.2 t/ ha in the main season,

**Table 1. Rice production; N, P, K content of straw; and N, P, K fertilizers used on rice in 3 countries in 1979.**

| | Amount ($10^6$ t) | | |
|---|---|---|---|
| | India | Philippines | Sri Lanka |
| Paddy production | 66.7 | 7.84 | 1.88 |
| Straw production[a] | 100.5 | 11.8 | 2.82 |
| N, P, K[b] content of straw | 5.7 | 0.31 | 0.16 |
| N, P, K[b] fertilizer used | 2.0 | 0.15 | 0.06 |

[a] Assuming a grain-straw ratio of 2:3. [b] N, P, K = N + $P_2O_5$ + $K_2O$.

**Table 2. Straw yields of leading cultivars at various locations and seasons under good management.**[a]

| Location | Season | cultivar | Straw yield (t/ha) | Grain:straw |
|---|---|---|---|---|
| Sapporo (Japan) | Summer | Shin-Ei | 4.3 | 1.2 |
| Taichung (Taiwan, China) | 1st | Tainan 3 | 3.7 | 1.2 |
| | 2nd | Tainan 3 | 2.8 | 1.2 |
| Chengmai (Thailand) | Main | Dawley 4-2 | 4.9 | 0.5 |
| | Main | Meung Naung 62 M | 15.2 | 0.3 |
| Los Baños (Philippines) | Wet | Peta | 8.5 | 0.4 |
| | Dry | Peta | 6.8 | 0.9 |
| Bukit Merah (Malaysia) | Main | Subang Intan 117 | 5.8 | 0.6 |

[a] Adapted from International Rice Research Institute (1965).

compared with 2.8 t/ha for short Tainan 3 in the second (unfavorable) season, and Peta produced more straw in the wet season than in the dry. Dei (1970) found that straw yield in north Japan was 6.5 t/ha and in the south 7.3 t/ha; the corresponding grain-straw ratios were 1.06 and 0.84.

*Soil fertility.* On poor, unfertilized soils, straw yields are about 2 t/ha (Tanaka 1978). Alleviation of growth-limiting factors increases straw yields. Table 3 illustrates the influence of soil amendments on straw production in several wetland rice cultivars under moderately good management. In all cases but IR34 under Zn-deficient conditions, supplying the missing nutrient made a significant difference in straw yield.

*Grain-straw ratio.* Results from tests on 32 modern cultivars or lines of wetland rice in farmers' fields in the Philippines at a moderate management level revealed a mean straw yield of 6.0 t/ha with a grain-straw ratio of 0.87 for the dry season, and 5.5 t/ha and 0.57 for the wet season. The proportion of straw in the harvest is higher in farmers' fields than in experiment stations, apparently because grain yield is more vulnerable than straw yield to environmental hazards. It is also higher in the wet

**Table 3. Influence of soil amendments on straw yield in several cultivars in 3 nutrient-deficient soils in farmers' fields, IRRI.**[a]

| Season | Cultivar | Straw yield (t/ha) | |
|---|---|---|---|
| | | *No N* | *N* |
| 1968 wet | IR8 | 4.1 | 6.5 |
| | Peta | 7.9 | 10.3 |
| | | *No P* | *P* |
| 1981 wet | IR42 | 3.8 | 4.4 |
| | IR48 | 5.5 | 8.2 |
| | | *No Zn* | *Zn* |
| 1981 wet | IR26 | 2.4 | 5.3 |
| | IR34 | 6.4 | 6.5 |

[a] Source: M. R. Orticio, IRRI, unpublished.

**Table 4. Nutrient content of 22 rice straw samples.**[a]

| Nutrient | Min (%) | Max (%) | X (%) | CV[b] |
|---|---|---|---|---|
| N | 0.38 | 1.01 | 0.57 | 24.7 |
| P | 0.01 | 0.12 | 0.07 | 43.2 |
| K | 1.0 | 3.0 | 1.50 | 31.0 |
| Si | 2.5 | 7.0 | 3.0 | 21.9 |

[a]Adapted from Tanaka (1978). [b]CV = coefficient of variation.

season than in the dry. Cultivars with a grain:straw > 1.0 produce less straw than those with a ratio of <1.0.

## Composition

The mineral nutrient content of straw at harvest depends on soil, irrigation-water quality, amount of fertilizer applied, cultivar, and season, reflected in high coefficients of variation (Table 4). But from published figures it is difficult to separate the effects of the factors affecting straw composition. Table 5 gives the N, P, K, and Si contents of straw from nine locations based on the analysis, in most cases, of unspecified cultivars grown on unspecified soils in unspecified seasons.

Takijima arid Gunawardena (1971) found no clear correlation between element content of straw and element availability in the soil except for P. The analyses of 44 straw samples from unfertilized experimental plots on a Tropaqualf on the IRRI farm, however, revealed high K (3.7%) and Si (6.5%) content, apparently because both the soil and irrigation water had a high concentration of these elements.

For practical purposes, in farmers' fields in the tropics the straw mass corresponding to 1 t sun-dried paddy is about 1.5 t, and it contains about 9 kg N, 2 kg each of P and S, 25 kg K, 70 kg Si, 6 kg Ca, and 2 kg Mg. Because straw yields are usually not available, this is a rough guide to the nutrient content of the straw of a paddy crop.

Straw also contains an indirect source of N—C compounds that provide a substrate for microbial metabolism, including sugars, starches, celluloses, hemicellu-

**Table 5. Nutrient content of rice straw from 9 locations based on unknown sample numbers.**[a]

| Location | Nutrient content (%) | | | |
|---|---|---|---|---|
| | N | P | K | Si |
| Taiwan, China | 0.7 | 0.13 | 1.2 | 4.0 |
| India | 0.5 | 0.15 | 1.8 | – |
| Indonesia | 0.4 | 0.02 | 1.4 | 5.6 |
| Japan (northern) | 0.7 | 0.12 | 1.4 | 4.4 |
| Japan (southern) | 0.5 | 0.07 | 1.1 | 4.7 |
| Malaysia | 0.4 | 0.10 | 1.4 | 3.5 |
| Philippines | 0.8 | 0.12 | 3.1 | 6.6 |
| Senegal | 0.8 | 0.17 | 1.4 | – |
| Sri Lanka[b] | 1.1 | 0.16 | 1.4 | 4.0 |

[a]Sources: Takijima and Gunawardena (1971); Tanaka (1973); Beye (1974); M. V. Rao, Central Rice Research Institute, India, unpublished. [b]n = 40.

loses, pectins, lignins, fats, and proteins. These compounds constitute about 40% (as C) of the dry matter of straw. Straw incorporation stimulates both heterotrophic and phototrophic N fixation in flooded soils (Matsuguchi 1979).

## Management

Straw is removed from the field, burned in situ, piled or spread in the field, incorporated in the soil, or used as a mulch for the succeeding dryland crop.

*Removal.* Straw is hauled away from the field for use as fuel; as animal feed and bedding; as a substrate for composting, biogas generation, or mushroom culture: and as a raw material in industry. Local conditions determine the disposal method.

Removal for industrial use represents a total loss from the field of the nutrients in the straw. Transfer of straw from the field to homesteads for farm uses is not so severe a nutrient drain if the products or residues are eventually returned to the field. In China most of the straw removed from the field is composted.

Compost is discussed in another paper in this session, but because composting is still a major use of straw, some aspects of compost need mention here.

The composition of aerobic compost is highly variable. On the average, it is poorer than rice straw in plant nutrients (Tanaka 1978). In temperate climates, letting the straw rot in the field adds more humus and nutrients than composting and applying it to the field (Russell 1973). Besides, some of the N in compost is present as nitrate, which is of little use to wetland rice. And because its content of readily decomposable C compounds is low, compost is a poor indirect source of N. Composting requires supplemental nutrients and consumes time and labor. Conversion of straw into compost aerobically or anaerobically for use as a manure for wetland rice needs reevaluation.

*Burning.* Burning is the major method of straw disposal in Australia, Burma, France, Indonesia, Italy, Malaysia, the Philippines, Spain, Thailand, and the United States (Tanaka 1978). It is a minor practice in Japan, India, and Sri Lanka. In Indonesia straw is burned in regions where rice pests are endemic. The drawbacks of burning straw are atmospheric pollution and nutrient loss. The advantages are destruction of pests and saving of labor and energy.

The temperature of straw burning in contact with the atmosphere is about 700° C (Amarasiri and Wickremasinghe 1977). In a laboratory experiment, at this temperature all the C and N, 25% of the P, and 21% of the K were lost. In field burning, the losses were 93% for N and 20% for K. Burning the straw from a 5-t/ha paddy crop causes a loss into the atmosphere of about 45 kg N, 2 kg P, 25 kg K, and perhaps 2 kg S. Besides, it renders silica less soluble than in fresh straw. The losses can be reduced by lowering the combustion temperature by compacting or moistening the straw heap. Such measures merit investigation.

*Piling and spreading.* Heaping straw in mounds in the field at threshing sites is common in the Philippines and Indonesia, where large tracts of rice fields dotted with straw mounds about 2 m high are a common sight. In Sri Lanka, heaping the straw in successive quadrants of a field each season is recommended to even out nutrient distribution. The straw decomposes slowly, largely aerobically. and is easily spread and incorporated into the soil at the beginning of the next season.

No quantitative data are available on the area occupied by the mounds, the course and rate of straw decomposition, the loss of N by denitrification, and the loss of both N and K from the heap by leaching. The following are commonly observed in Laguna, Philippines: about 5% of a block's surface is occupied by a heap. The pile virtually disappears in 4-6 months in wetland fields. That represents a loss of C for N fixation. Because of the ease with which K is lost from straw by leaching( Amarasiri and Wickremasinghe 1977), little K will be left in the residue of the heap, but some is probably retained in the soil at the base of the pile. Because of the high C:N, mineralization of straw N is slow, but what is mineralized is in nitrate form in the aerobic part of the heap. Nitrate may be leached out, or it may be denitrified at the aerobic-anaerobic interface at the base of the pile.

The practice of piling and spreading straw saves labor but reduces the planted area and causes nutrient loss. Besides, the exudates from the heap harm rice plants around it. In rat-infested areas, the straw pile is a haven for rats.

*Incorporation.* In mechanized rice culture, the crop is harvested by combine and the straw is spread on the land. It is incorporated into the soil by disking or plowing. The practice in most Asian farms is wet plowing of the stubble or straw. If only stubble is plowed in, the amount of straw returned to the soil depends on the manner and height of harvesting.

The manner and height of harvesting depend on local conditions. In rainfed tracts in Indonesia, only the panicle is harvested; the straw is slashed and heaped or spread in the field, then plowed in wet at the beginning of the next season (Ismunadji 1978). This practice returns most of the nutrients but reduces the N-fixing potential of straw. In wet areas, long straw is incorporated in flooded soils. In the Philippines, most farmers harvest the stalks 61-91 cm from the base of the panicle (De Datta 1981). In countries where straw is used for off-field purposes, harvesting is done at ground level, leaving little of the nutrients behind.

Spreading the straw in the field and allowing it to weather returns to the soil almost all the nutrients in the straw and facilitates incorporation. But it diminishes the N-fixing potential of the straw mass.

*Mulching.* Where a dryland crop is grown between rice crops, straw is sometimes used as a mulch. When it is time for the next rice crop, most of the straw has decomposed. Almost all the nutrients are returned to the soil, but what fraction is retained for the rice crop is not known.

### Water regime

Water regime determines the long-term effects of straw application on the soil's organic matter and N content. Under dryland conditions, application of organic materials over the years does not bring about an appreciable increase in organic matter or N content over the equilibrium value for the environment and cropping system. But the anaerobic conditions in wetland rice fields retard organic matter decomposition and cause an increase in both organic matter and N. If two wetland rice crops are grown per year in the tropics where none or one crop was grown before, accretion of C and N is detectable in 2-3 years by routine soil testing. Anaerobic conditions not only preserve straw N against the nitrification and leaching that occur in dryland soils, but also favor N conservation and fixation (Castro and Lantin 1976).

## EFFECTS ON SOIL FERTILITY

Soil fertility is the capacity of a soil to supply nutrients in the amount and balance needed by a crop. Nutrient reserves, availability, and delivery rate, as well as the absence of plant poisons and substances that interfere with nutrient uptake, determine fertility. Long-term straw application builds up organic matter and N reserves and also increases the availability of all nutrients except Zn and perhaps Cu.

### Organic matter

Soil organic matter (humus) contains almost all of a soil's N, 20-80% of its P, and most of the S in soils of humid regions (Stevenson 1982). It is the main source of N and an important source of P and S for dryland crops. In wetland rice 50-80% of the N even in fertilized crops comes from soil organic matter (Broadbent 1978). The organic matter content is a fairly good index of the N-supplying capacity of wetland rice soils (Ponnamperuma 1980). Other benefits of soil organic matter on fertility are increasing cation exchange capacity and rendering P and Fe available to plants. But excess organic matter may be undesirable because it decreases Zn availability. Peat soils and mineral wetland rice soils containing >3.0% organic C are Zn deficient (IRRI 1982). In Korea, an organic C content exceeding 2.9% did not benefit rice (Oh 1979).

Long-term experiments on different soil types in different countries have shown that straw incorporation increases the soil's organic C content (Table 6, 7). Incorporation is more effective than burning.

### Nitrogen

Up to 80% of the N absorbed by rice crops even in fertilized fields comes from the mineralization of soil organic matter. The fraction of soil organic matter mineralized during anaerobic incubation for 2 weeks in the laboratory varied from 0.3 to 26.5% for 410 South and Southeast Asian soils (Kawaguchi and Kyuma 1977) and from 3.5 to 26.0% for 280 Philippine wetland rice soils (Ponnamperuma 1980). If 5% of soil N is mineralized during a season, a N content of 0.2% is sufficient to produce 5 t/ha paddy (Ponnamperuma 1980). But 70% of the rice lands in South and Southeast Asia contain <0.2% N and are considered N deficient. If a soil's N content is

**Table 6. Effect of straw incorporation on soil nutrient content.**[a]

| Country | soil | Period (yr) | Rate (t/ha) | Absolute increase | | | |
|---|---|---|---|---|---|---|---|
| | | | | Organic C (%) | Total N (%) | Available P (mg/kg) | Available K (mg/kg) |
| India | Acid clay | 5 | 9 | 0.1 | 0.04 | 1.6 | 16 |
| Indonesia | Oxisol | 9 | – | 0.6 | – | 4.0 | 53 |
| Philippine | Alfisol | 8 | 5 | 0.3 | 0.03 | 3.0 | 66 |
| Philippines | Ultisol | 2 | 5 | 0.1 | 0.01 | 0.4 | 39 |
| Senegal | Acid clay | 3 | 6 | – | 0.01 | 9.0 | 8 |

[a] Sources: Beye 1974; A. M. Fagi, and S. Partohardjono, BORIF, Bogor, Indonesia, unpublished; International Rice Research Institute, Los Baños, Philippines, unpublished; and M. V Rao, Central Rice Research Institute, Cuttack, India, unpublished.

**Table 7. Effects of 4 straw treatments on the nutrient status of Maahas clay and grain yield, averaged for 5 cultivars after the 16th crop.[a]**

| Straw treatment | Organic C (%) | Total N (%) | Olsen P (mg/kg) | Exchange-able K (mmol/kg) | Grain yield (t/ha) |
|---|---|---|---|---|---|
| Removed | 1.81 b | 0.167 c | 9 b | 10.5 b | 3.2 b |
| Burned | 1.94 b | 0.173 bc | 12 b | 12.5 a | 3.4 b |
| Incorporated | 2.17 a | 0.182 b | 12 b | 11.6 ab | 4.1 a |
| Composted | 2.19 a | 0.203 a | 27 a | 10.4 b | 4.2 a |

[a] In a column, figures followed by a common letter are not significantly different. Source: A. B. Capati, IRRI, unpublished.

**Table 8. Nitrogen accumulation potential of Maahas clay computed from 7 years of field data.[a]**

| Management | N accumulation (kg/ha per year) |
|---|---|
| Two wetland rice crops per year, dry fallow | 117 |
| Two wetland rice crops per year plus straw, dry fallow | 208 |
| Two wetland rice crops per year, flood fallow | 217 |
| Two wetland rice crops per year plus straw plus flood fallow | 317 |

[a] Source: Ponnamperuma (1980).

**Table 9. Effect of incorporating straw at 5 t/ha on nutrient status and rice yield, averaged for 3 soils after the 11th crop, in a drum study.[a]**

|  | No straw | With straw | Δ |
|---|---|---|---|
| Organic C (%) | 1.38 | 1.62 | 0.24**[b] |
| Total N (%) | 0.130 | 0.157 | 0.027** |
| Available P (mg/kg) | 8.4 | 9.8 | 1.4*[b] |
| Exchangeable K (mmol/kg) | 3.2 | 6.3 | 3.1** |
| Straw yield (g/drum) | 68 | 89 | 21** |
| Grain yield (g/drum) | 77 | 112 | 35** |
| N uptake (g/drum) | 1.194 | 1.583 | 0.389** |

[a] Source: A. B. Capati, IRRI, unpublished. [b] * = significant at the 5% level, ** = significant at the 1% level.

**Table 10. Nitrogen gains in wetland rice soils due to straw incorporation in 3 experiments over 7 years.[a]**

| Experiment | Site | N (%) Straw removed | N (%) Straw incor-porated | N (%) Δ N | Crops (no.) | Yearly N gain (kg/ha) |
|---|---|---|---|---|---|---|
| Straw and water | Field | 0.1880 | 0.2150 | 0.0270 | 14 | 77 |
| Straw | Field | 0.1787 | 0.2183 | 0.0396 | 14 | 113 |
| Straw and soil | Drum | 0.1415 | 0.1615 | 0.0200 | 10 | 80 |

[a] Source: Ponnamperuma, IRRI, unpublished.

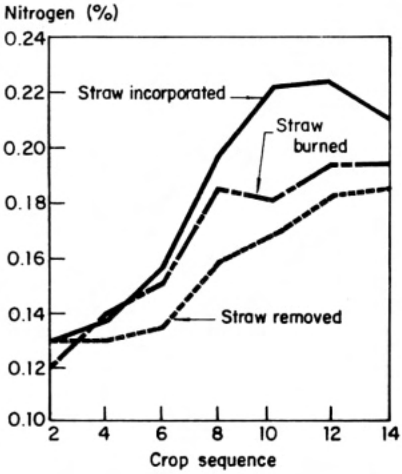
increased by 0.05% and maintained at that level, it may release an additional 50 kg N (worth $25)/ha per season. Incorporating straw is a simple way of increasing the N content of wetland rice fields (Tables 6-10). Within 3 years of plowing in the straw at 6-7 t/ha, the soil's N content increased by 0.021% in the straw management experiment (Fig. 2) and by 0.043% in the straw and water management experiment (Fig. 3) over the straw removal treatment. Flood fallowing, compared with the normal practice of dry fallowing between crops, enhances the contribution of straw to the N fertility of wetland rice soils (Table 8).

At IRRI, incorporating the straw produced in situ twice a year caused an increase of 48 kg N/ha per season, averaged for 2 field experiments lasting 7 years (Table 10). In a drum study with 3 soils over a 5-year period, the increase due to straw incorporation was computed to be 40 kg/ha per season, about 10 kg/ha per season more than the straw's N content. The extra N probably came from N fixation stimulated by straw acting as an energy source for heterotrophs and as a carbon dioxide supplement to surface phototrophs.

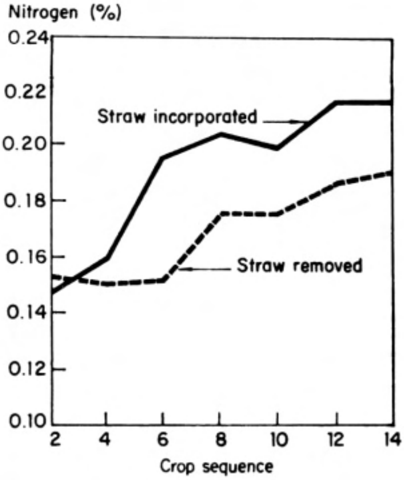
## Phosphorus

Phosphorus is a nonrenewable soil resource present largely in organic form to the extent of <0.l% in the topsoil. Soil erosion and crop removal gradually deplete this essential nutrient, which can be replenished by applying P fertilizers derived from the world's dwindling phosphate rock reserves. Recycling organic materials is one way of husbanding P.

Incorporating straw or burning it in the field returns to the soil about 10 kg P/ha per season. Tables 6, 7, and 9 show a slight increase in available P in soils receiving straw.



**2.** Effect of straw management on the nitrogen content of Maahas clay during 7 years, averaged for 5 cultivars in the field, IRRI, 1972-79.



**3.** Effect of straw management on the total nitrogen content of Maahas clay during 7 years, averaged for 3 water treatments in the field, IRRI, 1972-79.

## Potassium

Rice straw contains 1.1 to 3.7% K (Table 5). Amarasiri and Wickremasinghe (1977) remarked that the K content of the straw produced annually in Sri Lanka was four times the amount of chemical K fertilizer used on rice. Incorporating straw increases the available K content of the soil (Table 6, 7, 9). Potassium in straw is water soluble and is readily available to rice.

## Sulfur

The S content of tropical soils is about 100 mg/kg (Sanchez 1976), and up to 97% may be in organic form (Stevenson 1982). Unlike phosphates, sulfates are easily leached. Returning straw to the soil is one way of reducing S losses by recycling. No data on the effect of straw management on the S status of rice soils are available but because the incidence of S deficiency is increasing, and because S-containing fertilizers are going out of use, it is best to recycle S.

## Micronutrients

The micronutrient concentration of straw of wetland rice ranges from about 5 mg/kg for Cu to 200 mg/kg for Fe. Thus the amounts removed by a crop are insignificant compared with soil reserves. Straw incorporation may, however, increase the availability of Fe and depress that of Zn.

## Silicon

Although Si is not an essential element, it benefits rice indirectly (Yoshida 1981). Rice straw contains about 5% Si. Returning straw or its ash may help to build up the supply of available Si in soils low in available Si, but may be of little use in other soils. Excess Si may depress Zn availability (IRRI 1981).

## Effects on soil chemical process

Because about 40% by weight of dry straw consists of biodegradable C, straw is a substrate for the growth of soil microorganisms. Thus straw incorporation in a flooded soil leads to a burst of biochemical activity: soil reduction and associated electrochemical changes; N immobilization and fixation; production of organic acids; and release of $CO_2$, $CH_4$, $C_2H_4$, and $H_2S$ (Yoshida 1978).

These processes directly and indirectly affect the availability and uptake of nutrients and therefore the value of straw as a source of nutrients for wetland rice.

*Soil reduction.* Straw incorporation (compared with the strawless treatment) hastened and intensified soil reduction and also increased pH and electrical conductivity in two acid soils (Beye 1977a, Beye et al 1978). Associated with these electrochemical changes was an increase in the concentration in the soil solution of Fe, Mn, $NH_4^+$, K, organic acids, reducing substances, and $CO_2$. These effects were more pronounced in sandy soil than in clay. The ill effects of straw on the growth of rice in sandy soil were attributed to reduction products. The remedy was to delay planting for at least 1 month after straw incorporation. Other workers (IRRI 1976) had reported that a mixture of straw and green manure accelerated soil reduction in three strongly acid soils. The accompanying pH increase lowered the Fe concentration and reduced the severity of Fe toxicity. In a study of the effects of straw and green manure on the chemical and electrochemical kinetics of three soils, Katyal (1977) confirmed the acceleration and intensification of Eh and pH changes and the achievement of peak concentrations of water-soluble Fe, Mn, and $CO_2$. The possible adverse effects of organic matter incorporation did not last more than 3 weeks.

*Nitrogen immobilization.* One objection to the use of straw as a manure is that it immobilizes available soil N. If immobilization occurs, it is temporary and is much less in flooded soils than in dryland soils. The amount tied up decreases with increase in N content of straw and with temperature. The adverse effects of N immobilization on rice growth are shortlived and can be avoided by adding fertilizer N or delaying planting (Broadbent 1978, 1979).

*Nitrogen fixation.* Wetland rice soil is an ideal milieu for N fixation (Ponnamperuma 1972). Aerobic N fixers can thrive in the surface layer and the rhizosphere, sustained by soluble organic metabolites diffusing from the anaerobic soil matrix. The anaerobic bulk of the soil is an ideal medium for heterotrophic organisms. And N moving from shoot to root and diffusing into the soil enormously increases the soil's N supply. But energy is a limiting factor. Straw is a good energy source; thus straw application markedly increased both heterotrophic and phototrophic N fixation, as measured by acetylene-reduction activity (Matsuguchi 1979). Rice straw addition enhanced N fixation in both moist and flooded soils. Rice straw plus mineral N increased the population of aerobic N-fixing bacteria in flooded soils.

*Production of organic acids.* The decomposition of straw in anaerobic soils produces volatile fatty acids and phenolic acids (Tsutsuki 1983). Low temperature and acidity favor the production and persistence of fatty acids (Cho and Ponnamperuma 1971). At temperatures over 30°C these acids disappear within 2-3 weeks of straw incorporation. The concentration of organic acids in flooded soils in the tropics receiving 5-10 t straw/ha is not toxic to rice.

*Gas production.* The production of $Co_2$, $CH_4$, $C_2H_4$, and $H_2S$ is increased by incorporating straw in anaerobic soils (Neue and Scharpenseel 1983, Tsutsuki 1983). Although all the products except $CH_4$, when in excess, are toxic to rice, their toxicity in fields amended with straw has not been demonstrated.

## EFFECT ON RICE YIELD

The effect of straw on yield of wetland rice depends on management, amount, soil, fertilizers, and time and duration of application.

### Management

Long-term experiments show that straw incorporation generally produces higher rice yields than burning or removal.

*Burning vs incorporation.* In California, where only one wetland rice crop per year is grown, 5-year yield and N uptake data revealed no difference between burning and incorporation (Williams et al l972). Finassi (1976), in a 5-year study in Italy, found no significant differences among removal, plowing in long straw, plowing in chopped straw, and burning straw and stubble. Ismunadji (1978) applied 10 t straw/ha to an Indonesian Vertisol and obtained the following yields: removal, 2.2 t/ha; burned, 2.7 t/ha; and incorporated, 2.6 t/ha. But Vamadevan et al (1975) in

India found that in the dry season, incorporating 4 t straw/ha in the presence of 100 kg N/ ha gave 6.6 t paddy/ha; burning, 6.0 t/ha; and removal, 6.2 t/ha. And long-term field experiments at IRRI on a clay soil (pH 6.6, organic C 2.0%, total N 0.14%, Olsen P 12 mg/ kg, and exchangeable K 11.3 mmol/ kg) revealed that straw incorporation produced higher yields than straw removal or burning (Table 11, 12, 13). The increase in paddy yield due to straw application, averaged for 9 years, was 0.4 t/ ha per year compared with 0.6 t/ ha per year for compost application and zero for burning (Table 11). But excluding the yields for the first 5 years and the 8th year (during which 100 kg N/ha was applied), there was no yield advantage from burning; the yield advantage from incorporation was 0.7 t/ha per year and that from composting 0.9 t/ ha per year.

*Incorporation vs removal.* Beye (1974) obtained a response of 1.1 t/ ha, averaged for six seasons, to incorporation of 6 t straw, ha on an acid clay in Senegal. On an unfertilized P-deficient acid clay in a farmer's field, straw incorporation gave 2.1 t/ ha compared with 1.7 t/ ha for straw removal ( IRRI 1982). On an alkaline clay loam in West Bengal, India, Chatterjee et al (1979) found that, averaged for three nitrogen levels and two seasons, incorporating 10 t undecomposed straw/ ha yielded 5.2 t/ha, decomposition 4.8 t/ha, and straw removal 3.4 t/ha. Table 12 shows the effect of straw incorporation on paddy yields. averaged for three water regimes. The mean yield increase was 0.5 t/ ha per year. The decrease in annual yield with time was due partly to B toxicity (which was alleviated by changing the source of irrigation water after the 14th crop) and to the discontinuing of N fertilizers after the 10th crop.

The benefit of straw incorporation on paddy yield was confirmed in a drum study with three soils with pH values of 4.7, 6.6, and 7.5 (Table 9, 14) in the absence of fertilizer. The grain yield increase due to straw incorporation at a rate equivalent to 5

**Table 11. Influence of straw management over 10 years on paddy yields over 9 years on a Tropaqualf at IRRI.**[a]

| Straw management | Paddy yield of 2 crops (t/ha) in year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | $\bar{X}$ |
| Removed | 10.7 | 9.6 | 9.9 | 8.7 | 7.6 | 5.8 | 9.4 | 7.9 | 5.0 | 8.3 |
| Burned | 10.8 | 9.9 | 10.0 | 8.8 | 7.6 | 5.6 | 9.1 | 8.0 | 5.1 | 8.3 |
| Incorporated | 10.6 | 9.8 | 10.3 | 8.8 | 8.2 | 6.1 | 9.4 | 8.6 | 6.1 | 8.7 |
| Composted | 11.1 | 10.5 | 9.8 | 9.2 | 8.2 | 6.3 | 9.3 | 9.1 | 6.5 | 8.9 |

[a] Source: A. B. Capati, IRRI, unpublished.

**Table 12. Influence of straw management on paddy yields, averaged for 3 water regimes during 9 years on a Tropaqualf at IRRI.**[a]

| Straw management | Paddy yield of 2 crops (t/ha) in year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | $\bar{X}$ |
| Removed | 11.2 | 9.7 | 9.0 | 8.6 | 6.7 | 6.4 | 9.1 | 8.0 | 5.5 | 8.2 |
| Incorporated | 11.3 | 10.1 | 9.4 | 8.8 | 6.8 | 6.9 | 10.6 | 8.5 | 6.0 | 8.7 |
| Difference | 0.1 | 0.4 | 0.4 | 0.2 | 0.1 | 0.5 | 1.5 | 0.5 | 0.5 | 0.5 |

[a] Source: A. B. Capati, IRRI, unpublished.

**Table 13. Effect of straw management without NPK fertilizers on the nitrogen content of the soil, the degree of nitrogen deficiency, and the yield of IR50 in the 19th season in the IRRI farm.**[a]

| Straw management | Total N (%) | Score[b] | Straw (t/ha) | Grain (t/ha) |
|---|---|---|---|---|
| Removed | 0.181 b | 3.0 a | 3.0 a | 2.8 a |
| Burned | 0.183 b | 2.6 a | 3.1 a | 2.6 a |
| Incorporated | 0.202 a | 1.2 b | 3.6 a | 3.2 b |
| Composted | 0.214 a | 1.8 b | 3.3 a | 3.2 b |

[a] Source: A. B. Capati, IRRI, unpublished. In a column, figures followed by a common letter are not significantly different. [b] 1 = almost normal plant, 9 = almost dead plant.

**Table 14. Effect of straw management without fertilizers on paddy yield, averaged for 3 soils in a 7-year study in drums outdoors.**[a]

| Straw management | Paddy yield (g/drum) in year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | $\bar{X}$ |
| Removed | 319 | 315 | 223 | 215 | 180 | 155 | 156 | 223 |
| Incorporated | 355 | 353 | 292 | 226 | 206 | 222 | 246 | 271 |
| Difference | 36 | 38 | 69 | 11 | 26 | 67 | 90 | 48 |

[a] Source: A. B. Capati, IRRI, unpublished.

t/ha, averaged for 7 years, was 31% and the straw yield increase was 71%. In this controlled study, at no time was growth or yield of rice adversely affected by straw incorporation.

## Amount

Oh (1979), in a 3-year study in Korea, found that when the amount of straw incorporated was raised from 0 to 8 t/ha in the presence of 80 kg N/ha, rice yields increased by about 1 t/ha in each of 3 years. Rice straw produced larger increases than compost at twice the rate of straw application. Oh attributed the superiority of rice straw over compost to the promotion of late growth of rice. Tanaka (1974) reported that application of 8 t straw/ ha with complete NPK fertilizers increased paddy yield from 4.5 to about 6 t/ha over a 4-year period. More nitrogen was needed if the rate was increased to 10 t/ha. According to Dei (1975), in warm regions all the straw produced in a field may be returned to the soil without adverse effects on rice.

## Soil

Long-term field experiments in Hokkaido, Japan, indicate that incorporation of straw in poorly drained soils, especially in spring, depresses rice yields (Tanaka 1978). The harmful effects are likely to be less in warm, neutral soils than in cold, acid soils (Cho and Ponnamperuma 1971). Straw incorporation may harm rice on peat and polder soils (Dei 1975). Tanaka (1974) stated that the maximum amount that could be incorporated without adverse effects was 6 t/ha in northern Japan, even on good soils, presumably because of low temperature. In warm southern Japan, 6 t/ha was the maximum on poorly drained soils.

### Fertilizers

The presence of N and P fertilizers enhances the benefits of straw application. During the first year of a trial at Vercelli, Italy, incorporating straw alone did not affect yield, but incorporated straw combined with fertilizers yielded 6.9 t/ha paddy compared with 5.5 t/ha for the straw-alone and no-straw treatments (Russo 1974). In a 3-year experiment in Italy, straw alone produced no increase in mean yield, but in combination with N and P fertilizers it increased paddy yield from 5.7 to 6.8 t/ha (Russo 1976). Beye (l977b) found that a yield increase of 0.6 t/ha due to straw application was enhanced by 0.3 t/ha when nitrogen fertilizer was added.

Plant nutrients in straw augment the effect of fertilizers, but the nutrient content of 5 t straw/ha alone is insufficient to sustain paddy yields of 5 t/ha per season.

### Time of application

The effect of time of straw incorporation on grain yield depends on temperature, cultivar, and amount of straw.

Transplanting immediately after applying 12 t straw/ha at IRRI retarded growth of all five cultivars used in a trial but depressed the yield of only the three improved cultivars (Tanaka 1974). In warm regions, straw can be incorporated 1 month before transplanting without adverse effects. In cool temperate regions, straw should be incorporated the previous autumn, and the amount should not exceed 4 t/ ha (Dei 1975). Tanaka (1974) and Beye (1977a) recommended delaying transplanting at least 1 month after straw incorporation, even in warm regions, but Dei (1975) stated that all the rice straw produced in a field could be plowed in immediately before transplanting without adverse effects. Ismunadji (1978) reported that plowing in 10 t straw/ha 1 week before planting yielded as much as did plowing it in 2 and 4 weeks before planting, both with and without 120 kg N/ha.

Theory suggests that, in the tropics, plowing in straw in the dry soil 1-2 weeks before flooding should benefit the N economy of rice soils. Partial aerobic decomposition would immobilize the nitrate-N present in the soil and release it later for use by rice. That would minimize denitrification losses caused by flooding aerobic soils.

### Duration of application

The benefit of straw application on rice yield in field experiments may appear during the season of application, and it increases with duration of the practice.

In a long-term experiment at Saga, in a warm district in Japan, the benefits of straw incorporation at 5 t/ha in the presence of NPK fertilizers appeared in the first year, and in 2 years surpassed that of compost at 10 t/ha. Both straw and compost plus chemical fertilizer yielded more paddy than the chemical fertilizer treatment alone throughout the 26-year experimental period (Dei 1975). In a similar experiment, in the presence of NPK fertilizers at Shimane (also in a warm district of Japan), straw incorporated at 8 t/ha was slightly superior to compost at 12 t/ha and very much superior to chemical fertilizers alone. After 3 years, the paddy yields of the straw and compost treatments with NPK were about 1 t/ha higher than those of the NPK treatment (Tanaka 1974).

## MECHANISMS OF THE BENEFIT OF STRAW APPLICATION

The increase in grain yield caused by straw application is attributed to one or more of the following:

- Increase in N supply
- Favorable N-release pattern
- Increase in K supply
- Increase in supply of other nutrients
- Improvement of soil structure

### Nitrogen supply

Five tons of straw contain about 30 kg N. About 10% of the N is recovered during the first crop and another 10% in the second crop (Yoneyama and Yoshida 1977). In a greenhouse experiment, 25% was absorbed by rice plants in 130 days. Whereas fertilizer N is absorbed at an early stage, the peak of N absorption from straw comes in the middle growth stage, coinciding with peak crop demands.

Although the contribution of 5 t straw to the current N needs of rice is only about 3 kg/ha per season, the long-term effects are substantial. Continuous application of straw builds up the soil's organic matter content (Table 6, 7, 9) and ensures an adequate N supply. This is shown by greener color, higher N content and uptake (Table 13, 15), and partial substitution of straw N for fertilizer N (Beye 1977b, Tanaka 1974, Chatterjee et a1 1979, Kosuge and Zulkarnaini 1981).

### Nitrogen-release pattern

The N absorption pattern of rice is sigmoidal. So is the release of available N from soils high in inorganic matter (Broadbent 1979). Figure 4 suggests that soils high in total N need no fertilizer N, those moderate in N need no basal fertilizer, and those low in N need both basal application and topdressing.

### Potassium supply

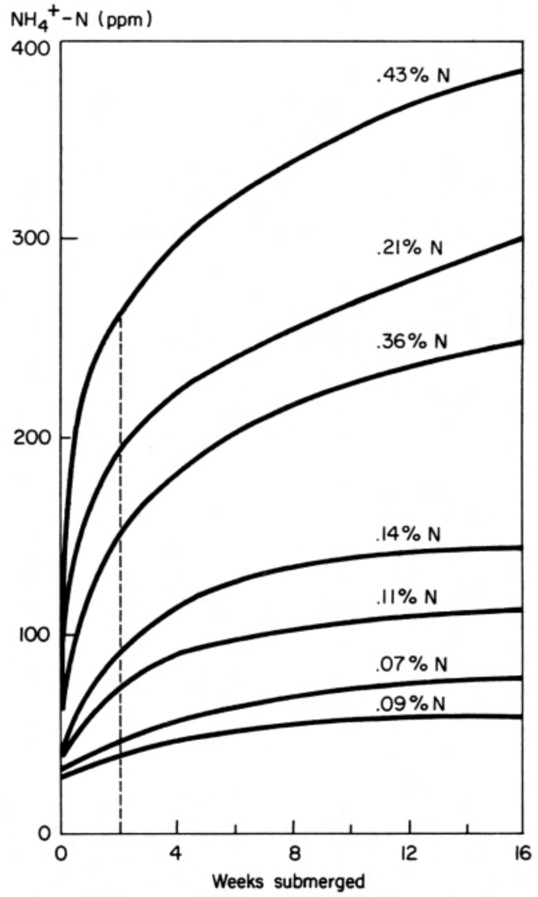
Rice straw contains 1.0-3.7% K (Table 4,5) in highly available form. Incorporating 5 t straw as unburned straw or ash adds about 100 kg K to the soil. On K-deficient soils, straw ash is a substitute for K fertilizer (Amarasiri and Wickremasinghe 1977).

The benefits of straw incorporation are reflected not only in increase in soil K (Table 6,7,9) but also in plant uptake (Table 15). Beye (1974) reported an increased uptake of K by rice when straw was incorporated into the soil.

**Table 15. Effect of straw incorporation on the uptake of N, P, and K by IR50, averaged for 3 soils in a drum study, IRRI, 1981 dry season.**[a]

| Nutrient | Plant uptake (g/drum) | | |
|---|---|---|---|
| | No straw | Plus straw | D[b] |
| N | 1.33 | 2.16 | 0.83** |
| P | 0.26 | 0.46 | 0.20** |
| K | 1.45 | 2.82 | 1.37** |

[a] Source: A. B. Capati, IRRI, unpublished. [b] ** = significant at the 1% level.



**4.** Kinetics of $NH_4^+$ release in 7 submerged soils. Source: Ponnamperuma (1980).

### Other nutrients

Five tons of rice straw contain about 7 kg each of P and S, 20 kg Ca, 5 kg Mg, and 350 kg Si. Because P and S are nonrenewable materials and because soil organic matter is the biggest source of these elements for crops in humid regions, returning the straw should slow their depletion. On acid sandy soils the recycling of Ca, Mg, and Si is beneficial. Straw incorporation increased the available P content and plant uptake of P in three soils (Table 15).

### Soil structure improvement

Organic manuring improves the physical properties of rice soils (Dei 1970). But there is no clear information on its effects on bulk density, porosity, water-holding capacity, or hydraulic conductivity. An improvement in these properties benefits both wetland rice (by improving internal drainage) and soil structure for the dryland crops in the rotation.

## PRACTICAL IMPLICATIONS

Rice straw contains almost all the K and about one-third of the N, P, and S removed from the soil by a rice crop, in addition to about 400 kg C/ t of straw, which can serve as an indirect source of N. Incorporating in the soil the straw produced in situ enables fertilizer saving and nutrient recycling. The buildup of fertility is reflected in increased yields. To get maximum benefits, the straw must be incorporated in the soil shortly before flooding. But there are practical problems:

- Spreading the straw in the field needs labor.
- Plowing in long straw is difficult.
- Straw may harbor insects and disease organisms and provide shelter for rats.
- The mass and nutrient content of straw in unfertilized fields is small.
- The practice may not be economic.

Spreading the straw around the field threshing sites probably needs less labor than piling or removal. The difficulty of plowing in long straw can be minimized by letting it weather for a few weeks before incorporation, although such a practice may involve loss of nutrients. Slow burning of straw, which can destroy pests, also causes nutrient losses. The value of straw as a source of nutrients can be increased by applying moderate amounts of fertilizer. The fertilizer value of the N, P, and K in 5 t straw at recent world prices is about $35. The increase in paddy per season due to straw incorporation is about 0.4 t/ ha. At current Philippine prices the extra paddy is worth about $70. If no extra labor is required for incorporating straw, the practice may benefit the farmer to the extent of about $100/season in the long run.

## REFERENCES CITED

Amarasiri, S. L., and K. Wickremasinghe. 1977. Use of rice straw as a fertilizer material. Trop. Agric. 133:39-49.

Beye, G. 1974. Comparative study of the effect of potassium and straw on the growth and yield of rice on a clay soil in Lower Casamance [in French, English summary]. Agron. Trop. 29:803-811.

Beye, G. 1977a. Effects of ploughing-under of straw and duration of flooding before transplanting on the physico-chemical properties of two rice fields on rice development and yield [in French]. Agron. Trop. 32:31-40.

Beye, G. 1977b. Study of the effects of increasing rates of nitrogen with and without ploughed-under rice straw on rice development in Lower Casamance [in French]. Agron. Trop. 32:41-50.

Beye, G., M. Toure, and G. Arial. 1978. Effect of incorporating straw on the physico-chemical properties of paddy soils of Lower Casamance and on the development of rice [in French]. Agron. Trop. 33:381-389.

Broadbent, F. E. 1978. Nitrogen transformation in flooded soils. Pages 543-559 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Broadbent, F. E. 1979. Mineralization of organic nitrogen in paddy soils. Pages 105-118 *in* International Rice Research Institute. Nitrogen and rice. Los Baños. Philippines.

Castro, R. U., and R. S. Lantin. 1976. Influence of water management on the nitrogen supply of rice soils. Philipp. J. Crop Sci. 1(1):56-59.

Chatterjee, B. N., K. I. Singh, A. Pal, and S. Maiti. 1979. Organic manures as substitute for chemical fertilizers for high-yielding rice varieties. Indian J. Agric. Sci. 49:188-192.

Cho, D. Y., and F. N. Ponnamperuma. 1971. Influence of soil temperature on the chemical kinetics of flooded soils and the growth of rice. Soil Sci. 112:184-194.

De Datta, S. K. 1981. Principles and practices of rice production. John Wiley & Sons, New York. 618 p.

Dei, Y. 1970. Application of rice straw to paddy fields. JAR 5:5-8.

Dei, Y. 1975. Effects of cereal crop residues on paddy soils. ASPAC Ext. Bull. 49:1-29.

Finassi, A. 1976. Rice straw incorporation [in Italian, English summary]. Riso 25:9-18.

IRRI (International Rice Research Institute). 1965. Annual report for 1964. Los Baños, Philippines. 335 p.

IRRI (International Rice Research Institute). 1976. Annual report for 1975. Los Baños, Philippines. 418 p.

IRRI (International Rice Research Institute). 1981. Annual report for 1980. Los Baños, Philippines. 467 p.

IRRI (International Rice Research Institute). 1982. Research highlights for 1981. Los Baños, Philippines. 138 p.

Ismunadji, M. 1978. Utilization of cereal crop residues and its agricultural significance in Indonesia. Contr. Centr. Res. Inst. Agric. Bogor 37. 14 p.

Katyal, J.C. 1977. Influence of organic matter on chemical and electrochemical properties of some flooded soils. Soil Biol. Biochem. 9:259-266.

Kawaguchi, K., and K. Kyuma. 1977. Paddy soils in tropical Asia. University Press of Hawaii, Hawaii, USA. 258 p.

Kosuge, N., and I. Zulkarnaini. 1981. Effect of straw application to paddy field in Indonesia. Bull. Hokuriku Natl. Agric. Exp. Stn. 23:167-186.

Matsuguchi, T. 1979. Factors affecting heterotrophic nitrogen fixation in submerged rice soils. Pages 207-221 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Neue, U., and H. W. Scharpenseel. 1983. Gaseous products in submerged soils. Pages 315-332 *in* International Rice Research Institute. Organic matter and rice. Los Baños, Philippines.

Oh, W. K. 1979. Effect of incorporating organic materials on paddy soils. Pages 435-449 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Palacpac, A. C. 1982. World rice statistics. International Rice Research Institute. Los Baños, Philippines. 152 p.

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Ponnamperuma, F. N. 1980. Nitrogen supply in tropical wetland rice soils. *In* Proceedings of the special workshop on nitrogen fixation and utilization in rice fields, Int. Rice Res. Inst. 28-30, April 1980. Los Baños, Philippines, 18 p.

Russell, E. W. 1973. Soil conditions and plant growth. Longman. 849 p.

Russo, S. 1974. Effects of plowing under rice straw in submerged soils with monocultural rotation [in Italian, English summary]. Riso 23:209-218.

Russo, S. 1976. Effects of straw incorporation on growth and paddy yield [in Italian, English summary]. Riso 25:19-36.

Sanchez, P. A. 1976. Properties and management of soils in the tropics. John Wiley and Sons, New York. 618 p.

Stevenson, F. J. 1982. Organic matter and nutrient availability. Trans. 12th Int. Congr. Soil Sci. 2:137-151. New Delhi.

Takijima, Y., and S. D. I. E. Gunawardena. 1971. Nutrient deficiency and physiological disease of lowland rice in Ceylon. Trop. Agric. 127:49-67.

Tanaka, A. 1974. Methods of handling of cereal crop residues in Asian countries and related problems. ASPAC Ext. Bull. 43. 29 p.

Tanaka, A. 1978. Role of organic matter. Pages 605-620 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

Tsutsuki, K. 1983. Volatile products and low-molecular-weight phenolic products of the anaerobic decomposition of organic matter. Pages 333-347 *in* International Rice Research Institute. Organic matter and rice. Los Baños, Philippines.

Vamadevan, V. K., J. E. Shinde, D. C. Asthana, and S. P. Chakravorty. 1975. Management of crop residues. Int. Rice Comm. Newsl. 24:52-59.

Williams, N. A., M. D. Morse, and J. E. Buckman. 1972. Burning vs incorporation of rice crop residues. Agron. J. 64:467-468.

Yoneyama, T., and T. Yoshida. 1977. Decomposition of rice residue in tropical soils. Soil Sci. Plant Nutr. 23:33-40.

Yoshida, S. 1981. Fundamentals of rice crop science. International Rice Research Institute. Los Baños, Philippines. 269 p.

Yoshida, T. 1978. Microbial metabolism in rice soils. Pages 445-463 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

## DISCUSSION

YOSHIDA: Can rice straw application increase the efficiency of chemical fertilizer under Philippine rice soil conditions?

*PONNAMPERUMA:* Rice straw application has increased the efficiency of chemical fertilizers in both temperate and tropical countries. There is no reason why it should not do the same in the Philippines.

YOSHIDA: What about the situation of rice straw management in deepwater rice areas?

*PONNAMPERUMA:* Rice straw is probably not suited to deepwater areas.

NAGAR:There is a growing literature in the field of use of straw as a source of bioenergy and Si. Although I am of the opinion that a part of the straw produced must be used to build up humus in soils, the economics of the alternative uses of straw should be worked out. What is your opinion?

*PONNAMPERUMA:* Your suggestion is good.

SINGH: Is not the organic matter contributed by rice stubble and roots sufficient for N-fixing heterotrophs?

*PONNAMPERUMA:* No.

SINGH. Continuous application or recycling of rice straw in the same field may lead to harboring of several diseases of rice, as has been experienced in several places. Would you comment, please?

*PONNAMPERUMA:* It is best to burn the straw.

BUNOAN: What would be the optimum conditions to hasten rice straw decomposition in the field under a) aerobic and b) anaerobic conditions?

*PONNAMPERUMA:* a) Moisture, free air circulation, and chemicals such as lime, urea, and phosphate will hasten aerobic decomposition. b) A temperature of 35°C, presence of N and P, and absence of strong acidity will favor anaerobic decomposition.

BUNOAN: Are there any enzymes or bacteria that can hasten decomposition of rice straw in the field?

*PONNAMPERUMA:* Cows turn straw into compost overnight. Thermophilic bacteria may be able to imitate cows.

PALANIAPPAN: The C-N ratio of the straw material you used appears to be very high, somewhere near 65, in which case the rate of decomposition of the straw is going to be very slow. Furthermore, in the process of decomposition, a lot of N meant for the main crop may be immobilized. Will it not be more beneficial if the straw material can be subjected to partial decomposition elsewhere prior to its incorporation into a cultivable soil?

*PONNAMPERUMA:* A C:N of 65 will retard decomposition. Nitrogen immobilization in anaerobic soils is much less than in aerobic soils.

SCHARPENSEEL: “Artificial manure” made from 110 kg straw (C:N ~ 70) + ~ 3 kg urea, with a final C:N of 12-1 5 has been known for about 50 years. Azolla is probably too N-rich for optimum N economy during its sometimes retarded decomposition. Are results about joint application of azolla plus rice straw available?

*PONNAMPERUMA:* Azolla has been used successfully in making compost out of straw.

# COMPOST AS A SOURCE OF PLANT NUTRIENTS

Akio Inoko

Composts and farmyard manures as organic sources of plant nutrients are discussed on the basis of experimental results obtained in Japan. In the case of no or low-level mineral fertilization, straw composts and farmyard manures could be effective sources of nutrients for rice plants. Nitrogen was the most important component among inorganic nutrients contained in composts and farmyard manures. In the case of suitable mineral fertilization, however, yield increases from the application of composts and farmyard manures were small, except in some experiments, in which utilization of N in farmyard manures was estimated at about 30% of the total N they contained. Long-term effects of the application of composts and farmyard manures were demonstrated through the selected experimental results of successive applications. Maturity problems of composts and farmyard manures were also examined along with some considerations of compost application from the viewpoint of energy flow.

The increase of soil fertility through organic matter application is most important in maintaining stable high crop yields (Cooke 1977). Furthermore, worldwide shortages of various resources and energy are causing the high costs of mineral fertilizers, and the effective use of plant nutrients contained in organic resources is receiving more emphasis. Organic recycling is considered from these two viewpoints.

There are limitations on the quality of organic matter that can be applied to soil. Hazardous or dangerous material should be excluded. And organic matter must be mature. When large amounts of fresh straw are applied directly to soil, crop plants are damaged through extremely severe N immobilization and the violent reduction of the soil. To avoid crop damage caused by fresh organic matter application, organic matter is piled, applied with water, and turned occasionally to supply air. This is called composting. Composting is one means of effectively utilizing organic matter.

Golueke (1977) clearly defines composting as a management method for solid waste. Animal wastes, wood materials, urban refuse, sewage sludges, and crop residues are raw materials of composts. This paper deals exclusively with composts produced from straw and farmyard manures.

---

National Institute of Agricultural Sciences, Soil Fertility Division, Yatabe-cho, 3-1-1, Kannondai, Tsukuba-gun, Ibaraki-ken, Japan.

## INORGANIC NUTRIENT CONTENT OF COMPOSTS AND FARMYARD MANURES

With successive applications of composts or farmyard manures, soil organic matter is enriched, and the physical, chemical, and biological properties of the soil are improved. These effects are comprehensive and extremely complex. When the soil environment is suitable for the growth of crop plants, yield increases through organic matter applications are usually less. When soil environments are unsuitable, greater yield increases are obtained through the application of organic matter.

Flaig (1974) attributed these effects of organic matter to the function of bioregulators, which are produced in the process of decomposition of organic matter or soil humic matter. Cooke (1977) considered them the result of organically provided N's behaving in ways not easily imitated by mineral fertilizer N.

It can be considered that among the various roles of organic matter, the role of nutrient source is most important when little or no mineral fertilizer is added to the soil.

Table 1 shows the average chemical compositions and ranges of 105 samples of composts and farmyard manures. Because chemical compositions are shown on a fresh-matter basis, nutrient content values are considerably low compared with those of dry straws. But, taking the mean values, 20 t compost or farmyard manure/ha could supply the equivalent amount of 78·kg N, 17 kg P, and 116 kg K. The total amounts of these nutrients are not absorbed by the crop during one crop season. Residual nutrients are accumulated in the soil and are absorbed gradually by successive crops. Therefore, composts and farmyard manures can be valuable sources of plant nutrients.

The chemical compositions of composts and farmyard manures vary with their raw materials and with composting practices. Inorganic nutrient content, especially of N, P, and K, is higher in animal wastes than in straw. To produce composts or

**Table 1. Chemical compositions of 105 samples of composts and farmyard manures from 4 sites in Ibaraki-ken, Japan.** [a]

| Component | Composition [b] (%) | | |
|---|---|---|---|
| | Mean value | Highest value | Lowest value |
| $H_2O$ | 75 ± 12 | 93 | 40 |
| pH ($H_2O$) | 7.9 ± 0.8 | 9.4 | 5.9 |
| C | 7.9 ± 2.1 | 13.3 | 1.4 |
| N | 0.39 ± 0.17 | 1.07 | 0.07 |
| C:N | 20.3 ± 6.5 | 46.0 | 4.7 |
| P | 0.08 ± 0.04 | 0.24 | 0.01 |
| K | 0.58 ± 0.37 | 1.84 | 0.07 |
| Ca | 0.32 ± 0.16 | 1.06 | 0.06 |
| Mg | 0.08 ± 0.04 | 0.29 | 0.01 |
| Na | 0.10 ± 0.02 | 0.33 | 0.01 |
| Mn [c] | 192 ± 86 | 464 | 32 |
| B [c] | 1.9 ± 1.3 | 11.9 | 0.3 |
| Si | 2.1 ± 0.7 | 7.7 | – |

[a] Source: Hashimoto and Ishikawa (1965). [b] Fresh-matter basis. [c] ppm.

farmyard manures, barley and wheat straw and litter other than rice straw are often used as livestock bedding materials. The inorganic nutrient content varies with the kind of straw used. Table 2 shows the inorganic nutrient content of farmyard manures produced from rice straw, wheat straw, and litter as bedding materials. Content of P, K, Si, Mn, and B are higher in farmyard manures produced from rice straw. Manganese and B content are high in farmyard manures produced from litter, but no trends are seen in the content of other nutrients. Because of shortages of straw for animal bedding, sawdust and other wood materials are often used in place of straw. In this case, a longer period of composting and more turning are necessary to produce mature farmyard manures (Hashimoto 1977, Fujiwara et al 1980). The inorganic nutrient content differs among tree species. Farmyard manures produced from different sources of animal wastes and bedding materials vary more in inorganic nutrient content than do straw composts.

The inorganic nutrient content of animal wastes varies with the kind and age of livestock, kind of feedstuff, and other composting practices. Therefore, it is difficult to predict the nutrient content of farmyard manures. Excreta of hogs and chickens usually contain more N than those of cattle. Carbon-nitrogen ratios of hog and chicken excreta are usually below 10; those of cattle are higher than 10. When farmyard manures are produced using hog and chicken excreta as raw materials, the contents of N and other components, especially of P and K, should be carefully monitored (Fujiwara et al 1981).

Furuno (cited by Hashimoto 1977) showed differences in inorganic nutrients of farmyard manures piled outdoors and indoors. The content of potash and other nutrients was lower when raw materials were piled outdoors, probably a result of leaching by rainwater. Consequently, indoor piling is preferable.

Composts and farmyard manures contain various micronutrients. Those that are produced from raw materials deficient in particular components will be low in those components. This is a serious problem when composts and farmyard manures are relied upon to provide micronutrients to crop plants. When composts or farmyard manures are used as sources of plant nutrients, the factors that affect their quality as well as the amount to be applied should be considered.

## INORGANIC NUTRIENT AVAILABILITY IN COMPOSTS AND FARMYARD MANURES

The nutrients contained in composts and farmyard manures are not absorbed completely by plants during a single crop season. At Aomori Prefectural Experiment Station, the successive applications of farmyard manures to rice fields are being studied. The amounts of inorganic nutrients absorbed by rice during one crop season were calculated (Yamashita 1964), and the results are shown in Table 3. Absorption of N, P, and K increased with increasing amounts of farmyard manures. Increases in K were highest, followed by those in N and P.

Residual nutrients are accumulated in soil and absorbed gradually by successive rice crops. With continuing application of composts or farmyard manures, residual nutrients accumulated in the soil and the amount of mineralization gradually increased. This is the cumulative effect of composts and farmyard manures.

**Table 2. Percentage inorganic nutrient content of farmyard manure as influenced by bedding materials.** [a]

| | Nutrient content [b] (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | N | C:N | P | K | Ca | Mg | Si | Mn [c] | B [c] |
| Rice straw | 6.2 | 0.32 | 19 | 0.08 | 0.60 | 0.24 | 0.05 | 2.6 | 178 | 1.5 |
| Wheat straw | 6.1 | 0.33 | 18 | 0.05 | 0.42 | 0.19 | 0.05 | 1.7 | 138 | 1.1 |
| Litter | 7.5 | 0.34 | 21 | 0.05 | 0.61 | 0.34 | 0.07 | 1.6 | 248 | 3.1 |

[a] Source: Hashimoto (1977). [b] Fresh-matter basis. [c] ppm.

**Table 3. Average annual amount of inorganic nutrients absorbed by rice crop with the addition of farmyard manure to mineral fertilizer during a 6-year study.** [a]

| Farmyard manure (t/ha) | Total amount of nutrients absorbed by rice crop (kg/ha) | | | Increment of nutrients absorbed by rice crop through application of farmyard manure (kg/ha) | | | Amount of nutrients in farmyard manure (kg/ha) | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | N | P | K | N | P | K |
| 0 | 60 | 16 | 50 | – | – | – | – | – | – |
| 5.6 | 67 | 18 | 83 | 7 | 2 | 23 | 30 | 11 | 35 |
| 11.3 | 82 | 20 | 110 | 22 | 4 | 51 | 60 | 22 | 69 |
| 18.8 | 88 | 21 | 129 | 28 | 5 | 69 | 100 | 36 | 114 |

[a] Source: Yamashita (1964). Each plot received a uniform application of 56 kg N/ha, 25 kg P/ha, and 46 kg K/ha; av nutrient content of farmyard manure was 0.53% N, 0.19% P, and 0.61% K on a fresh-matter basis.

Prolonged applications bring about equilibrium, at which point the amount of nutrients released from soil organic matter equals that of nutrients applied in composts and farmyard manures (Jenkinson and Raynes 1977, Inoko 1981).

The effects of composts and farmyard manures are less in irrigated rice fields than in dryland fields, because irrigated fields are submerged for some months and enriched by a natural supply of nutrient. The effect of N was the highest, followed by the effects of P and K.

The correlation of effects of composts or farmyard manures with soil type is important for the practical use of organic matter.

## LONG-TERM EFFECTS OF COMPOSTS AND FARMYARD MANURES

About 25-30% of the N contained in composts and farmyard manures can be absorbed by rice plants during one crop season. Consequently, continuous application of composts and farmyard manures accumulates N and other nutrients in the soil. These accumulated nutrients are gradually mineralized and utilized by successive rice crops.

Japanese experiments to elucidate the long-term effects of composts or farmyard manures on rice yields have been summarized by Matsuo et al (1976). The results of three long-term experiments — 32 years, 41 years, and 59 years — showed the positive effects of N contained in composts or farmyard manures. When sufficient nutrients were supplied by mineral fertilizers, however, the application of composts or farmyard manures had little additional effect on yield. Consequently, composts and farmyard manures can be considered as important sources of nutrients only when little or no mineral fertilization is used.

In the few cases where there was a small yield increase from the application of compost when adequate mineral fertilizers were available, the effect may have been due to factors other than nutrient supply. It may be necessary to consider influences due to the behavior of N organically provided (Cooke 1977) or the effects of bioregulators (Flaig 1974).

## MATURITY PROBLEMS OF COMPOSTS AND FARMYARD MANURES

Often the term *degree of maturity* is used to express degree of decomposition, degree of rotting, or degree of stabilization of organic constituents. The practice of maturing organic matter is called composting. As a practical matter, however, it is necessary to clarify the extent of oxidative decomposition of organic matter in a windrow, that is the degree of maturity. Maturity will be considered in the light of changes in the organic constituents of rice straw.

### Alteration of organic constituents during composting

In general, composting can be considered as the changing pattern of organic constituents of organic resources. Inoko et al (1982) characterized three groups based on their organic constituents: woody materials such as bark, cellulosic

Table 4. Changes in organic constituents of rice straw during composting.

| Piling period | Total C (%) | Total N (%) | C:N | Crude ash (%) | Hot water-soluble organic matter (%) | Carbohydrates (%) | | | Lignin |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Hemicellulose | Cellulose | Ratio[a] | |
| Straw | 41 | 0.8 | 51 | 19 | 11 | 21 | 25 | 45 | 8 |
| 1 week | 40 | 0.8 | 50 | 21 | 10 | 23 | 30 | 53 | 9 |
| 2 weeks | 40 | 0.8 | 44 | 22 | 10 | 22 | 31 | 53 | 9 |
| 3 weeks | 38 | 1.0 | 38 | 26 | 13 | 18 | 29 | 49 | 9 |
| 4 weeks | 38 | 1.0 | 38 | 27 | 13 | 18 | 28 | 48 | 9 |
| 5 weeks | 35 | 1.4 | 25 | 35 | 14 | 14 | 20 | 39 | 10 |
| 6 weeks | 34 | 1.5 | 23 | 34 | 11 | 15 | 20 | 41 | 11 |
| 8 weeks | 29 | 1.9 | 15 | 44 | 17 | 10 | 10 | 28 | 10 |
| 12 weeks | 26 | 2.2 | 12 | 51 | 19 | 6 | 4 | 16 | 9 |

[a] Ratio of carbon in hemicellulose and cellulose to total carbon, in percent.

materials such as rice straw, and nitrogenous materials such as animal wastes and sewage sludges. Rice straw is high in hemicellulose and cellulose. Therefore, when compost is produced from straw, we expect greater variations in hemicellulose and cellulose content.

Table 4 shows the changing pattern of organic constituents of rice straw piled under sufficient water and adequate air supply. No N source was added to promote fermentation. Total C decreased gradually, especially from 35 to 56 days after the start of the composting. Total N increased gradually, especially during the same period. Crude ash increased throughout the composting period. Hemicellulose and cellulose content increased slightly from 7 to 14 days after the start of composting and then decreased markedly.

Reducing sugar ratio (ratio of C in hemicellulose and cellulose to total C, in percent) showed a similar change in pattern to that of hemicellulose and cellulose. No trend was recognized in lignin content.

### Organic constituents after composting

As already mentioned, rice straws are high in hemicellulose and cellulose. These carbohydrates cause extremely severe immobilization of N and violent reduction of soil. Therefore one merit of composting is to decrease carbohydrate content.

Kumada (1977) examined several kinds of organic matter and concluded that materials with CN below 20 do not immobilize N. When the C:N of rice straw is lowered below 20 through biological reactions, the ratio of reducing sugars is lowered below 35%. These values become tentative guidelines of the maturity of straw composts (Inoko et al 1982). Skillful farmers, however, can classify straw composts as well matured, matured, medium matured, and unmatured through appearance and feel.

### Relation between nutrient contents and compost maturity

During composting of rice straw, carbohydrates are decomposed and total straw weight decreases. Inorganic nutrient content usually increases with maturity, making more inorganic nutrients available for the rice plants. The volatilization of N as $NH_3$ might occur in a slightly alkaline medium.

## COMPOST APPLICATION FROM THE VIEWPOINT OF ENERGY FLOW

In rice straw, hemicellulose content decreases by 69% and cellulose decreases by 84% during composting. Although hemicellulose and cellulose cause N immobilization and soil reduction, they are valuable in that they give soil microbes energy for their activities. Consequently, when composting problems are considered merely from the viewpoint of energy supply to soil, composting means a loss of the potential energy of organic matter. Direct application of straw to soil can supply much more energy compared with the application of compost. However, the direct application of straw carries with it inherent problems such as N immobilization and soil reduction.

From this viewpoint, it is safer to apply compost than fresh organic matter, especially in poorly drained rice fields at high temperature.

## CONCLUSION

One of the results of long-term field experiments is that organic nutrients contained in composts or farmyard manures have almost the same effect on yield as the nutrients contained in mineral fertilizers. Under suitable mineral fertilization, rice yield can be slightly increased by the application of composts and farmyard manures. Increasing the rate of mineral fertilizer to rice soil decreases the effects of composts and farmyard manures as organic sources of plant nutrients.

## REFERENCES CITED

Cooke, G. W. 1977. The roles of organic manures and organic matter in managing soils for higher crop yields — A review of the experimental evidence. Pages 53-64 *in* The proceedings of the international seminar on soil environment and fertility management in intensive agriculture. The Society of the Science of Soil and Manure, Japan (Nippon Dojyohiryo Gakkai), Tokyo.

Flaig, W. 1974. Biochemistry of soil organic matter. Pages 31-69 *in* Organic materials as fertilizers. Swedish International Development Authority/FAO, Soils Bulletin 27, Rome.

Fujiwara, S., H. Kamada, and A. Inoko. 1980. Decomposition of sawdust piled with chicken excreta — observation of changes of fine structure by scanning electron micrography [in Japanese, English summary]. J. Sci. Soil Manure Jpn. 51:203-209.

Fujiwara, S., A. Inoko, T. Matsuzaki, and H. Kamada. 1981. Changes of organic constituents of animal wastes through piling and check of their maturities by paper chromatography [in Japanese, English summary]. J. Sci. Soil Manure Jpn. 52:311-315.

Golueke, C. G. 1977. Pages 1-3 *in* Biological reclamation of solid wastes. Rodale Press, Emmaus PA.

Hashimoto, H., and M. Ishikawa. 1965. Studies on chemical compositions of composts and farmyard manures [in Japanese]. Bull. Ibaraki Pref. Agric. Exp. Stn. 6:l-29.

Hashimoto, H. 1977. Theory and application of organic matter [in Japanese]. Nobunkyo, Tokyo.

Inoko, A. 1981. Turnover of soil organic matter — a review [in Japanese]. J. Sci. Soil Manure Jpn. 52:548-558.

Inoko, A., Y. Harada, and K. Sugahara. 1982. Agricultural use of municipal refuse compost with special reference to the degree of maturity [in Japanese, English summary]. Bull. Natl. Inst. Agric. Sci., Jpn. Ser. B, 33:165-213.

Jenkinson, D. S., and J. H. Rayner. 1977. The turnover of soil organic matter in some of Rothamsted classical experiments. Soil Sci. 123:298-305.

Kumada, K. 1977. Decomposition of organic matter. Pages 171-198 *in* Chemistry of soil organic matter [in Japanese]. Todai Shuppan Kai, Tokyo.

Matsuo, H., T. Hayase, H. Yokoi, and Y. Onikura. 1976. Results of long-term fertilizer experiments on paddy rice in Japan. Ann. Agron. 27:957-968.

Yamashita, K. 1964. Some considerations on effects of compost in paddy field [in Japanese]. Nogyo Gijyutsu 19:6-11.

## DISCUSSION

FLAIG: In one of your tables the content of Lignin is relatively low. Is the value for dry matter or for fresh straw?

*INOKO.* Values of lignin contents of rice straw are expressed on an oven-dry basis.

FLAIG. Which method did you use?

*INOKO.* Determination was carried out following the method of proximate analysis described by Stevenson. A 0.5-1-g sample is immersed in 5ml 80% $H_2O$ at 14°C for 2.5 h after 2% HCl hydrolysis for hemicellulose determination. Then 150 ml $H_2O$ is added to the suspension and it is refluxed for 5 min. After filtration and drying, total C and N in residue are measured. [(Total C × 1.724 + total N × 6.25)/ wt of initial sample] × 100= content of lignin.

GAUR: Was a balance sheet in respect to N prepared at the beginning and end of composting to find out the gain or loss of N during composting?

*INOKO:* I showed the changing patterns of N content to use them as indices and criteria for the maturity of the rice plant. Therefore, their contents are expressed by materials including ash; that is, increase of N content can be seen as an offset of the decomposition of hemicellulose and cellulose through the composting process. When N contents are expressed on an ash-free basis, the contents are almost constant throughout the composting process, showing no N gain or loss.

AGBOOLA: In your paper you concluded that organic nutrients contained in composts of farmyard manures have almost the same effect on yield as the nutrients contained in mineral fertilizers. May I know whether there is any economic analysis in terms of cost of production using the two sources?

*INOKO:* I made this conclusion from the results of one long-term field experiment. In this experiment, the organic fertilizer plot received fertilizer components through applications of 12.0 t/ha compost and 0.6 t/ ha soybean cake. Almost the same amount of NPK was supplied to both the organic and the inorganic fertilizer plots. Because soybean cake is a very quickly effective organic fertilizer, this experimental condition as well as long-term application may give almost the same yield with organic and inorganic fertilizations. Therefore, it is impossible to generalize these results. Soybean cake is expensive; the production cost in the organic fertilizer plot was higher than that in the inorganic fertilizer plot.

# ALGAE AND AQUATIC WEEDS AS SOURCE OF ORGANIC MATTER AND PLANT NUTRIENTS FOR WETLAND RICE

P. A. Roger and I. Watanabe

Algae and aquatic weeds are possible sources of organic manure; they are usually as rich in nutrients as or richer than many green manures. However, their high water content (92% on the average) has been the major deterrent to the commerical use of aquatic weeds.

Algae and aquatic weeds developing in rice fields have both beneficial and detrimental effects. Nitrogen-fixing blue-green algae provide free N. Their growth can be encouraged by inoculation. The photosynthetic biomass growing in floodwaters acts as a trap for C and N released by the soil into the water and recycles it in an available form. On the other hand, algae and aquatic weeds compete with rice for space, light, and nutrients. Their biomass varies with cultural practices, but it is rarely higher than 1 t dry weight/ ha.

In irrigation canals and water sources, algae and aquatic weeds can develop large biomasses (1-13 t dry weight/ ha). Because they have mainly detrimental effects, their use as organic manure requires integrated management, permitting the reclamation of water bodies. The practice of incorporating composted aquatic plants has been developed mainly for dryland crops. Little is known about its potentialities in wetland rice, except in China. Detrimental effects such as weed dispersal and concentration of toxic products are possible.

The wetland rice ecosystem comprises a water layer in which a photosynthetic biomass of algae and aquatic macrophytes develops in addition to rice. Rice fields are connected, through irrigation canals, to reservoirs, rivers, and ponds, which are colonized by similar vegetation. Most of the aquatic plants developing in rice fields, irrigation canals, and water sources are weeds.

In a field, weeds compete with the crop for nutrients, space, and light. The importance of controlling weeds is emphasized in popularized books (see Vergara

---

Visiting scientist from the Office de la Recherche Scientifique et Technique Outre-Mer (France), and soil microbiologist, IRRI.

1979, Moody 1981). Detrimental effects of the lack of weed control range from a slight decrease in yield to intensive damage. In paddy fields in India(Bhubaneswar), a biomass of 9-15 t *Chara* (fresh weight)/ha caused yield losses of more than 30% (Misra et al 1976). *Limneocharis* and water hyacinth invading paddy fields in Sri Lanka were reported to take large areas out of production (Kotalawa 1976). Subsistence farmers in the wet lowlands of Bangladesh annually face disaster when rafts of water hyacinth, weighing up to 300 t/ ha, float over their rice paddies in floodwater; as the floods recede, the weeds remain on the germinating rice, killing it (Panel on Utilization of Aquatic Weeds 1976). The effects of *Salvinia* and *Pistia* have been reported to be similar (Kotalawa 1976). The photosynthetic aquatic biomass also increases the pH of submersion water, causing losses of N fertilizer by volatilization (Vlek and Craswell 1979).

Blue-green algae (BGA) have been sometimes cited as “weeds” in water-seeded rice because their growth pulls seedlings down into the water or mud (Smith et al 1977). However, the possible detrimental effects of BGA are negligible compared with the free N input provided by their N-fixing activity. The usefulness of these microorganisms in rice cultivation is clearly demonstrated in the literature (Roger and Kulasooriya 1980). Similarly, azolla, sometimes classified as a weed, has tremendous potential as a biofertilizer.

Whereas in the fields the photosynthetic biomass of aquatic plants can have both detrimental and beneficial effects, their presence in irrigation canals and water reservoirs seems to have a mainly detrimental effect. They reduce the water flow in canals and the utility of reservoirs for water storage, irrigation, and fish production. They also increase losses of water by transpiration from their leaves (National Science Research Council of Guyana and National Academy of Sciences, USA 1973; Varshney and Singh 1976).

Shortages of food and fertilizers and large expanses of aquatic weeds often exist in the same locality (Boyd 1974). Utilization of aquatic weeds from water bodies as a manure is an integrated management strategy permitting, at the same time, the reclamation of the water body and the fertilization of a crop with an organic manure frequently rich in N, P, and K. Moreover, aquatic plants can possibly be used to remove nutrients from waste-water effluents. Pilot studies with *Eichhornia* indicated that up to 29 t dry weight/ ha can be produced in ponds receiving additional nutrients (Wahlquist 1972).

This paper deals with non-N-fixing algae and aquatic weeds. Little emphasis is given to N-fixing BGA, as they were recently extensively reviewed (Roger and Kulasooriya 1980, Roger and Reynaud 1982). Azolla is covered elsewhere in this volume.

## NATURE OF FRESHWATER ALGAE AND AQUATIC WEEDS

Aquatic plants are classified as algae or macrophytes.

Algae are primitive plants devoid of true leaves or seeds. They reproduce vegetatively and through spores. Morphologically, three types can be distinguished:

- Phytoplanktons include microscopic single-celled, colonial, and simple filamentous forms; bloom-forming species such as *Microcystis* and *Anabaena* belong to the phytoplanktons.

- Filamentous algae such as *Cladophora* (cotton mat type), *Spirogyra* (slimy and green type), and *Hydrodictyon* (water net type) frequently form scum.
- Higher algae such as *Chara* and *Nitella* resemble vascular plants, grow as anchored species, and possess stems and branches.

Physiologically algae can be classified into N-fixing and non-N-fixing forms:

- N-fixing algae belong exclusively to the blue-green group, which are procaryotic. Their growth provides free N to the ecosystem.
- Non-X-fixing algae comprise part of the BGA and all the eucaryotic algae.

In a review on algal weeds and their chemical control, Das (1976) cited *Chara, Spirogyra, Oscillatoria, Nitella, Oedogonium, Cladophora, Pitophora, Rhizoctonium,* and filamentous algae without specific names. It appears that only filamentous and higher algae are considered weeds.

Aquatic macrophytic weeds are usually divided into three groups:

1. Submerged weeds produce most of their vegetative growth beneath the surface, rooted to the soil.
2. Surface (or floating) weeds have a majority of their leaves and flowers near the surface of water. Both rooted and free-floating species occur in this group, characterized by special parenchymatous tissues for buoyancy.
3. Emersed or marginal weeds growing in shallow water or wet soils.

Productivity differs among aquatic plants according to this classification. Ambasht and Ram (1976) studied the vertical distribution of dry matter and chlorophyll in different aquatic communities and distinguished three types of productivity: 1) the upright triangle type, represented mainly by emersed plants (e.g., *Eleocharis*), whose photosynthetic biomass is concentrated just above the basal layer; 2) the inverted triangle type, represented by submerged plants (e.g., *Hydrilla* or *Najas*), whose photosynthetic biomass is greatest in the 20-40 cm of the top layer of water body; 3) the flag type, represented by floating species (e.g., *Nymphea*), whose photosynthetic organs are concentrated on or above the water surface.

Lists and identification keys for common aquatic weeds are provided in several handbooks (e.g., Weldon et al 1979). Recently a list of major weeds of rice was published by Moody (1981).

Most of the important submerged weeds belong to the genera *Hydrilla, Myriophyllum, Ceratophyllum, Egeria, Elodea, Najas, Potamogeton, Vallisneria,* and *Chara.* Among floating weeds, water hyacinths (*Eichhornia* spp.), *Salvinia* spp., water lettuce (*Pistia stratiotes*), and duckweeds (Lemnaceae family) are the most common. The classification of a plant as a weed depends not only on the area but also on the method of crop cultivation. For example, submerged plants like *Chara* and *Hydrilla* are not considered main weeds in transplanted rice (Moody 1981). On the other hand, in areas where rice is directly seeded, they are considered detrimental (Mukherji and Laha 1969, cited by Das 1976).

Weeds can also be indirectly detrimental by inhibiting more or less the biological N fixation by BGA. Negative correlations have been observed between the N-fixing BGA biomass and the submerged weeds biomass (Roger and Kulasooriya 1980) or

**Table 1. References reporting biomass of planktonic algae in paddy fields and in fiesh waters.**

| Reference | Location | Dry wt (kg/ha) | Fresh wt (kg/ha) | Remarks |
|---|---|---|---|---|
| Institute of Hydrobiology Academia Sinica (1978) [a] | Paddy field, China | | 7,500 | After inoculation |
| Mahapatra et al (1971) [a] | Paddy field, India | 3 - 300<br>32 | 60 - 6,000<br>600 | Green algae dominant<br>N-fixing BGA dominant |
| Muzafarov (1953) [a] | Paddy field, USSR | | 16,000 | Total algal biomass |
| Reynaud and Roger (1981) | Uncultivated submerged sandy soil | | 41,000 | Total algal biomass |
| Roger and Reynaud (1977) [a] | Paddy fields, Senegal | | 2 - 6,000<br>2 - 2,300 | Total algal biomass<br>N-fixing algal biomass |
| Saito and Watanabe (1978) | Paddy field, Philippines | 2 - 114 | | |
| Singh (1976) [a] | Paddy field, India | 480 | 9,000 | *Aulosira* bloom |
| Srinivasan (1979) [a] | Paddy field, India | | 100 - 2,100 | |
| Watanabe et al (1977) [a] | Paddy field, Philippines | 177 | 24,000 | *Gloeotrichia* bloom |
| MacKenthun (1962) [b] | Lake, USA | 110 - 400 | | Phytoplankton |
| MacKenthun (1971) [b] | Lake, USA | 112 - 400<br>224 | | Phytoplankton<br>Attached algae |
| Forest (1965) [a] | Upland soils, USSR | | 40- 100 | For comparison |
| Patnaik and Ramachandran (1976) | Fish pond | 10 ml phytoplankton/ liter water | | Mycrocystis bloom |

[a] Cited by Roger and Kulasooriya (1980). [b] Cited by Little (1979).

the floating weeds biomass (Srinivasan 1982). But whether these were due to antagonism or to competition as well as to the inhibitory organism is still unknown.

## QUANTITATIVE EVALUATIONS OF THE PHOTOSYNTHETIC AQUATIC BIOMASS

Aquatic plants in the paddy field must compete with rice; therefore their biomass differs largely from that in irrigation canals and water sources, where they can occupy the whole available area.

### Paddy fields

Very little literature is available on the productivity of the floodwater in paddy fields. In the Philippines, Saito and Watanabe (1978) reported a net primary production of the flood community of 50-60 g C/m$^2$ in 90 days. The standing crop of algae ranged from 2 to 114 kg fresh weight/ha while the maximum standing crop of submerged weeds (*Najas* spp. and *Chara* spp.) was 400 kg dry weight/ha. The primary production of the floodwater community was equivalent to productivity values in eutrophic lakes, and the total gross primary production of the floodwater community during the cropping period corresponded to 10% of that of the rice plants in a fertilized plot and to 15% of that in a nonfertilized plot. A similar value was reported by Yamagishi et a1 (1980).

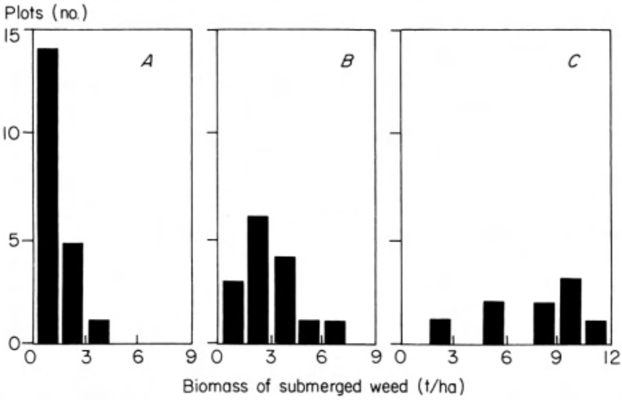
Probably because of technological difficulties in estimating algal abundance, quantitative evaluation of algal biomass in kilograms per hectare is also scarce. From the available data, summarized in 1980 by Roger and Kulasooriya, it appears that algae can develop a biomass of several tons (fresh wt) per hectare (Table 1). From the highest BGA biomass recorded in a paddy field (480 kg dry wt/ha), and assuming a protein content of 30-50%, it appears that under favorable conditions, a N-fixing algal bloom may contribute 30-40 kg N/ha. Reported data on N fixation related to BGA were summarized by Roger and Kulasooriya (1980). The estimated amount of N fixed varied from a few to 80 kg/ha and averaged 27 kg/ ha per crop.

The potential productivity of aquatic weeds in rice fields seems to be higher than that of algae (Table 2). The biomass of submerged weeds (mainly *Chara* and *Najas*) was studied in 44 plots at the IRRI farm by Kulasooriya et a1 (1981). Results (Fig. 1) show that the population of submerged weeds under a rice crop at the end of tillering had a mean biomass of about 1 t/ha (range, 0.4-3 t fresh weight/ ha) and that it increased at maturity to a mean of 3 t/ha (range, 0.2-4.5 t/ha). The highest values, which ranged from 2.7 to 12 t/ha, with a mean of 7.5 t/ha, were recorded in fallow plots. Twenty measurements of floating and emersed weeds in planted fields at the tillering stage gave a mean value of 1.7 and a maximum value of 4.1 t fresh weight/ha. Measurements conducted by the IRRI Agronomy Department over 9 crops in 3 years (De Datta, personal communication) gave similar values, ranging from 70 to 2,400 kg dry weight and averaging about 500 kg dry weight. In some cases, submerged weeds seem able to develop a very high biomass. Mukherji and Ray (1966, cited by Das 1976) reported that the growth of *Chara* and *Nitella* is favored by high temperatures (27°-35° C) and a slightly alkaline reaction of water. According to them, clear days with most of the rainfall at night, which allow the muddy water to clear in the day and light to penetrate the water, helped in their rapid

**Table 2. Standing crops and productivity of some aquatic macrophytes.**

| Species | Standing crop (t/ha) |  | Productivity (t dry wt/ha) | References | Remarks |
|---|---|---|---|---|---|
|  | Fresh wt | Dry wt |  |  |  |
| *Chara* spp.[b] | 9 - 15 |  |  | Misra et al (1976) | Rice fields, India |
| *Chara nitella*[b] | 5- 10 |  |  | Mukherji and Laha (1969) | Rice fields, India |
| *Ceratophyllum demersum* [b] |  | 6.8 | 9.0 | Boyd (1974), Gaudet (1974) | Temperate lake, USA |
| *Hydrilla verticillara*[b] |  |  | 2.5 | Steward (1970)[a] | Florida, USA |
| *Najas guadalupensis* [b] |  | 1.1 |  | Boyd (1974) | USA |
| *Najas* and *Chara*[b] |  | 0.4 |  | Saito and Watanabe (1978) | Rice fields, Philippines |
| *Nymphoides aquaticum* [b] |  | 1.8 |  | Boyd 1974 | USA |
| *Sagittaria subulata*[b] |  |  | 23.2 | Steward (1970)[a] | Florida, USA |
| *sagittaria eatonii* [b] |  |  | 27 | Gaudet (1974) | Subtropical spring |
| *Thalassia restudinum* [b] |  |  | 33.5 | Steward (1970)[a] | Puerto Rico |
| Total submerged vegetation | 1- 3 |  |  | Kulasooriya et al (1981) | Rice fields, Philippines |
| " | 7.5 |  |  | Kulasooriya et al (1981) | Fallow rice field |
| " | 25 - 350 |  |  | Gupta (undated) | Weedy canal |
| *Eichhornia crassipes* [c] | 250 | 12.8 | 36.8/167 | Gratch 1968[a]/Steward (1970)[a] | Louisiana, subtropic |
| *Marsilea quadrifolia* [c] | 2.32 |  |  | Srinivasan (in press) | Fallow fields, India |
| *Myriophyllum verticillatum* [c] |  | 2.4 |  | Boyd (1974) | USA |
| *Nelumbo lutea* [c] |  | 1.0 |  | Boyd (1974) | " |
| *Nuphar advena* [c] |  | 0.8 |  | Boyd (1974) | " |
| *Pistia stratiotes* [c] | 20 | 4.6 |  | Boyd (1974) | " |
| *Potamogeton pectinatus* [c] |  | 2.2 |  | Boyd (1974) | " |
| *Alternaria philoxeroides* [d] |  | 7.4 |  | Boyd (1974) | " |
| *Cyperus papyrus* [d] |  | 2.7 - 4.6 | 83.5 | Gaudet (1974), Steward (1970) [a] | Tropics |
| *Eleocharis quadrangula* [d] |  | 7.2 |  | Boyd (1974) | USA |
| *Justicia amencana* [d] |  | 7.1 |  | Boyd (1974) |  |
| *Orontium aquaticum* [d] |  | 2.4 |  | Boyd (1974) |  |
| *Phragmites communis* [d] |  |  | 32.5 | Steward (1970) [a] | Romania |
| *Sagittaria latifolia* [d] |  | 7.3 |  | Boyd (1974) | USA |
| *Typha latifolia* [d] |  | 15.3 | 51.5 | Boyd (1974), Steward (1970)[a] | Minnesota, USA |

[a]Cited by Little (1979). [b]Submerged. [c]Floating. [d]Emergent.



**1.** Distribution of biomass of submerged weeds (fresh weight, t/ha) among A) 20 plots at end of tillering (the plots had been hand weeded 4 weeks before the measurement), B) 15 plots at harvesting stage (no weeding was performed), and C) 9 fallow plots at harvesting stage of rice.

and luxuriant growth (5-10 t fresh weight/ha) on very large areas (about 50,000 ha in India). The biomass produced by *Chara* was reported to be 9-15 t fresh weight/ha by Misra et al(1976). Floating weeds also attained a very high biomass in Tamil Nadu (India), In Thaujavur Delta, submergence of fields during the fallow period encourages the growth of many aquatic weeds. Among such weeds, *Marsilea quadrifolia* is difficult to control and can develop a biomass of around 25 t fresh weight/ha (average of 44 locations; Srinivasan 1982).

### Irrigation canals and water sources

Little is known about the productivity of planktonic algae in fresh water. Densities of microcystis blooms observed in India (Cuttack) by Patnaik and Ramchandran (1976) ranged from 7 to 17 ml/liter. Assuming a colonized water layer of 20 cm, this leads to values of 14-30 t fresh weight/ha.

It can be assumed that the mass of algal cells per unit area in a culture or a natural ecosystem would not increase beyond a value that is probably determined by natural shading of the cells. Extrapolation of data from laboratory cultures indicates a maximal biomass of 2.75 t dry weight/ha (Roger and Reynaud 1979).

Much more is known about higher algae and macrophytes. Their very high productivity is frequently mentioned. A classical example is the water hyacinth; in one experiment 2 parent plants produced 30 offspring after 23 days and 1,200 at the end of 4 months (Holm and Yeo 1980). Water hyacinth has an average doubling time (vegetative reproduction) of 12.5 days during the warm season in the US; *Salvinia,* in open water at the edge of a mat, grows faster and can double the area it covers in 8.6 days (Holm and Yeo 1980). However, Sculthrope (1967) has discussed the mistaken notion that luxuriant submerged or floating macrophytes are unusually productive. The rapid spread of some weeds gives the observer the impression of phenomenal growth, but such vegetation is necessarily buoyant and contains very little dry matter. For example, the amount of dry matter produced in a *Hydrilla* mat averages only 2.25-4.5 t/ ha; the plant is 96% water, and mats are often limited to about 60 cm in thickness, because the density of the canopy eliminates all light and reduces growth beneath that level (Holm and Yeo 1980). According to Gaudet (1974) there is now adequate proof that in terms of dry weight such plants are not very productive compared with other plant communities.

Species differ greatly in inherent ability to produce dry matter. Large floating plants may have large standing crops, and values of dry matter above 10 t/ ha are commonly encountered in *Eichhornia crassipes* (Table 2). Other floating and submerged plants normally have standing crops with dry matter values ranging from 1 to 5 t/ ha. More information on productivity and standing crops of aquatic plants can be obtained from Little (1979).

## COMPOSITION OF ALGAE AND AQUATIC WEEDS

In 1953, Milner pointed out the scarcity of information on the composition of freshwater algae, which is still true today. Table 3 gives the composition of some freshwater microalgae and shows how variable the composition of a species can be. But the range of variation in the composition of *Chlorella* may be mainly due to the fact that no other plant species has been subjected to such extensive experimentation regarding the effects of environmental conditions and chemical composition. Other species might show as much variation as *Chlorella* (Milner 1953).

Despite the abundance of literature on the role of BGA in paddy soils, very little is known about their composition. From the analysis of 22 strains (Table 3) it appears that BGA have a low dry matter content, and their average protein content might not be as high as previously thought (Fogg et a1 1973). In fact, mucilagenous BGA can develop very impressive blooms, but the corresponding N content may be low. A *Nostoc* biomass of 13 t fresh weight/ ha, which corresponds to an almost continuous layer of colonies, 1-4 cm in diameter, frequently has a total N content of less than 5 kg/ha (Roger, unpublished).

Because of increasing interest in the pollution problems in water bodies, more information is available on the composition of higher algae and aquatic weeds. C. E. Boyd has probably done the most comprehensive analyses of aquatic macrophytes, culminating in an extensive review (Boyd and Scarsbrook 1975) in which data from 35 papers on temperate species were tabulated. Little (1979) summarized papers on both tropical and temperate species and concluded that the ingredients of aquatic plants other than water are similar to those of dryland plants.

A high water content is certainly the overwhelming characteristic of aquatic plants. Little and Henson (1967) presented results suggesting an average water content of 92%. By comparison, terrestrial forage plants contain 70-90% water.

A second characteristic of aquatic plants is a high content of ash (Sculthorpe 1967), which varies with location and season. Sand, silt, and encrusted carbonates often account for much of the mineral content. Although silt is most frequently removed during analysis, in practice it represents part of the chemical composition of the harvest. Submerged macrophyte communities contain, on the average, 21.3% ash on a dry weight basis; floating communities average 11.5% (Sculthorpe 1967); and upland plants usually contain less than 10%.

**Table 3. Composition of some freshwater algae.**

| Species[a] | Dry wt (% fresh wt) | Ash (% dry wt) | Ash-free dry wt (%) | | | C:N |
|---|---|---|---|---|---|---|
| | | | Protein | Carbohydrate | Lipid | |
| *Chlamydomonas* spp. | | 4.74 | 36.3 | 58.2 | 5.5 | 8.2 |
| *Anabaenopsis* spp. | | 9.35 | 45.5 | 45.6 | 8.9 | 6.8 |
| *Oikomonas termo*[a] | | 5.08 | 33.5 | 45.8 | 20.7 | 9.7 |
| *Stichococcus bacillaris* (sample A) | | 6.50 | 62.3 | 25.8 | 11.9 | 5.3 |
| *Stichococcus bacillaris* (sample B) | | 11.24 | 22.6 | 38.5 | 38.9 | 15.8 |
| *Chlorella pyrenoidosa* (sample A) | | 3.45 | 58.0 | 37.5 | 4.5 | 5.3 |
| *Chlorella pyrenoidosa* (sample B) | | 3.46 | 8.7 | 5.7 | 85.6 | 49.1 |
| Av | | 6.26 | 38.1 | 36.7 | 25.1 | 14.3 |
| Median | | 6.50 | 36.3 | 38.5 | 11.9 | 8.2 |
| Composition of 22 strains of blue-green algae[b] | | | | | | |
| *Composition of 22 strains of blue-green algae*[b] | | | | | | |
| Average | 3.85 | | 34.2[c] | 43.1[c] | | 7.6 |
| Highest value | 8.50 | | 51.6 | 68.4 | | 13.0 |
| Lowest value | 0.18 | | 21.2 | 19.9 | | 4.8 |

[a]Adapted from Milner (1953); [b]Strains belonging to the following genera: *Anabaena* (5), *Aulosira* (1), *Calothrix* (3), *Fischerella* (3), *Gloeotrichia* (2), *Nostoc* (6), *Oscillatoria* (1), *Tolypothrix* (1) (Roger, Tirol, and Watanabe, unpublished); [c]% of dry wt.

**Table 4. Variability of the composition of water hyacinth.**[a]

| | Number of data | Mean | Lower value | Higher value | CV (%)[b] |
|---|---|---|---|---|---|
| Dry matter (% fresh wt) | 13 | 7.79 | 4.50 | 12.00 | 23.7 |
| N (% dry wt) | 9 | 1.86 | 1.03 | 3.70 | 42.9 |
| P (% dry wt) | 8 | 0.36 | 0.10 | 0.63 | 43.9 |
| K (% dry wt) | 7 | 3.35 | 1.81 | 4.40 | 28.8 |
| Crude proteins (% dry wt) | 8 | 13.36 | 6.50 | 19.8 | 32.9 |
| Ash (% dry wt) | 6 | 13.40 | 11.90 | 25.6 | 28.3 |

[a]Data used for calculations have been collected from the papers summarized by Little (1979) in Chapter 3 of his *Handbook of utilization of aquatic weeds*. Data given on a fresh weight basis without indication of dry matter content of the plant have been recalculated on a 7.79% dry matter basis. [b]Variance expressed as a percentage of the mean.

A third characteristic of aquatic plants is the large variability of composition (as in algae), which is influenced by the composition of the water in which they grow. Lawrence and Mixon (1970) have shown how aquatic plants growing in water containing ample quantities of N, P, and K will exploit the situation by “luxury consumption” of these elements, far in excess of the amount they need for healthy growth. An extensive example was the K uptake by *Alternanthera philoxeroides:* in one case consumption was 20 times the content of plants grown in unfertilized pools (7.3% vs 0.36%). Table 4 shows the variability of the composition of water hyacinth. Table 5 is a compilation of data on the composition of some common aquatic weeds. It appears that aquatic weeds contain appreciable quantities of N, P, and K and, on a dry matter basis, have similar N and P contents to those of alfalfa but a higher K content. The amounts of Mg, Na, S, Mn, Cu, and Zn in aquatic weeds growing in nature are generally quite similar to those in terrestrial plants. However, aquatic plants are often richer in Fe and Ca than forage plants (Panel on Utilization of Aquatic Weeds 1976). The amount of all mineral elements can be exceptionally high in aquatic plants grown in sewage or agricultural and industrial waste water.

## DECOMPOSITION AND AVAILABILITY OF PRODUCTS TO RICE

### Mechanisms of release of nutrients

Living aquatic plants continuously excrete appreciable amounts of dissolved organic matter, including soluble nutrients (Kristritz 1978). Laboratory experiments have frequently shown that BGA liberate large portions of their assimilated nitrogenous substances; however, the large amounts recorded may be a methodological artifact due to osmotic shock in resuspending the cells or to physical damage of the algal material. No information on the exudation of organic compounds by BGA in field conditions is available (Roger and Kulasooriya 1980).

Excretion of nutrients by aquatic plants is particularly pronounced in senescent plants and, undoubtedly, the largest proportion of nutrients tied up in plant tissues would be released after death (Kristritz 1978). Nutrients are released after death mainly because of microbial decomposition. However, Otsuki and Wetzel (1974) demonstrated under laboratory conditions that 30-40%’ of the net production of the submerged freshwater angiosperm *Scirpus subterminales* was released as dissolved organic matter on autolysis; most of the autolytic organic matter was released within 5 days under both oxic and anoxic conditions.

A laboratory study by De Pinto and Verhoff (1977) illustrated the two mechanisms by which algae populations may decay under dark aerobic conditions – endogenous respiration by the algal cells themselves and decomposition by microorganisms. Active bacterial decomposition proved to be the more important mechanism by far. In the same study, the viability of the bacteria-free algal cultures after 70 days in the dark, with no net P regeneration, was regarded as an indirect proof that bacteria not only can decompose algae but, under certain circumstances, can cause the termination of an algal bloom. However, whether the lytic bacteria act as pathogens, and thus are the primary cause of decline, or act as saprophytes, decomposing the dead algal material resulting from other primary processes, remains a question (Fallon and Brock 1979).

**Table 5. Composition of some aquatic weeds.**[a]

| Aquatic weed | Dry matter (% fresh wt) | Protein[b] | N[b] | P[b] | K[b] |
|---|---|---|---|---|---|
| *Chara vulgaris* |  | 7.92 | 1.27[d] | 0.19 | 0.84 |
| *Ceratophyllum* spp. | 8.50 |  | 3.3 | 0.47 | 5.9 |
| *Elodea canadensis*[c] | 9.03 |  | 3.29 | 0.51 | 3.26 |
| *Hydrilla* spp.[c] | 8.00 | 17.1 | 2.7 | 0.28 | 2.9 |
| *Lagarosiphon* spp.[c] | 8.90 |  | 3.54 | 0.53 | 2.56 |
| *Lemna minor* |  | 17.86 | 2.87[d] | 0.17 | 1.20 |
| *Myriophyllum*[c] |  |  | 2.81 | 0.43 | 1.75 |
| *Nuphar variegatum* |  | 15.70 | 2.52[d] | 0.23 | 1.62 |
| *Pistia stratiotes* | 5.9 | 13.2 | 2.1 | 0.30 | 3.5 |
| *Potamogeton* spp.[c] |  |  | 2.51 | 0.33 | 2.28 |
| *Typha* spp.[c] |  |  | 1.37 | 0.21 | 2.38 |
| *Vallisneria* spp.[c] |  | 13.5 | 2.14 | 0.20 | 5.70 |
| Water hyacinth[c] | 7.8 | 13.4 | 1.86 | 0.36 | 3.35 |
| Av |  |  | 2.48 | 0.32 | 2.86 |
| Alfalfa hay | 15 |  | 2.7 | 0.26 | 1.77 |

[a] Data from Boyd (1969, 1970), Fish and Will (1966), Lancaster et al (1971), Lawrence and Mixon (1970), Lin et al (1975), and Riemer and Toth (1969) - all cited in Little (1979). [b] As % of dry matter. [c] Av value. [d] Extrapolated from protein content (Protein = 6.23 × N).

## Susceptibility to decomposition

The decomposition rate depends on the environment, the species, and the physiological state of the plant.

Survival of microbial bodies incorporated into the soil was studied by Casida (1980). The cells died more quickly when nutrients were added to the soil, whereas survival increased at lower temperature. At 20° C, 62% of the added cells were alive 1 week after incorporation, but at 37° C no living cell was observed after 1 week.

The susceptibility to microbial decomposition of 14 algal species was assessed by Gunnison and Alexander (1975) in pond water and with inocula from several environments. Some of the algae were destroyed in short periods, but others withstood microbial digestions for more than 4 weeks. The production of toxins did not account for the resistance of those algae not readily destroyed microbiologically. The suitability of the cell as a substrate for microorganisms was correlated with the longevity of three susceptible and three resistant algae. The differing susceptibility to decomposition may be related to the relative biodegradabilities of specific components of the algal walls like polyaromatic compounds.

The decomposition, by the action of various soil bacteria, of four nitrogen-fixing BGA at two different physiological stages was examined by Watanabe and Kiyohara (1960). Within 10 days of incubation with the most active strain (*Bacillus subtilis*), about 40% of the N from autolized cells and 5% of the N from fresh cells were converted to $NH_4^{+2}$.

## Regeneration of nutrients in floodwater

Most of the experiments concerning regeneration of nutrients from algae and aquatic plants have been conducted either in the laboratory or in enclosures replaced in situ. Therefore, the test samples were cut off from the circulation occurring under natural conditions, and the validity of the results are limited by this “enclosure effect.”

Studies in which field- or laboratory-grown algae were placed in the dark and the changes in N, or P, or both, were monitored for varying periods were summarized by Foree et al (1970). They reported three general stages of activity with nutrient regeneration:

1. the stage immediately after dark conditions — usually the first 24 hours — during which either a release to or absorption from solution or a release followed by an absorption of nutrients took place;
2. a stationary stage over a period of several days during which net nutrient regeneration was zero; and
3. the stage in which active nutrient regeneration occurred with a net release of nutrients to the solution, lasting a few hundred days.

The N and P regeneration of algae in dark aerobic (44 strains) and dark anaerobic (21 strains) conditions was studied by the same authors (Foree et a1 1970) for periods ranging from 40 to 360 days. In aerobic conditions, on the average, 50% of the initial N and P was regenerated but the extent of regeneration ranged from zero to nearly 100%. In anaerobic conditions, the extent of N and P regeneration averaged 40% and 60%, respectively, with a range similar to that for aerobic decomposition.

The dark aerobic decomposition of batch unialgal cultures inoculated with a natural bacterial community was studied in detail by De Pinto and Verhoff (1977). The P regeneration values obtained ranged from 3 1 to 95% (mean 74%), with higher percentages of release associated with higher initial cellular P. The conversion of particulate organic N to $NH_4^{+2}$ ranged from 51 to 94% (mean 74%). The incubation periods required for stabilization of the system varied from 29 to 55 days, about one-third of which was bacterial lag time. The P regeneration followed a pattern that indicated three stages:

1. after the algae were subjected to a darkened environment, a rapid release of P to solution associated with endogenous respiration, followed by an immediate absorption by the remaining cells;
2. a stationary lag phase lasting several days, during which there was a build-up of bacteria and no net P regeneration; and
3. when the viable algal population had been significantly reduced, an associated active P regeneration with a net release of orthophosphate to solution.

The regeneration pattern for N seemed to be less complicated than that for P. All organic N regenerated appeared first as $NH_4^{+2}$; then a portion of the $NH_4^{+2}$ was converted to $NO_3$ by nitrification. The state of P regeneration during the active phase of decomposition (3rd phase) depended on the initial P level, whereas N regeneration was a direct function of the amount of organic decomposition.

Studies dealing with the release of nutrients from decomposing aquatic macrophytes (Jewell 1971, Nichols and Keeney 1973, Kristritz 1978, Rho and Gunner 1978) have dealt also to different extents with the effects of the nutrients on the surrounding microflora, including algae. Kristritz (1978), who studied recycling of nutrients in an enclosed aquatic community of *Myriophyllum spicatum,* reported that total suspended bacterial biomass represented an average of 10% of the total organic N and P pool of the water column. Decaying *Myriophyllum heterophyllum* released $NH_4^{+3}$ and phosphate in concentrations sufficient to promote algal growth. The oxidation of $NH_4^{+2}$ by resident nitrifiers had a striking impact on microfloral succession. Nitrification was accompanied by a decrease in pH and thereafter by a decline in the numbers of bacteria and protozoa. Subsequently, coincident with the accumulation of nitrite and nitrate, the numbers of the resident green algal communities rose dramatically.

### Mineralization in soil

Mineralization of some algae and weeds under flooded conditions was studied by Mitsui (1954). Nitrogen contents varied from 2.2 to 6.6%, C contents from 39 to 44%, and C-N ratios from 6.6 to 20.1. The order of the accumulation of ammonium N followed the order of C-N ratios as long as the incubation period remained within 34 days. *Lemna* (floating weed; C:N = 6.6) accumulated the largest ammonium N whereas *Spirogyra* (filamentous green alga; C:N= 20.1) had even less than the check. However, a result contradictory to this “C:N rule” was quoted by Rho and Gunner (1978): “Though Boyd (1973) reported a higher nitrogen content of phytoplankton tissue than that of macropbytes, the decomposition of macrophytes was found to be more complete and to occur at twice the rate of phytoplankton (Jewell 1971).”

The rate and degree of nitrification, under aerobic conditions, of different aquatic weeds added to soil was studied by Riemer and Toth (1971) for 8 weeks. Considerable variations were observed, with rates ranging from high values (40-60% for *Nuphar advena* and *Lemna minor*) to low and even negative values (*Potamogetonpulcher, P. cordata,* and *Sparganium*). Some tissues not only showed poor nitrification but inhibited nitrification (old plants of *Phragmites*). It was also concluded that some aquatic weeds may be composted for agricultural use without added N.

### Effects on soil organic matter

Little is known about the nature of humus derived from algae and aquatic weeds. Their content of lignin, which is a major substance producing humus, seems to be low. Values ranging from 2.9% in *Hydrodictyon* (green alga) to 6.18% in *Hydrilla verticillata* (submerged weed) were recorded by Mitsui (1954), whereas ordinary green manures usually range from 9 to 24%.

Decomposition and humification of algal cells was studied by Verma and Martin (1976) using six strains of BGA and one green alga labeled with $^{14}C$. After 22 weeks of incubation of the whole cell in a sandy loam, between 61 and 81% of the added C had evolved as $CO_2$. Over 50% of the residual $^{14}C$ activity in the soil was not extractable with 0.5% NaOH.

Analysis of sedimentary organic matter from a cyanobacterial (BGA) mat by Disnar and Trichet (1981) indicated a wealth of amino acids and carbohydrates and a paucity of aromatic structures. Dzumaniyazou (1979) reported that green and blue-green algae stabilized humic acids and increased the content of humus and of free amino acids in an irrigated soil.

### Availability of the decomposition products to rice

Besides indirect evidence such as an increase in rice yield after algae or weeds were incorporated into the soil, there is very little information about how much and when nutrients released by this kind of manure are made available to the rice plant.

In a laboratory experiment, Wilson et al (1980) recovered from a rice crop 37% of the N from $^{15}$N-labeled *Aulosira* spp. spread on the soil and 51% of the N from the same material incorporated into the soil.

Recently, uptake by rice of $^{15}$N from a Nostoc strain was studied in pot and field experiments at IRRI (Tirol et al, in press). The availability of $^{15}$N from BGA incorporated into the soil was 23-28% for the first crop and 27-36% for the first and second crops. Surface application of the algal material reduced $^{15}$N availability to 14-23% for the first crop and 21-27% for the first and second crops. The pot experiment demonstrated that for the first crop algal $^{15}$N was less available than $(NH_4)_2SO_4$, but for two crops its availability was very similar. That indicates the slow-release nature of algal N; however, the very low C-N ratio (5-8) of BGA gives it better N availability than that of organic fertilizers such as farmyard manure. After two crops, 57% of $^{15}$N from BGA and 30-40% of $^{15}$N from $(NH_4)_2SO_4$ remained in the soil, suggesting that algal N is less susceptible to losses than mineral N.

Shi et al (1980) studied the N availability of $^{15}$X-labeled *Azolla, Astragalus sinicus,* and water hyacinth to rice and to a following crop of wheat. Water hyacinth had 1.53% N, a 21.3 C-N ratio, and 11.1% lignin. Twenty-five percent of the N from water hyacinth was absorbed by the first crop and 4.5% by the second. Nitrogen from water hyacinth was more available for rice than N from *Azolla,* and less available than N from *Astragalus sinicus.*

The foregoing results indicate that:

- Algae and aquatic weeds show great variations in their decomposition rate and in the conversion of plant N to $NO_3^-$ by soil microorganisms (Gunnison and Alexander 1975, Mitsui 1954, Riemer and Toth 1971).
- The extent of the decomposition of algae and aquatic weeds, and the consequent regeneration of N and P into the water in a soluble form are similar in aerated and nonaerated conditions (Foree and McCarty 1970, Jewell and McCarty 1971, Rho and Gunner 1978).
- The relative regeneration rate of P from the algae (Golterman 1964) and from the macrophytes (Rho and Gunner 1978, Kristritz 1978) is much higher than that of N.
- Humus resulting from the decomposition of algae is poor in aromatic structures; because of their paucity in lignin, a similar characteristic for the humus from aquatic plants, especially submerged ones, can be expected.
- If the decomposition of the photosynthetic biomass occurs in the floodwater, the nutrient regeneration, along with many other parameters, can markedly affect the dynamic seasonal succession of the phytoplankton, but availability of the nutrient to the rice plant is poor (Tirol et al, in press).

## AGRONOMICAL USE OF ALGAE AND AQUATIC WEEDS

In the paddy field, plants that can compete with the crop are usually removed, and the most common ‘‘use’’ of aquatic weeds is their incorporation into the soil during weeding.

One other possible technique is the use of BGA as a source of free N and organic matter for the crop. Literature concerning BGA and rice was summarized by Roger and Kulasooriya (1980). Since BGA were recognized to be one of the important N-fixing agents in the flooded rice soil, many trials have been conducted to increase rice yield by algal inoculation (algalization). Algalization has been reported to have a beneficial effect on grain yield in several countries; however, there are also reports indicating failure of algalization under widely different agroclimatic conditions. From the reports on field experiments, conducted mainly in India, it appears that, on the average, algal inoculation, where effective, caused about 14% relative increase in yield, corresponding to about 450 kg grain/ha per crop.

A method for producing algal inoculum easily adoptable by farmers has been developed and recommendations for field inoculation have been given (Venkataraman 1981). Unfortunately most of the experiments have been conducted on a "black-box" basis, where only the last indirect effect (grain yield) of an agronomic practice (algalization) was observed and the intermediate effects were not studied. Therefore, there are many uncertainties concerning the mechanism of action of BGA and the limiting factors for algal inoculation. In particular, it is still not known if the yield increase observed after algalization is simply due to an increase of N and organic matter in the soil resulting from the decomposing algae, or to some "auxinic effect" of exudation products, or both.

Plants that grow in irrigation canals (mainly submerged weeds and filamentous green algae) can also be incorporated into soil as a source of organic matter for rice. *Cladophora* and *Spirogyra,* two filamentous freshwater algae, were used by Pantastico and Rubio (1971) as manure for rice. A better increase in yield was obtained with dried algae than with fresh algae. *Spirogyra,* richer in N (5% dry weight), was more efficient than *Cladophora* (N = 2.39% dry weight). For an equivalent quantity of N, $(NH_4)_2SO_4$ was more efficient than dried algal material.

Because their NPK content is similar to that of many green manures used in dryland soil, partially dried aquatic plants that are composted can make a suitable soil fertilizer and conditioner. Several aquatic weeds have been used to make compost, mulches, and fertilizers, and a variety of methods are given in Little (1968). The same author (1979) recorded 26 papers dealing with this topic, among which 19 dealt with water hyacinth and only 3 with rice, clearly demonstrating the emphasis given to water hyacinth and dryland soils. The Indian Council of Scientific and Industrial Research (1952, cited by Little 1979) indicated that water hyacinth compost was eminently suitable for jute and rice fields. Subagyo and Vuong (1975, cited by Little 1979) reported that dead masses of *Salvinia molesta* stimulated the growth of rice seedlings in Indonesia.

Recently, Majid et al (1980) reported the effects of drained algae, composted aquatic weeds, and cow dung on a variety of crops including rice, soybean, sesame, brinjal, garlic, and onion. Drained algae and composted aquatic weeds yielded better results than cow dung in some experiments; in other experiments they were as good as cow dung. Field experiments indicated that rice yield has been increased by 24% through the use of composted *Eichhornia* in addition to the usual dose of chemical fertilizer. A recent note indicated that *Salvinia molesta* has been widely used by farmers in West Java as a soil additive in rice fields; 40 t/ha increased rice tillering by

30%. *Eichhornia crassipes* has also been used after being composted for 3-4 months (Soerjani 1980).

Aquatic weeds (mainly water hyacinth and *Pistia* ), naturally growing or artificially grown, are used as organic manure for wetland rice in China (Nan Kin Institute of Soil Science 1978). In Hunan Province aquatic plants, mainly *Pistia stratiotes, Eichhornia crassipes,* and *Alternanthera sessilis,* are collected or grown for making compost or pig food (IRRI 1980). In Fujian Province high-yield trials were conducted with a wheat-rice-rice rotation using organic manures. Use of 75 t mud manure/ha per year gave yields between 7.5 and 11.8 t/ha per crop. Mud manure is prepared by mixing mud with aquatic plants (mainly *Eichhornia*), flooding for a while to permit an anaerobic decomposition, and then draining to permit an aerobic incubation. In the same area, trials to grow aquatic plants (*Pistia stratiotes, Japonica narcissus,* and *Azolla pinnata*) within wide rows of late rice were conducted. Chinese scientists indicated that non-N-fixing aquatic weeds collected N from paddy water, and the accumulated N was turned down into the soil.

Very little is known about the effect of incorporation of weeds or weed compost on soil properties. Dhar (1961) reported that incorporation of water hyacinth into paddy soil resulted in a N-fixing activity that was higher when basic slag (0.5% $P_2O_5$) was added and when the soil was exposed to the light. Depending on the treatment, N-fixation efficiency ranged from 18.2 to 33.5 mg N/g oxidized C.

Thus, it appears that aquatic plants have been used as a source of organic matter and nutrients mainly in dryland soils and that their potentialities on wetland soils are very poorly documented, except in China.

There are limitations and possible noxious effects of the use of algae and aquatic macrophytes. One limitation is the bulkiness of the material, despite the fact that in most places where tropical water weeds are a problem there is ample hot sunshine that could be used to dry the harvest. Little and Henson (1967) pointed out that the harvest of water weeds is commonly believed to be too extensive a job because of their high water content (92% on the average). To obtain the same dry matter of plant material from water weeds (8%), about twice as much fresh material is needed as lucerne (15%) or 2.5 times that of pasture grasses (20%).

A second possible limitation on the use of aquatic weeds in wetland soils is that they can aid weed dispersal through the irrigation system to the rice fields. Gupta (undated) pointed out that many cuttings and rhizomes of the weeds regain viability even after composting.

A third limitation is that composting seems to be a recommendable precautionary measure because both fresh algae and aquatic weeds can release products toxic to rice when incorporated. Mats of BGA incubated anaerobically rapidly produced a large amount of volatile S compounds, including $H_2S$, methyl mercaptan, and dimethyl sulfide (Zinder et al 1977). In Sri Lanka, *Salvinia* growing in rice fields is buried during the preparatory stages. In marshy areas that helps in the aeration of the soil. On the other hand these buried plants decompose and liberate organic acids that are toxic to rice plants and create an unfavorable pH (Kotalawa 1976).

A fourth very important limitation is that certain stable pesticides, industrial chemicals, and heavy metals may be absorbed and retained by aquatic plants (Vance and Drummond 1969, Rose and McIntire 1970). Water hyacinths, in particular, have been shown to absorb large quantities of toxic materials, including heavy metals. Some filamentous algae appear to be especially efficient in accumulating pesticides; e.g., *Cladophora* concentrates DDT far more than other plants or animals (Meeks and Peterle 1967). Therefore, discretion should be used when considering use of aquatic weeds.

Incorporating organic matter from aquatic weeds is thus not invariably beneficial. Singh (1962) compared the effects of composts made from a number of aquatic weeds on the yield of different fruits. Composts of *Pistia Najas, Hydrilla,* and *Ottelia* gave higher yields than the control, but *Eichhornia* compost gave consistently lower yields than the control.

## CONCLUSION

Algae and aquatic weeds that develop in rice fields and their related bodies of water constitute a source of organic matter and nutrients that can be used as manure for rice. Average standing crops of the aquatic photosynthetic biomass range from around 500 kg dry weight/ ha in the fields to 1-5 t dry weight/ ha in irrigation canals and water tanks. Higher values (30 t dry weight/ha) have been reported in bodies of water receiving farm or factory effluents. Planktonic algae usually have a lower productivity than aquatic macrophytes.

The average composition of aquatic macrophytes is 8% dry matter, 2-3% N (dry weight basis), 0.2-0.3% P, and 2-3% K. Planktonic algae have higher N contents, averaging 5%. On a dry weight basis, this composition is very similar to that of many green manures except for K in macrophytes and N in planktonic algae, which are higher. However, the high water content of aquatic weeds has been the major deterrent to their use.

In rice fields, the photosynthetic aquatic biomass exhibits both beneficial and detrimental effects. Nitrogen-fixing BGA provide a free input of N; they have other beneficial effects like auxinic effects on the rice plant, as well as antagonistic effects against some aquatic macrophytes. Their growth can be encouraged by inoculation. However, the mechanisms of action and the limiting factors are still poorly understood.

Other algae and aquatic weeds: 1) compete with rice for space, light, and nutrients; 2) may have detrimental mechanical effects on the germinating seeds and the young plants; and 3) increase the pH of the floodwater and cause N loss by volatilization. On the other hand, as photoautotrophs assimilate $CO_2$ evolved from the soil and return it in the form of algal cells and aquatic weeds, they prevent C loss. A similar role in partially preventing $NH_4^+$ loss is possible. In a gas-lysimeter experiment with two different soils, Vlek and Craswell (1979) recovered 18.5% and 29.5% of N added as urea in the algal biomass. With $(NH_4)_2SO_4$, only 0.5% and 6.3% of added N was recovered in algae.

Saito and Watanabe (1978) reported that the productivity and turnover rate of the aquatic community in a rice field were higher than those of rice roots. A gross primary production of 60-70 g C/m$^2$ in 120 days was recorded. A similar value (71 g C/m$^2$ in 114 days) was reported by Yamagishi et a1 (1980). It is likely that the contribution of the organic matter produced in the floodwater community is important quantitatively as well as qualitatively in recycling nutrients into available forms. Readily decomposable soil N increased in the surface layer during flooding (Kobo and Uehara 1943), and the amount of chlorophyll-like substances in rice soils was correlated with the increment in $NH_4^+$ production by air drying of soils, which is a good index of the N-supplying ability of the soil (Wada 1968). This suggests the possibility that the photosynthetic biomass contributes to readily decomposable organic matter (Saito and Watanabe 1978).

Nitrogen from algae and aquatic weeds is available to the rice plant; around 30% of N from incorporated BGA and water hyacinth was recovered in the first two crops. (Tirol et al, in press; Shi et al 1980).

Algae and weeds growing in irrigation canals and in other bodies of water may have very high productivity and are, in most cases, considered detrimental. Their use as a source of compost can effect the reclamation of the bodies of water. Such use has been developed mainly for dryland crops and, except in China, little is known about its potential for wetland rice. This aspect is reported in other sections of this symposium. The positive effects on grain yield have been reported, but detrimental effects like weed dispersal and concentration of pesticides and heavy metals are possible. Therefore, discretion should be exercised when considering use of aquatic weeds in wetland soils. Moreover, because of the bulkiness of aquatic weeds, their use will be strongly influenced by agroeconomic conditions, the facility of harvest, and the distance between the field and the places of harvesting and composting.

## REFERENCES CITED

Ambasht, R. S., and K. Ram. 1976. Stratified primary productive structure of certain macrophytic weeds on a large Indian lake. Pages 147-155 in C. K. Varshney and J. Rzoska, eds. Aquatic weeds in Southeast Asia. W. Junk, B. V. La Hague Publ.

Boyd, C. E. 1974. Utilization of aquatic plants. Pages 107-115 *in* D. S. Mitchell, ed. Aquatic vegetation and its use and control. UNESCO, Paris.

Boyd, C. E., and E. Scarsbrook. 1975. Chemical composition of aquatic weeds. Pages 144-150 *in* Proceedings of the symposium on water quality and management through biological control. Gainesville, University of Florida.

Casida, L. E., Jr. 1980. Death of *Mocrococcus luteus* in soil. Appl. Environ. Microbiol. 39:1031-1034.

Das, S. S. 1976. Algal weeds their chemical control. A review. Indian J. Plant Prot. 4:201-208.

De Pinto, J. V., and F. H. Verhoff. 1977. Nutrient regeneration from aerobic decomposition of green algae. Environ. Sci. Technol. 11:371-377.

Dhar, R. R. 1961. Fixation of nitrogen by water hyacinth (*Eichhornia crassipes*). Pages 4-7 *in* Nitrogen problem, Suppl. Sci. Cult. (India) 27.

Disnar, J. R., and J. Trichet. 1981. Étude experimentale de la fixation des métaux par un materiau sédimentaire actuel d'origine algaire. I. Isolement, purification et caractérisation de la matrice organique. Geochemica et Cosmochimica Acta 45:353-362.

Dzumaniyazou, I. D. 1979. Influence of microalgae on biological and biochemical activity of soil and productivity of the crops. Pages 574-579 *in* B. Novak, J. Pokorna-Kozova, F. Kunc, J. Kubat, and J. Damaska, eds. Studies about humus (Transactions of "Humus et Planta VII").

Fallon, R. D., and T. D. Brock. 1979. Lytic organisms and photooxidative effects: influence on blue-green algae (Cyanobacteria) in Lake Mendota, Wisconsin. Appl. Environ. Microbiol. 38:499-505.

Fogg, G. E., W. D. P. Stewart, P. Fay, and A. E. Walsby. 1973. The blue-green algae. Acad. Press, London and NY. 459 p.

Foree, E. G., and P. L. McCarty. 1970. Anaerobic decomposition of algae. Environ. Sci. Tech. 10:842-849.

Foree, E. G., W. J. Jewell, and P. L. McCarty. 1970. The extent of nitrogen and phosphorus regeneration from decomposing algae. *In* Advances in Water Pollution Research, Proceedings of the 5th Int. Conf. held in San Francisco and Hawaii. Vol. 2, Paper III-26/1, III-27/15.

Gaudet, J. J. 1974. The normal role of vegetation in water. Pages 24-115 *in* D. S. Mitchell, ed. Aquatic vegetation and its use and control, UNESCO, Paris.

Golterman, H. L. 1964. Mineralization of algae under sterile conditions or by bacterial breakdown. Verh. Int. Ver. Limnol. 15:544-548.

Gunnison, D., and M. Alexander. 1975. Resistance and susceptibility of algae to decomposition by varietal microbial communities. Limnol Oceanogr. 20:64-70.

Gupta, O. P. [Undated]. Aquatic weed control for efficient water use. Rajasthan College of Agriculture, University of Udaipur, India, Tech. Bull. 2.

Holm, L., and R. Yeo. 1980. The biology, control, and utilization of aquatic weeds. Weeds Today 7:13 (Fall 1980).

IRRI. 1980 Report on the INSFFER field observation tour in China. The International Rice Research Institute, Los Baños, Philippines. 59 p.

Jewell, W. J. 1971. Aquatic weed decay: dissolved oxygen utilization and nitrogen and phosphorus regeneration. J. Wat. Poll. Contr. Fed. 43:1457-1467.

Jewell, W. J., and P. L. McCarty. 1971. Aerobic decomposition of algae. Environ. Sci. Tech. 10:1023-1031.

Kobo, K., and H. Uehara. 1943. The increase in soil fertility of paddy soil during flooding period. J. Sci. Soil Manure 17:344-346.

Kotalawa, J. 1976. Noxious water vegetation in Sri Lanka. The extent and impact of existing infestations. Pages 51-58 *in* C. K. Varshney and J. Rzoska, eds. Aquatic weeds in Southeast Asia. W. Junk, B. V. La Hague Publ.

Kristritz, R. U. 1978. Recycling of nutrients in an enclosed aquatic community of decomposing macrophytes (*Myriophyllus spicatum*). Oikos 30:561-569.

Kulasooriya, S. A., P. A. Roger, W. L. Barraquio, and I. Watanabe. 1981. Epiphytic nitrogen fixation on weeds in rice field ecosystem. Pages 56-61 *in* R. Wetselaar, J. R. Simpson, and T. Roswall, eds. Nitrogen cycling in Southeast Asian wet monsoonal ecosystem, Canberra, Australian Academy of Sciences.

Lawrence, J. M., and W. W. Mixon. 1970. Comparative nutrient content of aquatic plants from different habitats. Proc. Ann. Meet. South Weed Sci. Soc. 23:306-310.

Little, E. C. S. 1968. Handbook of utilization of aquatic plants. FAO Crop Protection Branch. 123 p.

Little, E. C. S. 1979. Handbook of utilization of aquatic plants. FAO Fisheries Technical Paper 187. 176 p.

Little, E. C. S., and I. E. Henson. 1967. The water content of some important tropical water weeds. PANS (c) 13:223-227.

Majid, F. Z., L. Nahar, S. Begum, R. Khatun, and N. Akhtar. 1980. Use of naturally occurring algae as biofertilizer or organic manure. National Workshop on Algal Systems, Madras, India. 1980.

Meeks, R. L., and T. J. Peterle. 1967. R. F. Project 1794, Report No. COO-1358-3. The Ohio State University Research Foundation, Columbus, Ohio, USA.

Milner, H. W. 1953. The chemical composition of algae. Pages 285-306 *in* Algal culture from laboratory to pilot plant. Carnegie Institution of Washington publications. No. 600-177.

Misra, A., G. K. Patro, and G. C. Tosh. 1976. Studies on chemical control of *Chara.* Pages 265-268 *in* C. K. Varshney and J. Rzoska, eds. Aquatic weeds in Southeast Asia, W. Junk, B. V. La Hague Publ.

Mitsui, S. 1954. Inorganic nutrition, fertilization and soil amelioration for lowland rice. Yokendo, Ltd. Tokyo Publ.

Moody, K. 1981. Major weeds of rice in South and Southeast Asia. The International Rice Research Institute. 79 p.

Mukerji, S. K., and J. N. Laha. 1969. Recent studies on the chemical control of algal weeds of paddy fields in West Bengal. Plant Prot. Bull. 3:13-17.

Nan Kin Institute of Soil Science. 1978. Soils of China, Academia Sinica, 229 p.

National Science Research Council of Guyana and National Academy of Sciences, USA. 1973. Some prospects for aquatic weed management in Guyana. Workshop on aquatic weeds management and utilization. Georgetown, Guyana, 15-17 March 1973.

Nichols, D. S., and D. R. Keeney. 1973. Nitrogen and phosphorus release from decaying water milfoil. Hydrobiologia 42:509-525.

Otsuki, A., and R. G. Wetzel. 1974. Release of dissolved organic matter by autolysis of a submerged macrophyte *Scirpus subterminalis.* Limnol Oceanogr. 19:842-845.

Panel on Utilization of Aquatic Weeds. 1976. Making aquatic weeds useful: Some perspectives for developing countries, National Academy of Sciences, Washington, D. C. USA. 166 p.

Pantastico, J. B., and P. P. Rubio. 1971. Algae as fertilizer for rice. Pages 5-8 *in* Agriculture at Los Baños (Philippines) Jul-Sept. issue.

Patnaik, S., and V. Ramachandran. 1976. Control of BGA shown with simazine in fish ponds. Pages 285-291 *in* C. K. Varshney and J. Rzoska, eds. Aquatic weeds in Southeast Asia. W. Junk, B. V. La Hague Publ.

Reynaud, P. A., and P. A. Roger. 1981. Variations saisonnières de la flore algale et de l'activité fixatrice d'azote dans un sol engorgé de bas de dune. Rev. Ecol. Biol. Sol 18(1)9-27.

Rho, J., and H. B. Gunner. 1978. Microfloral response to aquatic weed decomposition. Water Res. 12:165-170.

Riemer, D. N., and S. J. Toth. 1971. Nitrification of aquatic weed tissues in soil. Hyacinth control J. 9:34-36.

Roger, P. A., and P. A. Reynaud. 1979. Ecology of blue-green algae in paddy fields. Pages 289-309 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Roger, P. A., and S. A. Kulasooriya. 1980. Blue-green algae and rice. International Rice Research Institute, Los Baños, Philippines, 113 p.

Roger, P. A., and P. A. Reynaud. 1982. Free living blue-green algae in tropical soils. Pages 147-168 *in* Y. Dommergues and H. Diem, eds. Microbiology of tropical soils and plant productivity, Martin Nijhoff, La Hague.

Rose, F. L., and C. D. McIntire. 1970. Accumulation of dieldrin by bentic algae in laboratory streams. Hydrobiologia 35:481-493.

Saito, M., and I. Watanabe. 1978. Organic matter production in rice fields flood water. Soil Sci. Plant Nutr. 24:427-440.

Sculthorpe, C. D. 1967. The biology of aquatic vascular plants. Edward Arnold Publishers, London, England.

Shi Shu-lian, Qi-xiao Wen, and Hai-qui Liao. 1980. The availability of nitrogen of green manures in relation to their chemical composition. Acta Pedol. Sin. 17:240-246.

Singh, S. B. 1962. Preliminary experiments on the relative manurial values of some aquatic weeds as composts. Pages 141-145 *in* Proceedings, 10th Session Indo-Pacific Fisheries Council, Seoul.

Smith, R. J., W. T. Flinchum, and D. E. Seaman. 1977. Weed control in US rice production. Agriculture handbook 497, US Department of Agriculture.

Soejani, M. 1980. Aquatic plant management in Indonesia. Trop. Ecol. and Dev. 725-737.

Srinivasan, S. 1982. BGA can control the problem weed *Marsilia quadrifoliata* IRRN (in press)

Tirol, A. C., P. A. Roger, and I. Watanabe. 1982. Fate of nitrogen from a blue-green algae in flooded rice soil. Soil Sci. Plant Nutr. 28(4):559-570.

Vance, V. D., and W. Drummond. 1969. Biological concentration of pesticides. J. Am. Waterworks Assn. 61:360-362.

Varshney, C. K., and K. P. Singh. 1976. A survey of aquatic weed problem in India. Pages 31-41 *in* C. K. Varshney and J. Rzoska, eds. Aquatic weeds in Southeast Asia. W. Junk, B. V. La Hague Publ.

Venkataraman, G. S. 1981. Blue-green algae for rice production — a manual for its promotion. FAO Soil Bull. 46. 102 p.

Vergara, V. S. 1979. A farmer's primer on growing rice. The International Rice Research Institute. Los Baños, Philippines. 220 p.

Verma, L., and J. P. Martin. 1976. Decomposition of algal cells and components and their mobilization through complexing with model humic acid-type phenolic polymers. Soil Biol. Biochem. 8:85-90.

Vlek, P. L. G., and E. T. Craswell. 1979. Effect of nitrogen source and management on ammonia volatilization losses from flooded rice-soil systems. Soil Sci. Soc. Am. J. 43:352-358.

Wada, H. 1968. Some characteristics of organic matter in paddy soil [in Japanese]. Pedologist 12:25-31.

Wahlquist, H. 1972. Production of water hyacinths and resulting water quality on earthen ponds. Hyacinth Control J. 10:9-11.

Watanabe, A., and T. Kiyohara. 1960. Decomposition of blue-green algae as affected by the action of soil bacteria. J. Gen. Appl. Microbiol. 5(4): 175-179.

Weldon, L. W., R. D. Blackburn, and D. S. Harrison. 1979. Common aquatic weeds. Agriculture Handbook 352. US Department of Agriculture. 43 p.

Wilson, J. T., D. L. Eskew, and M. Habte. 1980. Recovery of nitrogen by rice from blue-green algae added in a flooded soil. Soil Sci. Soc. Am. J. 44:1330-1331.

Yamagishi, T., K. Okada, T. Hayashi, A. Kimura, and Y. Murata. 1980. Cycling of carbon in a paddy field. Jpn. J. Crop Sci. 49:135-145.

Zinder, S. H., W. N. Doemel, and T. D. Brock. 1977. Production of volatile sulfur compound during the decomposition of algal mats. Appl. Environ. Microbiol. 34:859-860.

## DISCUSSION

PALANIAPPAN: Does the increased or decreased N content of the soil N or added nitrogenous fertilizers influence the rate of N fixation by blue-green algal forms?

*ROGER:* Addition of nitrogenous fertilizers at the beginning of the crop cycle inhibits the development of N-fixing algae. Laboratory experiments have clearly demonstrated the inhibitory effect of mineral N on the N-fixing activity of BGA. However, in the field this inhibition seems to be frequently only partial and decreases during the growth cycle because of the uptake of N by plants. Little is known about the organic N content of soil and the occurrence and activity of BGA.

NAGAR: Do you encounter the problem of the presence of heavy metals when you use water hyacinth as a source of organic matter and plant nutrients?

*ROGER:* The paper I presented is a review of the literature. We did not conduct any trials with water hyacinth. For more information, please refer to Little's handbook.

GAUR: What may be the cause of the very slow mineralization of BGA and *Chlorella* on soil although the C-N ratio is quite narrow (5-6) and they are poor in lignin?

*ROGER:* Algal material rich in akinetes or spores is less susceptible to decomposition than material comprising vegetative cells only. Also, there are differences among strains. However, from the few data available, it does not appear at all that BGA and *Chlorella* have a very slow mineralization rate.

PALANIAPPAN (comment): I have found that living or senescing leaf material, if allowed to decompose as it is, decomposes and releases its nutrient contents faster than leaf material subjected to decomposition after sun- or oven-drying. The delay observed in the current study could be due to the sun-drying of the N-fixing algal materials.

# AZOLLA IN THE PADDY FIELDS OF EASTERN CHINA

Shi-ye Li

In Eastern China, azolla has been used as a green manure for more than a hundred years. Recently, the techniques of propagating and utilizing azolla have been modified. Diversified species of azolla such as *Azolla imbricata, A. filiculoides, A. caroliniana,* and *A. microphylla* have been adopted for cultivation between rice crops in multiple cropping systems to increase nutrient efficiency. Advances in the study of azolla sexual reproduction have indicated the possibility of using sporocarps over the summer to replace azolla seedlings. Adjusting the nutrient requirements of azolla can accelerate the multiplication rate and N-fixing activity of various species in different seasons. An investigation of the mineralization rate. nutrient-releasing capacity, and N recovery from azolla showed the desirability of incorporating azolla completely into soil. Different azolla management practices increase rice yields, and, through a series of modified techniques, the full potential of azolla in rice production is likely to be realized in China in the future.

Azolla has been multiplied and applied as a major green manure to the paddy fields of Eastern China for more than 100 years (Lu et al 1963, Lumpkin et al 1980, Li et al 1982). The moderate temperature required for the multiplication of the native species *Azolla imbricata* corresponds to the rice transplanting seasons in Eastern China. Incorporation of the species into paddy soils contributes a desirable increase in rice yield (ISF 1975). With the development of agriculture and the extension of multiple cropping systems to the paddy fields, the selection of azolla varieties for adaptability to new cropping patterns and for multiplication capability has become the important objective. To meet these requirements, studies on the propagation and utilization of azolla during the past 20 years have been done to

- select adaptable species,
- develop improved propagation methods,
- adjust the nutrient status of azolla to increase its N-fixing activity,
- research the mineralization characteristics of azolla after it is incorporated into the soil, and
- promote the N efficiency of azolla application.

This paper describes the present status of azolla in the paddy fields of Eastern China and discusses the potential of modified propagation and utilization methods for the culture and use of azolla.

---

Institute of Soil and Fertilizer, Zhejiang Academy of Agricultural Sciences, Hangzhou, China.

## DEVELOPMENT OF VARIOUS SPECIES OF AZOLLA

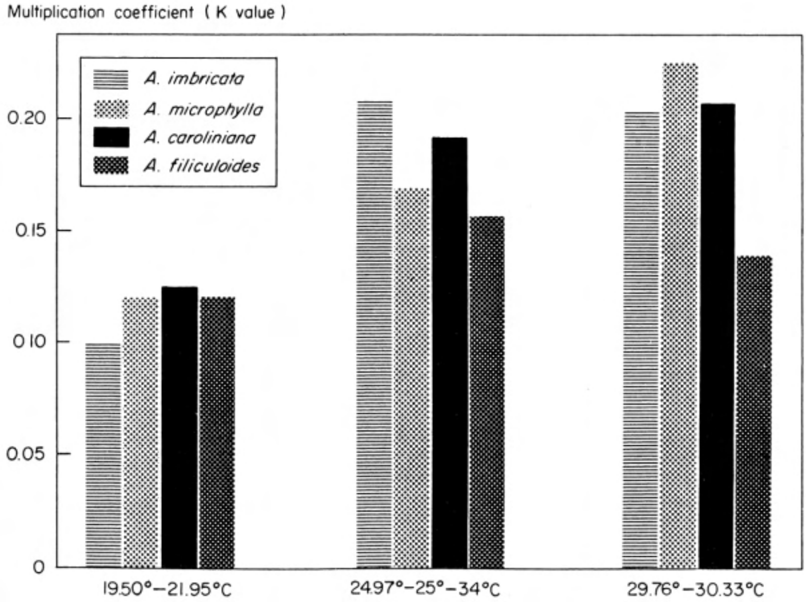
Only the native species *A. imbricata* was utilized in Eastern China before the 1970s. Its regional adaptability ensures its continued use. However, it has shortcomings such as susceptibility to cold, slow multiplication in early spring, and low biomass yield, all of which limit its usefulness. In the late 1970s, *A. filiculoides* was introduced from East Germany, followed by *A. caroliniana, A. microphylla,* and other species, including more than 100 ecological varieties. The introduction of various new species increases not only the availability of azolla as fodder but also the utilization of azolla as a green manure for the rice crop in various cropping patterns.

### Azolla multiplication

The rate of multiplication of various species at different temperature ranges was studied by Li et al (1982). *A. microphylla* grew best at about 30° C. *A. filiculoides* stopped growing at a temperature higher than 25°C. *A. caroliniana* and *A. imbricata* maintained a stable growth rate at temperatures ranging from 20° to 30° C (Fig. 1). Nitrogen fixed by several species expressed as N accumulated over a 1-year period was about 1 t/ ha (Table 1) in paddy fields (Li et al 1982). *A. microphylla* fixed three times more N in the summer than *A. filiculoides.* Conversely, in winter *A. filiculoides* fixed eight times more N than *A. microphylla.* These multiplication and N-fixing rates demonstrate the importance of selecting species on the basis of their seasonal adaptability.

### Chemical composition of azolla

The chemical composition of a given azolla species varies from season to season (Li



**1.** Multiplication rate of 4 azolla species at 3 temperature ranges.

Table 1. **Amount of nitrogen fixed by various azolla species in different seasons.**

| Species | N fixed by azolla (g/m$^2$) | | | | Nitrogen fixed during the whole year (t/ha) |
|---|---|---|---|---|---|
| | Spring<br>May - Jun | Summer<br>Jul - Aug | Autumn<br>Sep - Oct | Winter<br>Nov - Apr | |
| *A. filiculoides* | 29 | 14 | 58 | 14 | 1.2 |
| *A. microphylla* | 25 | 40 | 31 | 1 | 1.0 |
| *A. caroliniana* | 36 | 24 | 40 | 8 | 1.1 |
| *A. imbricata* | 24 | 30 | 37 | 10 | 1.0 |

et al 1982). Even when different species are grown under similar conditions, some differences in chemical composition are observed. *A. microphylla,* for example, is rich in Ca and Fe and has the highest lignin content of any of the four species studied. *A. filiculoides* was highest in N, K, cellulose, and crude protein, but lowest in Fe, Mn, Cu, and Zn.

Azolla species may be classified into three types for use in Eastern China on the basis of mineralization, N-fixing ability, and nutrient composition, as well as practicality as fertilizers for rice production:

1. Cold tolerant, heat intolerant. Optimum growing temperature: 20° C; minimum: below 0° C; maximum: 38° -40° C. Representative species: *A. filiculoides.* Use: in early rice.
2. Heat tolerant, cold intolerant. Optimum growing temperature: 25°-30°C; minimum: 8° -5° C; maximum: 45° C. Representative species: *A. microphylla.* Use: in single cropped rice or late rice nurseries.
3. Cold and heat tolerant. Optimum growing temperature: 25°-30° C; minimum: 0°C; maximum: 45°C. Representative species: *A. imbricata, A. caroliniana.* Use: in early rice of triple cropping systems, medium and early medium rice.

## SEXUAL REPRODUCTION OF AZOLLA

The routine propagation of azolla has been improved in recent years (Lui 1978, FAO 1978). For instance, the “double narrow row method” for culturing azolla most of the year is one of the best methods. Nevertheless, the key problem of propagating azolla and maintaining seedlings over winter or summer has not been solved. Since *A. filiculoides* was introduced and widely adopted in Eastern China, maintaining the azolla seedlings through the winter is no longer a problem. Maintaining the seedlings through the summer, however, is a continuing problem (Cheng 1978). Although the vegetative lobes of *A. filiculoides* are injured easily by hot weather, its sporocarps survive. The technique of using *A. filiculoides* sporocarps to maintain the seedlings through the summer has proved effective in the field (ZRG 1981). There are three problems in the sexual reproduction of azolla: nature of sporulation, collection of sporocarps, and nourishing the seedling.

### Nature of sporulation

There is evidence that variations in sporulation rate and number of sporocarps of *A. filiculoides* are closely related to temperature. Observation of the dynamics of sporulation in a nursery field during the summer showed that sporocarp formation commenced at an average air temperature over 13° C (ranging from 6.5° to 26.5° C). Sporocarps developed rapidly after the temperature rose, but declined sharply when the field temperature exceeded 25° C (Fig. 2). At that time, the azolla sporocarps matured and sporulation ceased.

The peak period of *A. filiculoides* sporulation in Eastern China was the 30 days from mid-May to mid-June.

In addition to temperature, sporulation of *A. filiculoides* was related to the morphological stage of the azolla lobe and to fertilization management. Generally, by controlling the nutrient status, a higher yield of sporocarps can be realized, which, in Eastern China, is about 225 kg sporocarps/ ha.

### Collection of sporocarps

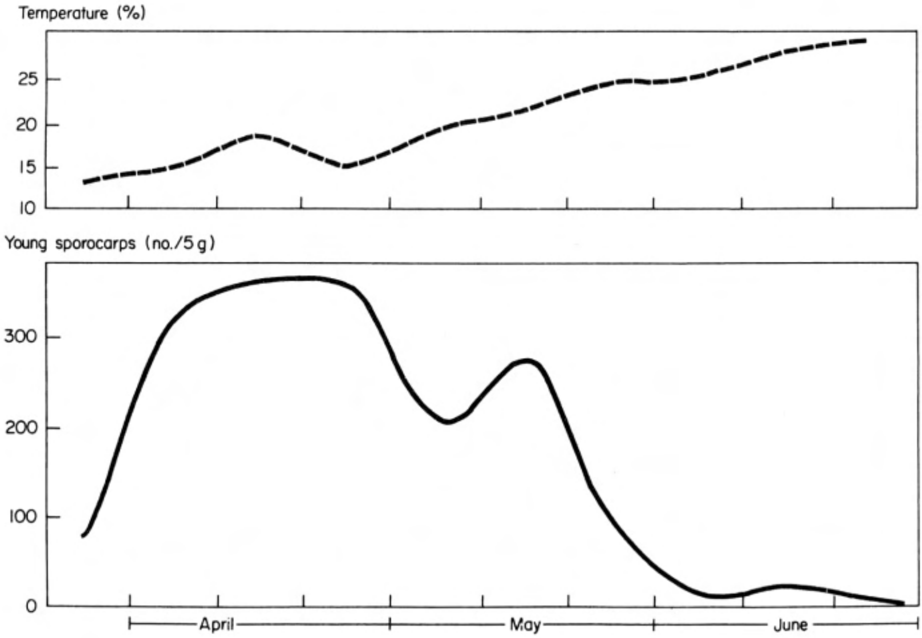
There are two methods for collecting azolla sporocarps:

1. The dried screening method.
2. The water floating method.

The efficiencies of the two collection methods are shown in Table 2.

### Nourishing the azolla seedling

When the sporocarps are well maintained through the summer, they develop into seedlings sooner in autumn. It is essential to avoid germinating sporocarps under strong light. Light intensity should be held below 25 klx, about one third the level of



**2.** Relation between temperature and azolla spore production.

**Table 2. Effect of collection of azolla sporocarps from various methods.**

| Collection method | Azolla fresh wt (kg) | Megaspores (x $10^3$) Calculated number | Megaspores (x $10^3$) Number collected | Rate of collection (%) |
|---|---|---|---|---|
| Dried screening | 10 | 1528 | 236 | 15.5 |
| Water floating crushed, floating | 10 | 1428 | 566 | 37.0 |
| Decayed, floating | 5 | 764 | 402 | 52.7 |
| Comprehensive, floating [a] | 7.5 | 328 | 293 | 89.4 |

[a] Total of crushed and decayed.

natural light during the early autumn. A temperature range of 15°-20° C and relative humidity of 85% should be maintained.

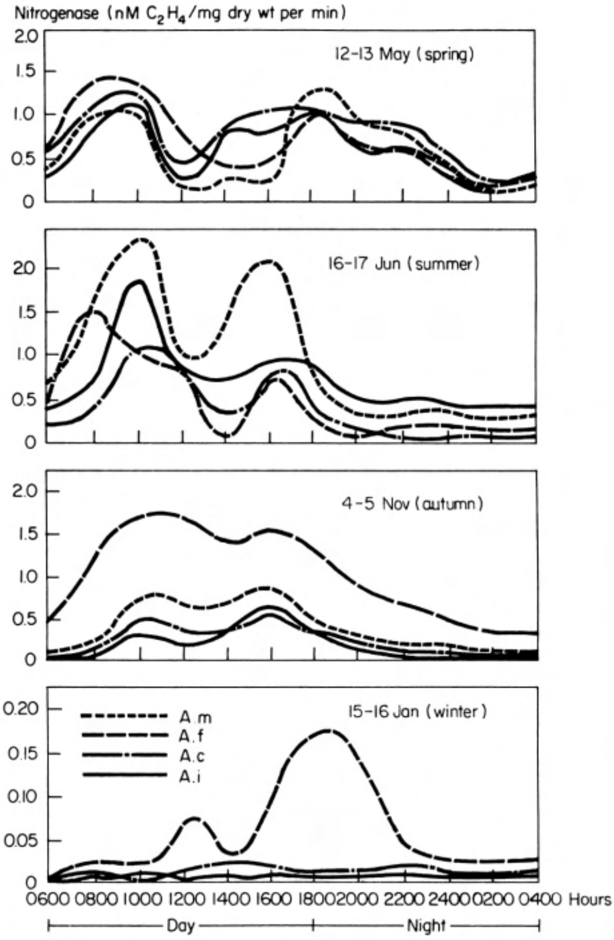
Sporocarps should not be sown directly in the water layer of the flooded nursery bed. Instead, a moistened nursing method in diversified nurseries is preferred. The optimum sowing time of sporocarps in Eastern China is from the end of August to the middle of September. Mixing soil with sporocarps before they are sown ensures uniform coverage. The sporocarps will germinate within 7 days after seeding, exhibit vigorous growth within 10 days, and be fully lobed in 12-15 days. It is necessary to provide adequate nutrients for the young seedlings by using a culture solution containing 15-30 ppm N, 30-40 ppm P, and 10-20 ppm K.

## NUTRIENT REQUIREMENTS AND N-FIXING ACTIVITY OF AZOLLA

Numerous studies discuss the nutrient requirements of azolla, but few of them focus on the seasonal nutrient requirements of different species (Singh 1972, Watanabe 1978, Zhang 1981). In general, P has the greatest effect on multiplication of azolla in every season of the year (Lu et a1 1966). Applied N usually restricts azolla growth and reduces nitrogenase activity by disturbing the normal growth of azolla (Lui 1979). Potassium is most important for growth only at low temperature. The nutrient requirements of various species are similar, yet there are individual differences mainly because of their differing temperature tolerances (Yu 1982). Applying P in autumn resulted in the highest net multiplication value.

The daily N-fixing activity of azolla usually varies with light intensity, temperature, and the population density of azolla. The amount of N fixed at night is about 25-30% of that fixed during the day. Nitrogen-fixing activity was 8-10% higher on sunny days than on cloudy or rainy days. Therefore, it is necessary to have a complete evaluation of the N-fixing ability of certain species based on continuous observation of the N-fixing activity over several seasons.

The seasonal variations of day and night N-fixing activity of four azolla species are shown in Figure 3. There were two peaks of N-fixing activity in the day (0800-1000 and 1600-1800 hours) in spring, summer, and autumn. N-fixation dropped sharply at noon because of the relatively higher temperature (>30°C) and strong light (>60 klx) conditions. *A. microphylla* showed the strongest N-fixing activity in summer. *A. filiculoides* had the dominant N-fixing activity in the autumn.



**3.** Typical seasonal variation in daily N-fixing activity of 4 azolla species.

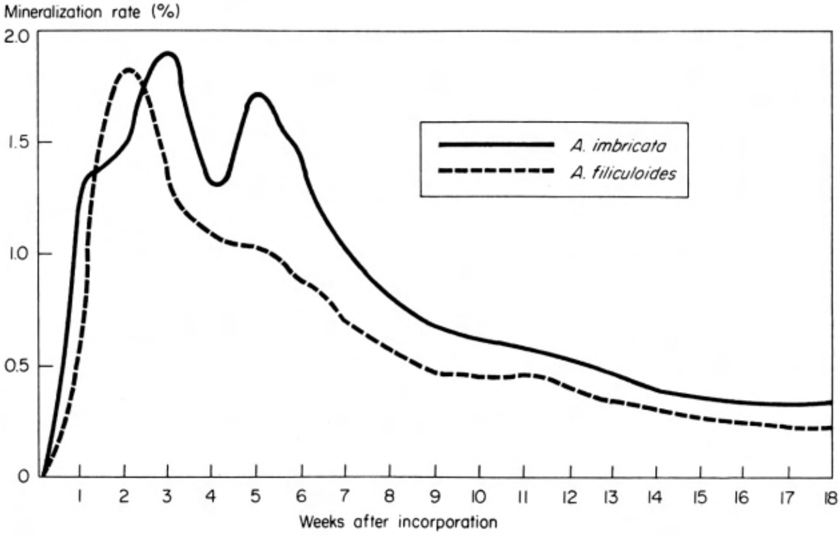
In winter, the N-fixing activity of *A. microphylla* ceased, *A. caroliniana* and *A. imbricata* merely survived, and *A. filiculoides* maintained weak activity.

## MINERALIZATION OF AZOLLA IN PADDY SOIL

Under flooded soil conditions, the rate of mineralization and the amount of nutrients released from the decomposition of azolla biomass are important indices of the availability of mineral nutrition for rice. Understanding these indices is important not only for improving techniques of azolla propagation and incorporation, but also for controlling the balance of soil nutrients.

### Peak of mineralization

Results of studies with $^{14}CO_2$ indicated that mineralization of azolla biomass peaked at 2-3 weeks after incorporation into the soil and then declined markedly by the 9th



**4.** The mineralization of azolla in paddy soils.

week (Fig. 4). There was a relationship between the rate and amount of mineralization of species with different C:N values (Shi et al 1980). For instance, mineralization of *A. imbricata* and *A. filiculoides* differed according to their different C:N values. *A. imbricata* showed a significant amount of mineralization within 2 days after it was incorporated into the soil; however, *A. filiculoides* did not begin to be mineralized until 5-7 days after incorporation. At the peak phase in the third week, the amount of mineralization of *A. imbricata* was 12.33% of the total C added, but that of *A. filiculoides* was only 11.07%. Six weeks later mineralization of A. *imbricata* was 59.55% of the total and that of *A. filiculoides* was 57.6%. *A. imbricata,* which has a low C:N value, consistently has a larger amount of mineralization than *A. filiculoides,* which has a higher C:N value (Wang 1982).

## Nitrogen availability

The released N of azolla can be utilized by the present rice crop and by subsequent crops via some residual effect (Shi et a1 1980). The amount of N absorbed from azolla by the rice plant is an index of the efficiency of azolla as a green manure.

**Table 3. Recovery of nitrogen from *A. filiculoides* by crops in different seasons.**

| Site | C:N | Recovery of $^{15}N$ (%) | | |
|---|---|---|---|---|
| | | 1st crop | 2nd crop | |
| | | Early rice | Late rice | Buckwheat |
| Hanzhou, Zhejiang | 11.2 | 14.8 | 5.3 | – |
| Nanking, Jiangsu | 11.6 | 20.4 | – | 4.3 |
| Wushi, Jiangsu | 12.0 | 17.3 | 1.3 | – |

**Table 4. Effects of azolla management practices on yield of early rice.**

| Azolla species | Yield (t/ha) | | |
|---|---|---|---|
| | Topdressed | Basal | Basal + topdressed |
| *A. caroliniana* | 4.96 | 5.59 | 5.93 |
| *A. imbricata* | 5.25 | 5.57 | 6.11 |
| *A. filiculoides* | 5.13 | 5.60 | 5.73 |
| N fertilizer (60 kg N/ha) | 5.65 | 5.65 | 5.65 |
| Control | 4.75 | 4.75 | 4.75 |

The rate at which rice recovers N from azolla has been computed with the difference method to range from 24.6 to 39.7% (Tsai et al 1962). When the same species of azolla was applied to different soils under rice culture, the recovery rates were quite different (Shi et al 1980), indicating that some inherent soil properties affected the efficiency of azolla as green manure on rice. Recently, the rate of N recovery was determined in a pot experiment with $^{15}$N-labeled azolla (Table 3). When azolla was incorporated into flooded soil, the N recovery rate in the first crop (rice) could be as high as 20.4%. The residual effect in the second crop (late rice or buckwheat) was 4.3% for buckwheat and 5.3% for late rice. In the third crop, the residual effect was equal to or less than the organic N availability of the native soil.

### Consumption of soil organic carbon

The relation between the consumption and accumulation of soil organic C due to the application of fresh green materials to soils is a critical problem because it directly influences soil fertility (Cheng et a1 1981). Azolla can supply a considerable amount of organic C when it is repeatedly incorporated into the soil over time; however, the consequent priming effect of incorporated fresh azolla will consume a portion of the native soil C (Lin et a1 1980). Current studies (Wang 1982) have found that it takes fresh azolla applied at a rate of at least 22.5 t/ha to overcome C loss caused by the priming effect and gain some C accumulation. The results from a pot experiment suggest that a reference index be used for achieving a realistic balance between the application of azolla and the conservation of soil fertility in practice.

## EFFECT OF AZOLLA MANAGEMENT PRACTICES ON RICE YIELD

Because the native species *A. imbricata* is not cold tolerant and thus multiplies slowly in the early spring, farmers of Eastern China usually inoculate the azolla between rice rows as an intercrop and then incorporate it into the soils as topdressed manure. After the cold-tolerant species *A. filiculoides* was introduced, it was possible to multiply a moderate quantity before transplanting the rice and apply it to the paddy field as a basal manure. Whether azolla is used as a topdressing or as a basal manure, its effect on rice yields is the same, and it has been adopted widely in rice production (Moore 1969, Lumpkin et al 1980). The effects of different azolla management practices on yield of rice are shown in Table 4. The dominant effects on yield of the basal + topdressed treatment seem to have resulted from the increased time for growing azolla and the supply of more nutrients between applications.

## REFERENCES CITED

Cheng, C. F. 1978. The sporocarp and cultured young sporophytes of *Azolla imbricata.* Acta Bot. Sin. 20(1):54-58.

Cheng, L. L., Q. X. Wen, S. L. Wu, and N. Xu. 1981. The effect of chemical composition and decomposition conditions of plant materials on the newly formed humus. Acta Pedol. Sin. 18(4):360-367.

Food and Agriculture Organization (FAO). 1978. China: Azolla propagation and small scale biogas technology. Soils Bull. 41:l-20.

ISF (Institute of Soil and Fertilizer), Zhejiang Academy of Agricultural Science. 1975. Cultivation, propagation and utilization of azolla. Agricultural Press, Beijing, China.

Li, Z. X., L. S. Ye, and L. F. Yu. 1964. Studies on promoting the yield effects by divided incorporation of azolla in paddy fields. Zhejiang Agric. Sci. 5:243-247.

Li, Z. X., S. X. Zu, M. F. Mao, and T. Lumpkin. 1982. Study on the utilization of 8 azolla species in agriculture I. An investigation of their utilization properties. Chinese Agric. Sci. 1:19-27.

Li, Z. X., S. X. Zu, M. F. Mao, and T. Lumpkin. 1982. Study on the utilization of 8 azolla species in agriculture II. An investigation on their cultivation in paddy fields and utilization methods. Chinese Agric. Sci. 2:72-77.

Li, Z. X. 1982. Nitrogen fixation by azolla in rice fields and its utilization in China. Symposia paper I. Transactions of 12th ISSS:83-95.

Lin, X. X., L. L. Cheng, S. L. Shi, and Q. X. Wen. 1980. Characteristics of decomposition of plant residues in soils of southern part in Jiangsu Province. Acta Pedol. Sin. 17(4):319-327.

Liu, C. C. 1978. Studies on cultivation of azolla in the rice fields for most of the year. Institute of Soil and Fertilizer, Fukien Academy of Agricultural Sciences. Paper presented at the National Azolla Research Conference, Jan 17, 1978.

Liu, C. C. 1979. Preliminary studies on the physiological characteristics of azolla. Chinese Agric. Sci. 2:63-70

Liu, C. C. 1979. Use of azolla in rice production in China. Pages 375-394 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Lu, S. Y., K. C. Cheng, and Z. H. Sun. 1963. Biological features of azolla: as a green manure in paddy fields. Chinese Agric. Sci. 11:35-40

Lu, S. Y., C. P. Chao, and K. C. Cheng. 1966. Effect of P on the multiplication and N-fixation of azolla. Soil Sci. Bull. 2:7-9.

Lumpkin, T., and D. L. Plucknett. 1980. Azolla: botany, physiology and use as a green manure. Econ. Bot. 24(2):133-134.

Moore, A. W. 1969. Azolla biology and agronomic significance. Bot. Rev, 35:17-34.

Shi, S. L., Q. X. Wen, and H. Q. Liao. 1980. The availability of N of green manures in relation to their chemical composition. Acta Pedol. Sin. 17(3):240-246.

Singh, P. K. 1972. Multiplication and utilization of fern "Azolla" containing N-fixing algal symbiont as green manure in rice cultivation. Estratto da Rivista IL RISO Anno.

Tsai, D. C., J. C. Chao, and L. L. Cheng. 1962. Studies on the propagation and utilization of azolla, a green manure in paddy fields. Soil Sci. Bull. 4.

Wang, T. S. 1982. Studies on the dynamics of the mineralization rate and nutrients releasing of azolla (Unpublished).

Watanabe, I. 1978. Azolla and its use in lowland rice culture. Soil Microb. Japan.

Yu, L. F. 1982. Study on the N, P, K requirements of various azolla (Unpublished).

Zhang, W. M. 1981. Studies on the effects of N, P, K of three azolla. Zhejiang Agric. Sei. 4:191-194.

ZRG (Zhejiang Provincial Research Cooperation Group) for the Techniques Applied of Sporocarps of *A. filiculoides.* 1981. Studies on the technology of nursing seedlings from sporocarps. Zhejiang Agric. Sci. 4:185-190.

## DISCUSSION

OH: How far can the growth of azolla be extended in north China?

*LI:* As of now, we can propagate azolla moderately just to the southern part of the Yangtze River, where the annual average temperature is around 15° -20° C.

OH: Azolla can fix about 1 t N/ ha per year. If you produce azolla in good quality and use it properly, you can save a large amount of chemical fertilizer, which may mean that you can also save energy. What is your opinion about this?

*LI:* I agree very strongly with your comments.

LEE: Is there any practical stock culture method for use over the winter?

*LI:* In the case of some azolla species that are not cold tolerant, we may adopt the stock culture method to keep the seedlings safe over the winter.

ROSALES: Of the total N composition of azolla, what do you think is the percentage fixed from the atmosphere and what amount comes from the water? What method did you use in measuring the percentage N coming from the atmosphere?

*LI:* Since the experiment on azolla propagation was conducted in a no-N solution, we confirmed that the accumulated N in the azolla was all fixed by the symbiont *Anabaena* from the atmosphere.

HESSE: When I was in China looking at azolla, it was exclusively *A. pinnata.* Do we understand that you have given this up now?

*LI: A. imbricata* was the only species used in China for many years. At the end of the 1970s, *A. filiculoides* was introduced from East Germany. Meanwhile, we have also introduced the other azolla species such as *A. pinnata* for experimental purposes but not in rice production.

AGBOOLA: The soils in the humid tropics are highly weathered and we have to use inorganic fertilizer to grow legumes. It has also been reported that N affects the N-fixing ability of legumes. What has been the effect of inorganic fertilizer, especially N, on the N-fixing ability of Azolla spp?

*LI:* Nitrogen usually restricts the growth of azolla in ordinary conditions because of the activity of nitrogenase in the applied N fertilizer, which disturbs the normal growth of azolla.

AGBOOLA: It is hard for me to evaluate the contribution of azolla to the nutrient status of your soil because your paper does not contain the analysis of the soil used. Could you please supply the chemical composition of the source of the experimental soils?

*LI:* My experiment was conducted on the farm of Zhejiang Academy of Agricultural Sciences where the soil is derived from alluvial deposits and has the texture of loamy clay. The chemical composition of that soil was pH 6.7, C 1.81%, N 0.16%, P 0.08% and K 1.94%.

NAGAR: Do you encounter in China location-specific problems in the use of azolla for rice crops?

*LI:* Generally speaking, we have encountered some technical problems such as finding an adaptable azolla species, retaining the azolla seedling safety over the summer or winter, promoting the rate of multiplication of azolla, and improving the efficiency of incorporating azolla into the soils in different regions.

AMIEN: Since you are also using azolla as feed, do you have any data on the protein and vitamin contents of azolla?

*LI:* We have analyzed the crude protein content of various azolla and found a range of 26-35%, but we have not analyzed vitamin content.

# THE UTILIZATION OF ANIMAL AND HUMAN WASTES IN RICE PRODUCTION IN CHINA

Cong-yi Yuan

The amounts of animal and human wastes that can be utilized and of the nutrients they can provide for rice production in China are estimated. The collection, preservation, and preparation of the wastes, as well as methods of application, are described.

A unique manure-waterlogged compost — processed by mixing animal and human wastes with straw, green manure, and a large amount of sludge under anaerobic conditions — displays a number of beneficial effects on rice plants.

Some distinguishing features of small-scale biogas technology in China are briefly illustrated: the unique design of the biogas unit, the lower construction expenditures, and the efficient use of effluents for improving soil fertility.

The combination of organic with inorganic fertilizers is most desirable as far as the productive efficiency of manures and efficiency of N in manures are concerned.

Animal and human wastes have been utilized in rice production in China for thousands of years to increase yields and to maintain soil fertility. During the past 3 decades, although chemical fertilizers have been widely used, the utilization of animal and human wastes has not been neglected and is even being improved.

In China, crop growing is closely integrated with animal husbandry in cropping areas. Crops provide food and other farm products for humans and feed for animals. Animal husbandry provides meat, milk, and other products for people, as well as manure for crop growing. Thus, a relationship of mutual dependency has been formed between crop growing and animal husbandry.

"Turning wastes into valuables" is a tenet of Chinese farmers. Yuan et al (1981) noted that the recycling of organic matter and mineral nutrients should not only be regarded as a benefit of traditional agriculture but also become a part of modern agriculture.

## ANIMAL AND HUMAN WASTES AS RESOURCES IN RICE PRODUCTION

Pigs are the major farm animals in rice regions in China. The other common farm animals are cattle, mostly working animals, and a few goats and sheep. In 1979, each

---

Associate professor and deputy director, Institute of Agricultural Modernization, Jiangsu Academy of Agricultural Sciences, Nanjing, China.

hectare of rice-growing area had 4.6 pigs, 0.6 cattle, and 0.7 goat or sheep on the average. The amount of animal and human wastes that could be collected in rice areas is estimated at an average of 17.6 t/ha.

The C, N, P, and K contents of animal and human wastes were calculated; from those values the losses in storage and preparation were deducted. The resulting values indicate that 475 kg C, 38 kg N, 13 kg P, and 44 kg K could be added to each hectare of rice land (Table 1).

## COLLECTION, PRESERVATION, AND PREPARATION OF ANIMAL AND HUMAN WASTES FOR FERTILIZER

### Night soil

In villages in the rice regions, night soil is collected daily and stored in large, glazed earthen vats to prevent loss from leaching. However. the volatilization loss is still significant. Some reports place the loss of total N at 56-69% after 78-90 days of storage in open pots, whereas the loss was 45% in shaded pots and 25% in covered, shaded pots (Institute of Soil and Fertilizer, Chinese Academy of Agricultural Science 1962). It is evident that the method of preservation is extremely important, but unfortunately its importance has not been fully recognized and not all people in the countryside have used it.

Since night soil is rich in available nutrients, the storage period should be as short as possible to avoid loss of nutrients, particularly nitrogen; but from the viewpoint of sanitation, adequate storage is necessary to kill pathogenic organisms. It has been reported that the bacteria of cholera and typhoid can survive 2 weeks in night soil under storage, and the hatching rate of blood fluke is greatly reduced within that period. It is believed that $NH_3$ produced during storage plays an important role as a powerful detergent. Therefore, keeping the container airtight will lead to the best sanitary conditions (Institute of Soil and Fertilizer, Chinese Academy of Agricultural Science 1962).

In suburban areas, night soil can be mixed with garbage for making compost, in which the high temperature (above 60°C) will kill almost all organisms. In rural areas, using night soil as a raw material to evolve biogas is considered most appropriate for sanitary purposes; details will be discussed later.

### Animal wastes

Most families in rice areas raise one, two, or more pigs every year; some production teams or brigades breed hundreds of pigs each year. The pigs generally are raised in various types of pigsty, one type being the dry sty or bedding sty. The pigs excrete their waste into an open shallow pit near the living area. The collected excrement and slurry are discharged from the pit every 3 or 4 months and piled to allow rotting. This method is more beneficial to the pigs' health, but it causes severe leaching and losses of volatile nutrients.

A model prevailing in the lower reaches of the Changjiang River is quite different. The pigs are raised in a sty not more than a few square meters. The farmers put rice straw, dried mud, or stove ashes into the sty every day to absorb the liquid wastes. Day by day, as the pigs tread on the accumulated manure, a slow anaerobic rotting

**Table 1. Nutrients potentially returned from animal and human wastes to rice production in China (× $10^6$ kg).**

| | Nutrient (× $10^6$ kg) returned from | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Feces | | | | Urine | | | | Total | | | |
| | C | N | P | K | C | N | P | K | C | N | P | K |
| Humans | 941 | 103 | 33 | 46 | 566 | 208 | 37 | 87 | 1507 | 311 | 70 | 133 |
| Pigs | 8266 | 441 | 227 | 546 | 1187 | 297 | 71 | 633 | 9453 | 738 | 298 | 1179 |
| Cattle | 4704 | 191 | 75 | 106 | 102 | 36 | 1 | 58 | 4806 | 227 | 76 | 164 |
| Goats and sheep | 357 | 16 | 6 | 8 | 6 | 3 | 1 | 5 | 363 | 19 | 7 | 13 |
| Total | | | | | | | | | 16129 | 1295 | 451 | 1489 |
| Av[a] (kg/ha) | | | | | | | | | 475 | 38 | 13 | 44 |

[a] 33.94 × $10^6$ ha rice were grown in 1979. After "1980 China's Yearbook of Agriculture" (Taiwan, China, not included).

process goes on. After several months, the manure is taken out and can be either applied directly as basal manure or topdressed after a few weeks of heaping for further decomposition. If sufficient litter has been used, the loss of nutrients is not serious; the manure is rich in organic matter and mineral elements and is regarded as a good soil amendment. However, this method is adverse to the health of pigs.

A third method is the wet sty or flush sty (Zou and You 1961). The floor is constructed of impermeable material such as brick or concrete. The excreta are flushed with water into channels underneath slotted alleys or into pits outside the sty. The liquid manure contains much water but fewer solids, so it is more adaptable for topdressing than for basal dressing. Such a sty is quite sanitary, and the loss of nutrients is insignificant if the pit is free from leaching and well covered. But the ground is too cold for pigs to lie on during the winter months, so the farmers usually add beddings and transform it into dry sty.

A recent development is the merger of latrine, pigsty, and biogas-pit into an integrated “three-in-one” unit. Animal and human wastes are flushed directly into the biogas-pit, saving labor and providing excellent sanitary conditions. Because this method has many advantages, it is now being promoted in many parts of China.

Many studies have been done to reduce the loss of N in storage and preparation of animal wastes. It has been reported (Institute of Soil and Fertilizer, Chinese Academy of Agricultural Science 1962) that liquid pig manure at a concentration of 0.17% N lost 41.2% of its N after 1 month of storage in an open pit, but only 14.7% in a covered pit. The easiest way to reduce N loss in pig manure is to seal the manure pile with mud. Liang et a1 (1961) reported that the N loss after 39 days of mud-sealed storage was only 5.8%. Adding an equal part of dry soil to pig manure resulted in a loss of 19.3%, and the loss was as high as 49.4% for the ordinary piling.

An interesting controversy in the early 1950’s was the use of stove ashes (generally the remains of burned rice straw) as the bedding material for pigsties. Some scientists claimed that alkaline ashes might accelerate the decomposition and volatilization of N compounds and thus should not be used. But experienced farmers insisted that this was not so, creating the impetus for research studies. Zhu and Gao (1964,1965) carried out five experiments in pots and in pigsties. They found that under compact and excessive moisture conditions, anaerobic decay took place within the pig manure. The amount of nitrates formed was little (only 1% of the total N), and denitrification loss was negligible. On the other hand, $NH_3$ and $CO_2$ were evolved to an extent near saturation and combined with each other. Under such conditions, they were preserved in a comparatively steady state. The active C remaining in the ashes played an important role in the absorption of ammonia.

## APPLICATION OF ANIMAL AND HUMAN WASTES

Animal and human wastes can be either topdressed or basally applied to rice fields. Generally, night soil or liquid manures are surface broadcasted, preferably after plowing, when the furrow slices become dry, to facilitate absorption by the soil. The application rate may be 8-15 t/ha. Pig manure at 15-20 t/ha is evenly spread; then the paddy is flooded and harrowed promptly to obtain a faster and more economical effect. If the application rate is more than 20 t/ha, the manure may be spread over the ground and plowed into the soil at greater depth to make it more durable.

For topdressing, night soil or pig dung should be diluted with water and splashed into the paddy at the late tillering stage, after the field has been dried; the water layer is then reestablished 1 or 2 days later. The rotten pig manure may also be topdressed, provided that a water layer of 2-3 cm is present in the paddy, which will be irrigated a few days later. Usually, the application rate will be 8-15 t/ ha.

## WATERLOGGED COMPOST

Waterlogged compost is a unique manure that has been widely used in the middle and lower reaches of the Changjiang River. Unlike ordinary compost, it contains large amounts of sludge and decomposes under waterlogged conditions. Therefore, the raw materials, the method of preparation, and the microbiological activity are quite different from those of compost. There are two kinds of waterlogged compost, basically the same, but with some minor differences: Chao-tang sludge, used in the lower reaches of the Changjiang, and Dang-manure, used in the middle reaches of the Changjiang.

### Preparation

To prepare Chao-tang sludge, circular pits with a diameter of 2 m and a depth of 1.6-1.7 m are dug in paddy fields in early spring. A low, narrow mud dike is built around each pit. Sludge, previously collected from the river bottom and temporarily stored in shallow pits located on the bank, is mixed with chopped rice straw. In early May, when milk vetch has grown up, the sludge that has been mixed with rice straw, green manure, and pig manure is placed in the pits and watered. A water layer a few centimeters deep is maintained. Three or four days later, bubbles, mostly methane, evolve continuously, and a brownish-red colloidal substance floats on the surface. Two weeks later, the contents in the pit may be turned over and more water and animal or human wastes may be added. After another 2 weeks, the compost will be ready for use as basal manure for rice plants.

In the preparation of Dang-manure, pits are dug in fallow paddy fields, especially those that have held water. The pits are only 10-20 cm deep and are surrounded by low, narrow dikes. Grasses, sludge, or other wastes are put into the pits in winter. Animal or human wastes, or both, are added in early spring to regulate the C-N ratio. Lime is necessary if the soil is acidic. When rotting is completed, more pits are dug in the same field and the rotten manure in the original pits can be used as an inoculant for the new pits (Yu et a1 1955).

### Characteristics

The decaying process in waterlogged compost takes place under ordinary temperatures (12° -22° C in early spring) and under a layer of water, thus making it distinct from aerated compost, which generates higher temperatures and exists under aerobic conditions.

The following materials are needed for building up a Chao-tang pit with a volume of 17 m$^3$: milk vetch, 0.35 t; rice straw, 0.8 t; pig manure, 1.5 t; sludge, 16 t. A mixture with an initial C:N of 20-25 will be obtained. The amount of processed sludge in the pit can provide the basal fertilizer for 0.5 ha of paddy. Some of its major chemical indexes are: pH 6.4, moisture 50%, N 0.24%, P 0.17%. loss on ignition 9.3% (Liu 1958).

Some characteristics of the rotting process of Chao-tang sludge were studied (Nanjing Pedology Institute, Academia Sinica and Waxi Agricultural School 1960). The pH decreased to 6.3-6.8 in the first 3 days and then rose to 6.8-7.0 and stabilized. The Eh decreased to 25 to–25 mV in 6-9 days, indicating that an anaerobic process was taking place. Meanwhile, the organic carbon contained in the raw materials was gradually transferred into the sludge. The organic matter content in the silty portion was 6.0% after 23 days but increased to 7.1% after 60 days. Meanwhile, the total N and hydrolyzable N tended to increase, and the exchangeable K increased twofold, but the variation of available P was not detectable. Pot trials confirmed that the isolated silty portion from Chao-tang sludge had very beneficial and durable effects on the growth of rice plants. Because Chao-tang sludge is rich in both readily available and moderately available nutrients, a grain yield of 6 t/ ha can be easily obtained with an application rate of 40 t Chao-tang sludge/ ha with no additional fertilizers.

The researchers also found that the active humus formed in the decomposing process can chelate $Fe^{++}$ effectively. That might greatly reduce the detrimental effects of $Fe^{++}$ on rice plants. An experiment showed that rice plants were killed quickly in a culture containing 200 ppm $Fe^{++}$ but survived in the same culture plus an extract of Chao-tang sludge.

It has been found that the N loss in Chao-tang sludge is not more than 3-5%, when the $NH_4$-N content in it makes up 10-20% of the total N. That can be explained by the regular temperature, neutral and anaerobic decomposing conditions, and presence of a large amount of sludge. On the contrary, the N loss in aerobic compost reaches as high as 40% (Yuan and He 1980).

### Problems in collection and preparation

The labor cost of collecting and preparing waterlogged compost is very high. About 180 person-days/ha are required, and the process is difficult to mechanize. Therefore, the application is restricted mainly to intensive rice production areas, and it is doubtful if waterlogged sludge is universally applicable.

## SMALL-SCALE BIOGAS PRODUCTION

The incorporation of animal or human wastes, or both, with other organic waste materials to produce biogas is not novel, nor is the technology confined to China. However, there are a number of distinguishing features in Chinese biogas technology: the unique design of the units wherein the digester acts also as the gas holder; lower expenditure on the construction of biogas units by using locally available materials and communal labor; and the efficient use of the effluents for improving soil fertility. These factors have made small-scale biogas units popular in the recent decade over most of the rice-growing areas in China and have attracted a number of interested foreign scientists.

### Design, construction, and management of the biogas unit

The design, construction, and management of the biogas unit have been described in detail in a report made by the Study Group organized under the FAO/UNDP program in cooperation with the People's Republic of China (FAO Soils Bulletin 41, 1978).

In the most common type of small-scale biogas unit constructed in China, the complex and costly metal gas holder being used in other countries (Indian Ministry of Agriculture 1975) is replaced by a dome-shaped structure. In general, the biogas unit is constructed completely underground in an open space not far from the house, or inside the house underneath the kitchen or animal stalls to save land and to improve temperature conditions for fermentation. Such a biogas unit can be built with locally available materials by well-trained personnel.

The size of the household biogas plants in China is determined by the amount of gas required for daily use. Usually the size ranges from 6-10 $m^3$, which can meet the cooking and lighting needs of a 4- to 6-person family. A typical 10-$m^3$ biogas unit is shown in Figure 1. Its cost is estimated at $60, exclusive of labor.

### Operation and management of biogas units

*Raw material input.* The raw materials used for household biogas production are of two kinds:

1. source of C such as straw, grasses, water weeds, and other agricultural remains;
2. source of N such as animal and human wastes and legumes.

Generally, raw materials are prepared in different combinations to make the C:N of the mixture around 25. A high C:N leads to an insufficient supply of N and produces biogas very slowly. On the other hand, in a mixture with a low C:N, production cannot be sustained for a long time and causes greater loss of N (Shen et al 1982). It was found (Department of Soil and Fertilizer, Guangdong Agricultural Research Institute 1959) that a mixture with a C:N of 20.2 produced more biogas than mixtures with a C:N of 30 or 9. In practice, a combination of 1 part rice straw with 5-10 parts animal or human waste, or both (in fresh weight), is often adopted.

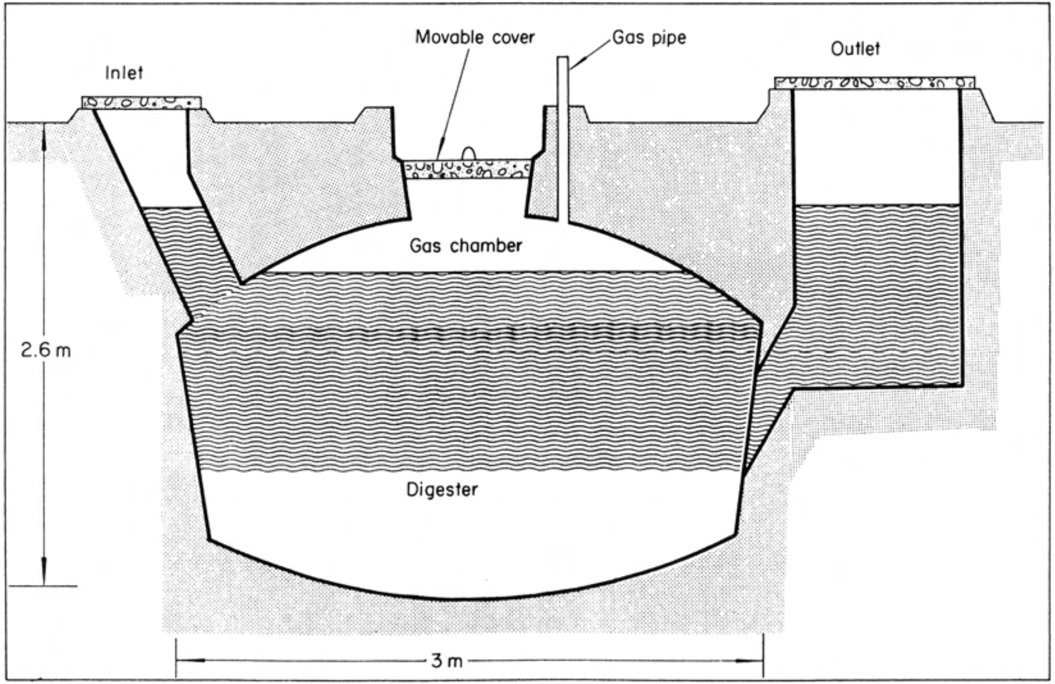
*Loading.* Since the Chinese household-size biogas units are of the batch-feed type and most of the ingredients are mixed and loaded at one time, the batch-feed input should preferably contain a larger proportion of C-source material; the N-source materials are continuously added later (Biogas Study Group, Nanjing Geology and Palacontology Institute and Nanjing Pedology Institute 1975).

Water is added after loading, resulting in a dry matter content of about 10% by weight in the mixture.

In some cases, straw or grass is composted with biogas slurry for a few days before loading. This helps to produce biogas immediately after loading.

*Management.* Biogas is produced 3-5 days after loading, slowing down about 1 month later. A daily supplement of raw materials is necessary to ensure regular production. In the "three-in-one" units, a certain amount of excreta flows into the digester every day, making the loading work much easier.

Stirring the fermenting mixture would enhance bacterial activity and result in more gas production. But the present small-scale units are not fitted with a stirring



**1.** A 10-$m^3$ biogas unit (FAO Soils Bull. 41).

device. Daily addition of raw materials agitates the fermenting mixture to some extent.

When gas pressure in the digestion tank is increasing, or after the addition of raw materials, the effluent will rise in the outlet chamber. The surplus slurry must be taken away and can be used as fertilizer. Under normal conditions, the slurry can be discharged frequently for fertilizer; water is supplemented at the same time.

The digestion chamber is emptied of sludge before each periodic loading with fresh raw material, two or three times a year. Actually, the chamber is not completely emptied; 20-25% of the sludge is usually left to inoculate the new raw material.

## Agricultural use of effluents

Both effluents from the unit, slurry and sludge, are good sources of plant nutrients. Sludge is also regarded as a soil conditioner.

In the biological process of biogas production, about 40-50% organic C is transformed into gases, and only 3-5% N is lost. But in the open pit of waterlogged compost using the same raw material, 40-50% C and 20-30% N are lost. Besides, loss of P and K may be noticeable if leaching occurs in the pit.

In biogas slurry, N reaches a concentration of around 0.1%, soluble K ranges from 0.4 to 1.5%. In the sludge, nutrient contents on a dry matter basis are: 20-40% C; 1.3-2.6% N (in which hydrolyzable N makes up 1/4 to l/5); 0.5-0.75% P; and 0.9-1.0% K. The distribution of nutrients between the two components is: 13-25% of the N, 2% of the P, and 42-45% of the K in the liquid; and the balance in the sludge. This indicates that biogas sludge is a complex manure rich in most nutrients, and that the slurry is a valuable liquid manure rich in N and K.

Based on its agrochemical features, biogas sludge is used mostly as a basal fertilizer at 20 t/ ha, and the slurry is more often used for topdressing. Results of pilot experiments carried out in Shanghai by Shen et a1 (1982) show an increase in yield of 3-13%, mostly around 10%, for biogas sludge, as compared to that for waterlogged compost. It was also noticed that the poorer the tested soils were, the higher the yield increases.

## Ecological benefits

Agricultural production in China has been greatly dependent upon the proper utilization and recycling of organic matter. However, the shortage of fuel is a serious problem in the countryside. In most rice areas, about one-half to three-fourths of the straw is burned as fuel with a heat efficiency of 10-15%. When organic materials are transformed into biogas and used as fuel, the heat efficiency may reach 50-60%. A biogas unit of 10 $m^3$ running 8 months in a year can save 1,200 kg straw, which contains 500 kg C and 8 kg N.

The major benefits brought about through biogas production are:

- reducing the loss of N, P, K, and other nutrients by utilizing them in the preparation of fertilizer, leading to increased grain yields,
- saving fuel straw and putting it into the recycling of organic matter to improve soil fertility,
- less destruction of woods, shrubs, and grasslands, resulting in better soil and water conservation,

- easier cooking, thus releasing housewives from some of the burden of housework, and
- improving sanitary conditions.

## ROLE OF ANIMAL AND HUMAN WASTES IN RICE PRODUCTION

Some data concerning the utilization rate of N (Murayama 1979) in various kinds of manure are shown in Table 2. The yield increases per kilogram of nitrogen contained in basally applied manures as compared to check plots were 6- 19 kg for pig or cattle manure; and 5-17 kg for waterlogged compost. Both values are lower than those for chemical fertilizers (14-53 kg) but are much higher than the value for compost, 3-5 kg. Undoubtedly, the results can be related to the available N contained in those fertilizers. The utilization rates of N in various fertilizers were: stable manures, 7-14%; waterlogged compost, 15-20%; green manures, 15-30%; compost, 2-6%; chemical fertilizers, 66%. This pattern is similar to that shown in productive efficiency.

As shown in Table 3, not only the grain yield, but also the productivity and

**Table 2. Rice yield increases with application of organic N and the utilization rate of N in manures.**

| Cultivar | Fertilizer | Yield increase (kg/kg N) | Utilization rate of N[a] (%) | Source |
|---|---|---|---|---|
| Early japonica | Stable manure | 5.68 | 7.2 | Zhu et al(1980) |
| | Waterlogged compost | 11.6 | 20.1 | |
| | Milk vetch | 15.1 | 28.9 | |
| | Compost | 4.9 | 6.3 | |
| | Ammonium sulfate[b] | 21-29 | 65.7 | |
| Medium indica | Stable manure | | 13.6 | Zhu (1959) |
| | Waterlogged compost | | 14.9-15.6 | |
| | Green manure | | 17.0-17.7 | |
| Medium japonica | Stable manure | | 12.9-14.4 | |
| | Green manure | | 14.6 | |
| | Waterlogged compost | 4.88 | 15.6 | Zhu (1957) |
| | Compost | 3.38 | 2.1 | |
| Medium japonica | Pig manure | 19.4 | | Zhu et al(1960) |
| | Waterlogged compost | 14.2 | | |
| | Green manure | 8.3 | | |
| | Ammonium sulfate | 14.1 | | |
| Double-cropped rice | Cattle manure | 12.1 | | Institute of Soil and Fertilizer (1962) |
| | Pig manure | 9.5 | | |
| | Stable manure | 16.7 | | Nanjing Pedology Institute (1978) |
| | Compost and waterlogged compost | 16.6 | | |
| | Ammonium sulfate | 53.3 | | |

[a] Utilization rate of N = $\dfrac{\text{N absorbed by rice plants (under fertilization - check)}}{\text{N in manure or fertilizer}}$ . [b] Topdressed.

**Table 3. The productive efficiency and utilization rate of N of manures and of manures combined with fertilizer.[a]**

| Treatment[b] | | Rice yield | | Productive efficiency (kg grain/kg N) | | Utilization rate of N (%) | |
|---|---|---|---|---|---|---|---|
| | | t/ha | Increase by TD (%) | Manure | Manure + fertilizer | Manure | Manure + fertilizer |
| Check | TD | 3.5 | 127 | | | | |
| | No | 1.6 | | | | | |
| Stable manure | TD | 3.9 | 67.8 | | 11.5 | | 19.3 |
| | No | 2.3 | | 5.68 | | 7.2 | |
| Green manure | TD | 4.7 | 48.3 | | 17.7 | | 34.4 |
| | No | 3.2 | | 15.1 | | 28.9 | |
| Compost | TD | 4.0 | 84.8 | | 12.6 | | 29.5 |
| | No | 2.2 | | 4.94 | | 6.3 | |
| Water-logged compost | TD | 4.7 | 43.2 | | 14.6 | | 22.3 |
| | No | 3.3 | | 11.6 | | 20.1 | |

[a] Source: Department of Soil and Fertilizer, Chinese Academy of Agricultural Sciences, Jiangsu Branch, 1960. [b] Manures were applied basally at the following rates: stable manure, 135 kg N/ha; green manure, 111 kg N/ha; compost, 128 kg N/ha; waterlogged compost, 145 kg N/ha. Ammonium sulfate – 67.5 kg N/ha was used as top dressing (TD).

utilization rate of N were increased when organic manures were incorporated with chemical fertilizers, especially in stable manure and compost, which contain less available N. Furthermore, although the immediate productivity of manures is lower than that of chemical fertilizers applied to the first crop, higher residual effects can be expected in succeeding crops.

Due to great diversity in the components and preparation of various sources of animal and human wastes, as well as in the compost or waterlogged compost from such wastes, difficulties are encountered in making recommendations for application rates. Zhu (1959) noted that even though the application rates of manures in field trials were designed to give them the same level of total N, differences in productivity and N efficiency still resulted. Likewise, different values were obtained when the same manure was applied to early or medium cultivars of rice. Based on the results of field trials over 4 years, Zhu proposed the following productivity equivalents: for early rice: 1 kg N in stable manure = 0.38 kg N in green manure = 0.49 kg N in waterlogged compost= 1.15 kg N in compost made from grasses; for medium rice: 1 kg N in stable manure = 0.55 kg N in green manure = 0.7 kg N in waterlogged compost. During the early growth phase of early rice, the N supply from the soil is insufficient because of low temperature conditions, and manures containing a larger proportion of available N will meet the demand of rice plants to a greater extent and result in higher productivity. In medium rice, the N supply from the soil is greater, and the differences between manures are not as great as those shown with early rice. It is logical to infer that the differences will be still smaller for late rice.

Another report (Department of Soil and Fertilizer, Chinese Academy of Agricultural Sciences, Jiangsu Branch 1959) suggested a scheme for making

**Table 4. Effects of different combinations of organic and inorganic fertilizers on the yield and on the soil C and N content in a long-term experiment.** [a]

| Treatment (organic N : inorganic N) | Application rate[b] (t/ha) | | | Yield[e] (t/ha) | soil C (%) | soil N (%) | soil C:N |
|---|---|---|---|---|---|---|---|
| | C | N | | | | | |
| | | Organic[c] | Inorganic[d] | | | | |
| 0 : 0 | 0 | 0 | 0 | 3.0 | 1.25 | 0.130 | 9.6 |
| 0 : 10 | 0 | 0 | 0.89 | 3.9 | 1.20 | 0.134 | 9.0 |
| 3 : 7 | 5.12 | 0.3 | 0.61 | 4.4 | 1.41 | 0.144 | 9.8 |
| 5 : 5 | 8.53 | 0.5 | 0.45 | 4.7 | 1.48 | 0.146 | 10.1 |
| 7 : 3 | 12.0 | 0.7 | 0.27 | 4.4 | 1.54 | 0.149 | 10.3 |
| 10 : 0 | 17.1 | 1.0 | 0 | 4.0 | 1.64 | 0.168 | 9.8 |
| original soil | | | | | 1.42 | 0.141 | 10.04 |

[a] Source: Pers. comm. from Prof, D. M. You, Institute of Soil and Fertilizer, Jiangsu Academy of Agricultural Sciences. [b] Total application rate of Seven crops in 3 years. [c] Pig manure, 0.382% total N on the average. [d] Ammonium bicarbonate. [e] Av grain yield of seven crops of rice and barley.

recommendations for rice plants using manures as basal fertilizers. The total N requirement for a definite grain yield should be estimated; then the rate of application of one or more manures can be calculated based on the equivalents listed previously.

While manures alone have good effects on soil fertility, the combination of organic manures with inorganic fertilizers is preferable; but the actual optimum combination still has not been determined. Unpublished data from a long-term field experiment (Table 4) on the average yields of 7 crops in 3 years obtained from different combinations of organic and inorganic N show that the treatment of 5:5 gave the highest yield; the soil C and N content remained almost constant but a little higher than the initial levels. On the other hand, treatments of 3:7 and 0:10 gave lower yields and resulted in lower soil C and N. In treatments of 7:3 and 10:0, the soil C and N were increased, but the yields were not as high as with the 5:5 combination. So it appears that organic and inorganic N combined at 5:5 result in higher and more stable yields plus the maintenance of soil fertility. The 3:7 combination is acceptable if the organic manures are not sufficient. The regression line of yield on percentage of organic nitrogen was quadratic and highly significant ( $R^2 = 0.97$). The regression of soil carbon content on applied organic carbon was linear and highly significant ( $Y = 1.27 + 0.022x$; $r = 0.991$). The slope of 0.022 means that 2.2% of the amount of organic C applied to a paddy field was transferred into soil C under the experimental conditions.

## REFERENCES CITED

INCHINESE:

Biogas Study Group, Nanjing Geology and Palacontology Institute and Nanjing Pedology Institute. 1975. Biogas and biogas manure. Soils 4:166-171.

Department of Soil and Fertilizer, Chinese Academy of Agricultural Sciences, Jiangsu Branch. 1959. The comparative N efficiency in green manure, pig manure and sludge. J. East-China Agric. Sci. 5:213-216.

Department of Soil and Fertilizer, Chinese Academy of Agricultural Sciences, Jiangsu Branch, 1960. Report on fertility evaluation for farm manures on early-rice. J. East-China Agric. Sci. 5:236-238.

Department of Soil and Fertilizer, Guangdong Agricultural Research Institute. 1959. Fermentation experiment on biogas using farm manures. J. Guangdong Agric. 6:32-35.

Institute of Soil and Fertilizer, Chinese Academy of Agricultural Sciences 1962. An introduction to fertilizers in China. Shanghai Science and Technology Press. Shanghai.

Liang, Y., S. H, Quiao, F. X. Chen, W. X. He, D. Y. Liang, and Y. M. Hu. 1961. The role of pig manure on improving soil fertility and yield increase. Sci. Agric. Sin. 3:44-77.

Liu, M.L. 1958. Chao-tang sludge. J. East-China Agric. Sci. 1:39-94.

Nanjing Pedology Institute, Academia Sinica and Wuxi Agricultural School. 1960. Study on characteristics in decomposing process and effect of waterlogged compost. J. East-China Agric. Sci. 4:184-189.

Nanjing Pedology Institute. 1978. Soils of China. Science Press. Beijing. 368 p.

Shen, R. Z., H. F. Zhu, P. H. Cheng, and W. X. Huang. 1982. Study on effect of biogas manure on rice. Institute of Soil Fertility, Shanghai Academy of Agricultural Sciences. (Unpubl.).

Yu, Y. X., Z. H. Chen, and Q. M. Zhou. 1955. Investigation on Dang-manure. Central-China Agric. Sci. 1:42-46.

Yuan, C.Y., and F.C. He. 1980. Preliminary study on technology of compost in Tai-lake District, Jiangsu Province. Bull. Comprehensive Experimental Base, No. 12 Tai-lake District, Jiangsu Province.

Yuan, C. Y., Q. J. Zhao, J. Y. Chu, and N. Z. Liu. 1981. Investigation on mass-cycling of cropping systems in Tai-lake District, Jiangsu Province. Bull. Comprehensive Experimental Base, No. 18 Tai-lake District, Jiangsu Province.

Zhu, G. Q. 1957. Compost and waterlogged compost. J. Agric. Sci. 9:502-503.

Zhu, G. Q. 1959. Studies on fertility effect of farm manures. (1) Fertility effect of farm manures on paddy rice [English summary]. Acta Pedol. Sin. 7:180-189.

Zhu, G. Q. et al. 1960. Experiment on residual effect of farm manures. Department of Soil and Fertilizer, Chinese Academy of Agriculture, Jiangsu Branch. (Unpubl.).

Zhu, G. Q., and J. H. Gao. 1964. The role of rice-straw ash as bedding in pigsty. J. Soil Sci. 1:19-20.

Zhu, G. Q., and J. H. Gao. 1965. Study on rice-straw ash as bedding in pigsty. Jiangsu Agron. J. 4:40-44.

Zou, M.W., and K. You. 1961. The construction of closed manure pit in pigsty and the effect on preservation of nutrients. Sci. Agric. Sin. No. 1.44 p.

INENGLISH:

FAO Soils Bulletin 41. 1978. China: Azolla propagation and small-scale biogas technology.

Indian Ministry of Agriculture. 1975. The use of organic fertilizers in India. Soils Bull. 27:273-303 FAO/SIDA. Rome.

Murayama, N. 1979. The importance of nitrogen for rice production Pages 5-23 *in* International Rice Research Institute. Nitrogen and Rice. Los Baños, Philippines.

## DISCUSSION

DE DATTA: What proportion of nutrient requirements is met by organic fertilizers (including compost, azolla, etc.) and what proportion is provided by inorganic fertilizer in China?

*YUAN:* The N provided by organic manures makes up about one-third of the total N input in rice production in China.

OH: In the northern part of China, how do they keep the biogas digestor warm in winter?

*YUAN:* They put the unit completely underground or even underneath the stable, latrine, kitchen, or barn.

NAGAR: Has China developed prefabricated biogas plants? If so, what are the economics and the materials used for construction?

*YUAN:* I am not able to provide any information on this question.

AMIEN: In Indonesia people raise eels in the waterlogged compost pits. Some succeed and some fail; perhaps some toxic substances produced during the composting process cause the failure. In waterlogged composting do you record any chemical changes during the process?

*YUAN:* In waterlogged composting, some chemical changes have been recorded, such as pH, Eh, Fe, $NH_4$, available P and K, etc. In China, the failure of waterlogged composting occurs mainly when the pit fails to hold water or when the proportion of raw materials is not correct. Toxic substances have not been well studied.

WAIN: Is the biogas used directly from the generators or is $CO_2$ first removed by passing the gas through water?

*YUAN:* The biogas is used directly.

# URBAN AND INDUSTRIAL WASTES AS FERTILIZER MATERIALS

Kiyoshi Kurihara

Land application is recognized as a feasible and desirable alternative for effecting stages of waste water treatment and for ultimate disposal of solid wastes.

Urban and industrial organic wastes and their processed products, judged from their nutritional and organic composition. have many beneficial uses but there are certain constraints in their use in agriculture. These constraints are the presence of heavy metals, toxic organic compounds, and pathogens, and eutrophication.

Composting is one of the effective methods for minimizing the impact of toxic organic compounds and pathogens on the environment. Primary municipal refuse digested only in mechanical composters is not sufficiently mature and thus N immobilization and N starvation of crops occur when it is applied to soil.

Data currently available indicate that it is advisable to gear application to supply sufficient but not excessive N for crop requirements, and that the available N in wastes is the limiting factor when the heavy metal content is normal.

Guidelines for waste application to croplands, which are proposed or established by many developed countries, adopt this concept. At the same time, maximum limits for concentrations of trace elements in the wastes are proposed or established to prevent their impact on the environment.

At present, one of the most important problems facing metropolitan areas is the disposal of large volumes of liquid and solid wastes generated by urban and industrial activities. Water pollution resulting from the discharge of wastewater into surface water, air pollution caused by the incineration of wastes, and the scarcity of suitable sites for landfill operations have prompted the search for alternative means of waste disposal. Moreover, the increasing price of chemical fertilizers and their limited availability, plus concern for efficient utilization of energy and natural resources, have generated further interest in alternative uses for urban and industrial wastes. Golueke (1977) claims that using organic fertilizer instead of chemical fertilizer can result in a two-thirds energy saving. In the Federal Republic of Germany, a computer analysis indicated that the NPK content of wastes exceeded

---

Fukui Agricultural Experiment Station, 52-21 Henguri, Ryo-machi, Fukui-shi, Fukui 910, Japan.

the amount of chemical fertilizer used annually (Bassam and Thorman 1980). Almost 99% of agricultural wastes and 39% of sludges were used on agricultural land, but only 3.4% of household garbage was so recycled. Sludges produced at municipal waste water treatment plants in the USA amounted to about 4.5 million dry tons annually in 1977, and this figure was expected to reach 8 million by now (Bastian 1977).

The daily output of domestic refuse per inhabitant in Japan is now about 800 g, and the total amount collected for treatment by municipalities and other governmental agencies was 45 million tons in 1979. This domestic refuse contains 30-40% paper and 10-20% garbage.

The current national breakdown of the solid waste collected is estimated as 70% for incineration and 30% for landfill, the percentage of which has recently decreased. Only 0.3% of the domestic refuse was utilized as composted material on farmland in 1979. Sludge produced at more than 450 waste water treatment plants is estimated at 3.1 million m$^3$ (as sludge cake containing 70% moisture). Sludge disposal is estimated as 78.5% landfill, 14% land application, and 7.5% ocean disposal. Organic sludges generated from wastewater treatment at food-processing plants, paper pulp plants, etc. are estimated at about 1 million dry tons annually. Moreover, night soil (human feces) collected from flushless toilets by municipalities and other governmental agencies is treated similarly to sewage water and amounts to approximately 30 million kiloliters/ year. As a consequence, a huge amount of feces sludge is also generated in urban areas. The utilization of this sludge on agricultural land is rather high. A survey in Kanagawa Prefecture indicated that about 50% of feces sludge was recycled on agricultural land (Matsuzaki 1973). Matsuzaki and Wachi (1979) also reported that the total output of organic material and the major nutrients in the wastes in Kanagawa Prefecture highly exceeded the required amount calculated from Kanagawa's standard application rate for crops (see Table 1).

There is now some evidence of decreasing soil fertility caused by a short supply of organic matter for the soil. For example, an average application rate of manure to paddy fields in Japan was 6.5 t/ ha in 1955, but only 2.6 t/ha in 1974, although direct application of rice straw had increased to 0.76 t ha. The reasons for the decrease were the labor consumed in composting, transportation, and application of the product as well as a regional shortage of raw materials.

**Table 1. Total annual production of organic matter and major plant nutrients from organic wastes, and their consumption calculated from a standard application rate for crops in Kanagawa Prefecture, 1977 (Matsuzaki 1979).**

| Organic waste | Annual production (t × 10$^3$ /yr) | | | |
|---|---|---|---|---|
| | Organic matter | N | P | K |
| Municipal refuse | 221 | 8.3 | 24 | 3.4 |
| Animal waste | 108 | 7.7 | 2.6 | 3.4 |
| Human feces | 25 | 8.4 | 9.3 | 2.3 |
| Sewage sludge | 12 | 0.93 | 0.26 | 0.02 |
| Total production | 366 | 25.4 | 14.9 | 9.1 |
| Total consumption | 194 | 6.7 | 2.0 | 4.6 |

Recently there have been renewed discussions of the fertilizer value of wastes, their benefits to the soil, the potential for heavy metal buildup with continued application, and resultant human health problems. In this paper, the author attempts to evaluate these questions on the basis of the published information available.

## PROCESSING OF WASTE FOR AGRICULTURAL USE

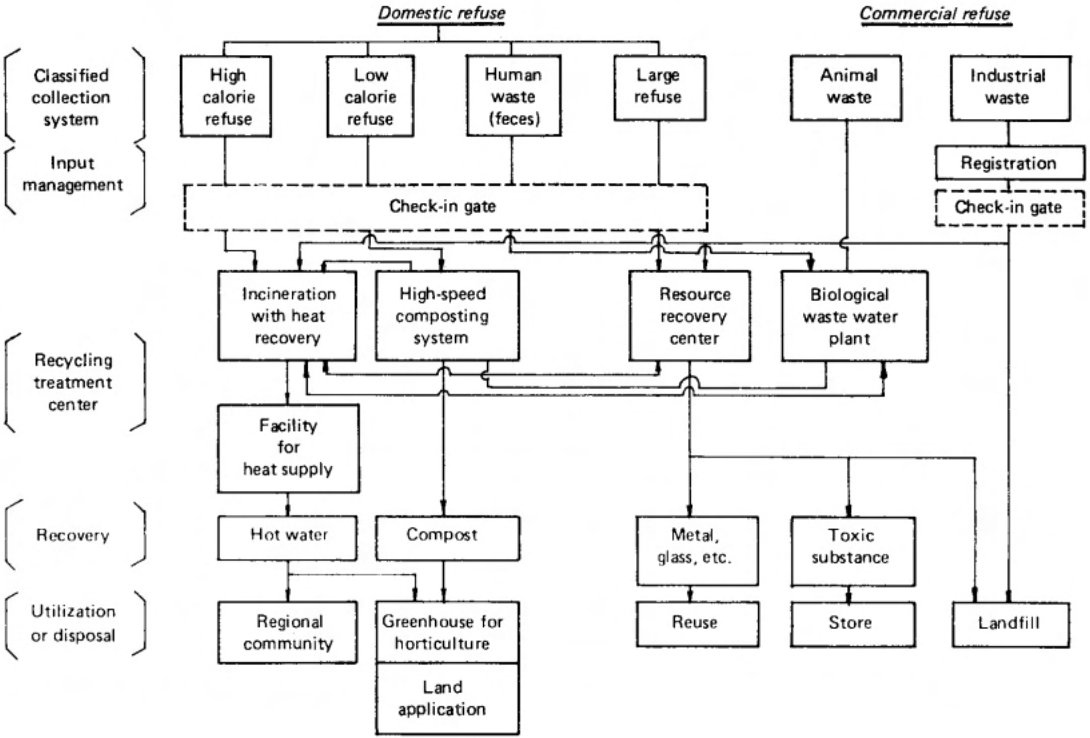
### Composting of mechanical refuse

The only biological method of solid waste treatment that has been developed beyond the pilot stage is composting, but until quite recently composting was not considered in many developed countries as a viable municipal solid waste treatment. In Japan, the Ministry of Public Welfare recommended mechanical composting of municipal refuse as a disposal method in the 1950s. As a result, more than 30 composting plants were constructed in relatively small cities by 1963. However, most of the composting plants were closed in the early 1970s because of 1) the change in the government's recommended disposal method to incineration, 2) farmers' refusal of the product, possibly because of unwelcome ingredients and insufficient maturity of the product, 3) the economic imbalance between production costs and selling price, and 4) changes in the composition of municipal refuse.

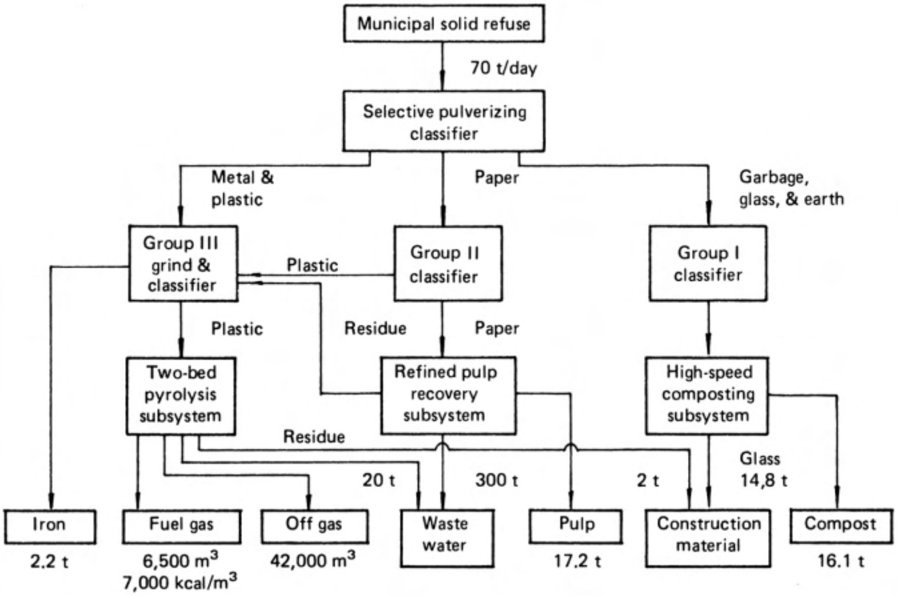
Fortunately, the factors responsible for the recent return of the trend to biological systems in the treatment of waste water are applicable to solid wastes. Among such factors is the reduced energy requirement for biological systems, making the systems more economical. Also, the impact of biological systems on the environment is far less unfavorable than that of physical or chemical processes. Finally, a generally more complete conversion of resources is possible with biological approaches.

The Agency of Industrial Science and Technology has prompted the development of a system for municipal refuse treatment aimed at resource recovery, i.e., replacing current treatment methods of incineration or landfill or both. Many enterprises in Japan have thus developed mechanical composting processes suitable for Japanese refuse, whose characteristics are high moisture content and high content of noncompostable components such as plastic. For example, Saga City's plant, built in 1976, is designed to process about 100 metric tons of incoming municipal refuse and feces sludge. In 1978, Toyohashi City established an overall recycling system, including urban and rural areas, with financial support from the Ministry of Public Welfare and the Ministry of Agriculture, Forestry, and Fishery. A flow diagram of the total recycling and energy recovery system is shown in Figure 1. Low calorie refuse (mainly household garbage) and sludge generated by biological treatment of human and animal wastes are composted in a vertical silo digester followed by a Dano Bio-stabilizer (Suzuki 1981). A new plant in Yokohama City processes up to 100 metric tons of municipal refuse (Nishizaki 1981). A flow diagram of this plant is shown in Figure 2. The composting system consists of forced bottom aeration coupled with stirring by means of an endless moving belt. The plant recovers, besides fine compost, refined pulp, high-calorie fuel, and ferrous metal. In addition, this plant performs almost pollution-free and stable refuse treatments.

Golueke (1977) defines composting as a "a method of solid waste management whereby the organic component of the solid waste stream is biologically decom-



**1.** Flow diagram of Toyohashi City's resource recovery system (Suzuki 1981).



**2.** Flow diagram of resource recovery system from municipal solid refuse developed by the Agency of Industrial Science and Technology, Japan (Nishizaki 1981).

posed under controlled conditions to a state in which it can be handled, stored, or applied to the land without adversely affecting the environment." Three important factors in composting are degree of aeration, temperature, and technology. The resulting classes are 1) aerobic vs anaerobic, 2) mesophilic vs thermophilic, and 3) mechanized vs nonmechanized systems. Synonyms for the classification are closed vs open composting and mechanized vs windrow composting. Modern compost systems are aerobic and call for mesophilic followed by thermophilic conditions. Mechanical systems provide optimum conditions and hence accelerate the process. A number of these systems have been developed and used, such as the Dano process, involving the use of a large, slowly rotating drum; the Naturizer system, in which the composting wastes are tumbled from one floor to the next; the Metro system, consisting of forced-bottom aeration coupled with stirring by means of an endless moving belt; the Fairfield Hardy system, involving the placing of ground refuse in an open cylindrical tank equipped with a set of screws supported by a bridge attached to a central pivoting structure; and the Earp-Thomas system, consisting of a vertical silo divided into many tiers (Golueke 1977).

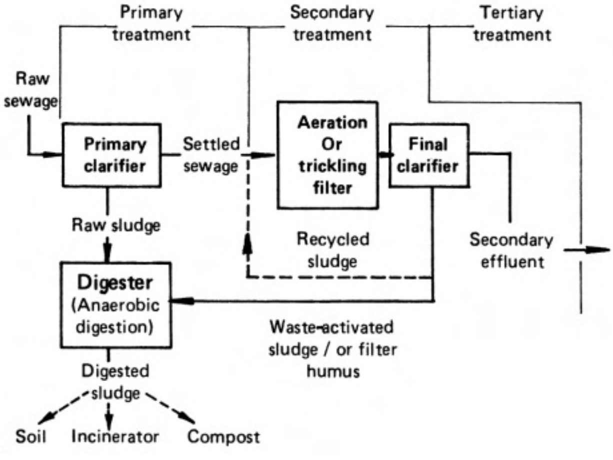
## Composting of sludges

Composting sludges can solve several major problems inherent in their utilization on agricultural land by 1) stabilizing quantities of N that might percolate into the groundwater, 2) killing disease-causing organisms, 3) minimizing the concentration of toxic substances, and 4) eliminating aesthetically objectionable characteristics. In sludge composted with another organic material, the concentration of toxic substances is diluted. In composting, more N in the sludge is assimilated into organisms. Composting broadens the variety of uses by converting the sludge into an easily handled and stable product suitable for general farming.

Sludges are generally classified according to their source. The various sources are indicated in Figure 3, a flow diagram of a typical sewage treatment system. There are three major sources of sludges in primary and secondary treatment, viz., raw sludge from the primary clarifier, digested sludge from the anaerobic digester, and activated sludge from the final clarifier.

In the USA and European countries, direct application of liquid digested sludge is more popular than solid disposal after dewatering. In Japan, the increasing shortage and cost of land and the environmental and agricultural conditions have encouraged the application of solid sludge to land. Sludges are conditioned with $FeCl_3$, $FeSO_4$, aluminum chlorohydrate, lime, or mixtures of these, or with organic compounds known as polyelectrolytes. Although polyelectrolyte flocculents are expensive, only about 0.25-0.5% (dry solid basis) is required, as against up to 20% of lime. After conditioning, dewatering is achieved with filter presses, vacuum filters, belt presses, drum screens, or centrifuges. The dewatered sludge cake generally contains 30-35% solid when inorganic conditioner is used or 15-25% solid when polyelectrolyte is used. Heat conditioning of sludge 180°-200° C under pressure is very effective for dewatering and sterilization but causes some of the solid matter to go into solution so that the separated liquid requires further treatment.

Methods for composting dewatered sludge depend upon its moisture content. If the sludge contains less than 60% moisture, an absorbent material to adjust moisture content for composting is not necessary. In fact, air-dried lime sludge (55-60% moisture) and the mixture of dewatered sludge (70% moisture) and well-composted sludge (30% moisture), whose moisture content does not exceed 55-60%, are successfully stabilized under aerobic conditions for 7-10 days (Date 1982). However, sludges dewatered with organic flocculents must be mixed with some absorbent materials that provide porosity to the composting mass such as wood chips, sawdust, bark, rice hulls, or municipal refuse. If the mixture of sludge and absorbent contains less than 60% moisture, the sludge can be stabilized without any difficulty. But, when



**3.** Flow diagram of a conventional wastewater treatment plant (Golueke 1977).

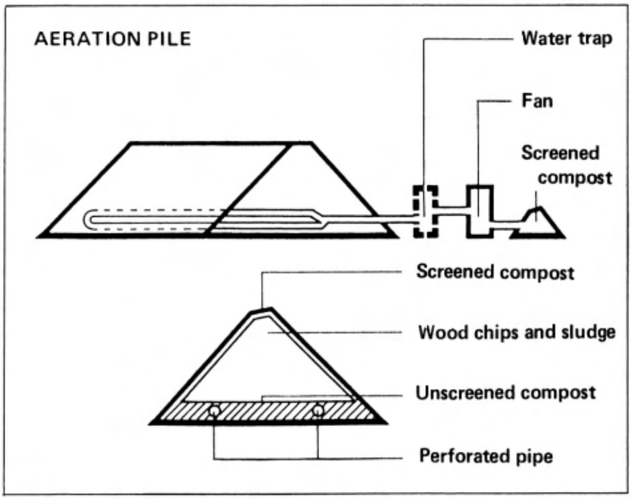
hardly decomposable absorbents such as rice hulls and sawdust are used, the primary product must be moved to a stockpile and matured for 1-2 months to accelerate decomposition of absorbents.

Some experimental data are shown in Table 2. The pH of lime sludge rapidly decreased with time because $Ca(OH)_2$ may be converted to $Ca(CO_3)_2$ without changing the C-N ratio. On the other hand, the C-N ratios of sludge dewatered with polyelectrolyte flocculents plus rice hulls and of heat-treated sludge plus rice hulls decreased with time.

A promising new system of composting sludges developed by the Agricultural Environmental Institute in the USA (Epstein and Wilson 1975) involves the building of a pile of raw sludge mixed with wood chips or shredded bark to provide bulk and the application of a vacuum to draw air through the pile. A mixture (1:3 volume basis) of filter cake (raw sludge, 23% solid) is placed to a height of 2.5-3.0 m over the pile. Suction is applied over 10-14 days, after which the blower is reversed and air is pushed into the pile for 7-10 days. The compost is moved to a stockpile and cured for about 4 weeks. The coarser absorbent can be reused because it largely retains its original physical dimensions. The final product is excellent in appearance and as a soil conditioner. The arrangement of this system is presented in Figure 4.

**Table 2. Change in sludge constituents during composting (Date 1982).**

| Source | | pH | Total C (%) | Total N (%) | C:N | $NH_4^+$-N (%) |
|---|---|---|---|---|---|---|
| Lime sludge | Raw material | 10.3 | 18.9 | 1.8 | 10 | 0.36 |
| | Compost | 7.9 | 15.7 | 1.5 | 10 | 0.42 |
| Polyelectrolyte sludge + rice hulls | Raw material | 6.9 | 31.7 | 1.7 | 19 | 0.37 |
| | Compost | 6.6 | 27.9 | 1.8 | 16 | 0.43 |
| Heat-treated sludge + rice hulls | Raw material | 6.6 | 34.4 | 2.4 | 14 | 0.16 |
| | Compost | 6.8 | 29.9 | 2.6 | 12 | 0.20 |



**4.** USDA aeration pile for composting raw sewage sludge (Golueke 1977).

## CHARACTERISTICS OF URBAN AND INDUSTRIAL WASTES AND THE PROCESSED PRODUCT

### Municipal refuse compost

A 5-year National Research Project on “Improvement of composting process of municipal refuse and agricultural use of the product” was carried out from 1976 to 1980 in Japan. This comprehensive study evaluated the characteristics of municipal refuse compost from the agricultural standpoint, as follows:

*Appearance and undesirable contaminants.* Moisture content of the composts treated in various composters for 2-10 days was 50-60%. Screening as a final processing resulted in the desired uniformity in size for handling and increased the eye appeal of the final product. However, the product contained undesirable contaminants such as tiny bits of glass, ceramic, metal, plastic, etc. depending upon the composting systems used and the quality of collected refuse. At present, the content of undesirable contaminants is considered less than 3% on an oven-dry basis. Glass bits not only pose a visual problem but are a handicap in crop production. Municipal refuse compost has not been recommended for application to paddy fields because of contamination with glass. Heavy metal contamination is also a problem in the compost plant.

*Nutrient content.* Summarized data concerning nutrient content in municipal refuse compost are presented in Table 3, which show wide variation in chemical composition. Compared with crop residue compost, municipal refuse compost is roughly equal in N content, higher in P, and lower in K. Municipal refuse compost generally has a high Ca content and a higher CaO-MgO ratio than crop residue compost.

The nutrient content of municipal refuse compost generally increased with time of composting and maturation, but its N content did not always increase (Watanabe and Kurihara 1982). Ammonia volatilization was observed under high pH and relatively low moisture conditions during the maturation period.

*Organic composition.* Inoko et al (1979) analyzed the organic composition of municipal refuse composts produced in Japan from the standpoint of their suitability for application to land. Their results indicated that the C-N ratio ranged from 19 to 31. There is much evidence that composted materials having a C-N ratio less than 20 cause no N starvation when applied to the soil. Consequently, most of the samples taken from mechanical digesters (retention time: less than 10 days) are

**Table 3. Nutrient contents of 21 municipal refuse composts and 6 crop residue composts (Watanabe and Kurihara 1982).**

| Element | Municipal refuse compost | | | Crop residue compost | | |
|---|---|---|---|---|---|---|
| | Range (%) | Av (%) | CV (%) | Range (%) | Av (%) | CV (%) |
| N | 1.24-3.47 | 1.95 | 27.3 | 0.96-2.30 | 1.50 | 33.6 |
| P | 0.21-1.57 | 0.55 | 55.7 | 0.12-0.38 | 0.24 | 36.6 |
| K | 0.45-2.60 | 1.19 | 50.7 | 1.18-3.25 | 2.37 | 35.6 |
| Ca | 2.30-6.74 | 4.17 | 26.4 | 0.52-1.94 | 1.21 | 42.0 |
| Mg | 0.11-1.69 | 0.34 | 93.2 | 0.15-0.53 | 0.35 | 45.7 |
| CaO:MgO | 11.9-38.7 | 15.6 | 44.1 | 2.4 -7.1 | 3.9 | 45.2 |

immature. Although hot water-soluble organic matter, hemicellulose, cellulose, and reducing sugar also varied widely from plant to plant, immature samples with a high C-N ratio had higher contents of cellulose and hemicellulose determined as reducing sugar.

Total C, C-N ratio, cellulose, hemicellulose, and the ratio of reducing sugar C to total C decreased during the 5-week maturation period; after that period their content did not change, while total N, lignin, and ash content slightly increased and then maintained a constant value (Harada et al 1981). The decreasing rate of cellulose and the ratio of reducing sugar C to total C were much larger. Moreover, they indicated that the distribution of N in the acid, nonhydrolyzible ammonium amide, hexoamine amino acid, and unidentified fractions was not significantly different among municipal refuse compost and did not change during the maturation process. It can be concluded from these results that the primary product prepared in the mechanical composter is not a sufficiently mature one for land application. Inoko et al (1982) proposed a guideline for organic components of municipal refuse compost as follows: 1) a C-N ratio below 20, 2) total N content above 2%, and 3) the ratio of reducing sugar C to total C below 35%.

*Microorganisms.* Microbial population and composition vary very widely. The following range per gram dry weight was obtained: bacteria ($10^7$-$10^8$), fungi ($10^3$-$10^7$), actinomycetes ($10^4$-$10^7$), coliform group ($10^2$-$10^4$) (Tsuru 1981). All microbial groups in the primary product decreased markedly within a few days after 60° C had been reached under conditions of aeration and turning, and the composition of microflora was stabilized within 2 weeks. This finding suggests that maturation of the primary product is necessary for stabilization of the microbial population.

*Nitrogen mineralization and immobilization.* If the C-N ratio of compost is too high (more than 20), the danger of N starvation in crops and abnormal reduction in soil Eh becomes apparent (Parr 1975). A soil incubation test is widely used to evaluate the N behavior in the soil when organic matter is applied. This test (Watanabe and Kurihara 1982) indicated that N immobilization was largely enhanced by the addition to the soil of immature compost with a high C-N ratio, whereas N release occurred in mature compost with a C-N ratio less than 20 (see Table 4). The same authors further examined the N robbing effect of immature municipal refuse compost on wheat growth under greenhouse conditions. The growth, yield, and nitrogen uptake were significantly affected by the addition of the compost. The yield for the immature compost was 70-80% of that of the control treatment. Nitrogen uptake also showed the same trend. There was a close relationship between N uptake and immobilization or mineralization (or both) of N obtained by the soil incubation test. Hence the decrease in yield and N uptake is possibly attributed to the N robbing effect. Although N starvation can be avoided by applying sufficient chemical N fertilizer to the soil to compensate for any deficiency, the final product should be sufficiently mature to prevent N starvation of crops.

## Sludge and its processed material

Japanese fertilizer law classifies sludge and related fertilizer material from wastes as follows.

- Dried activated sludge (dried microflora fertilizer) — sludge produced at waste

**Table 4. Effect of various municipal refuse composts on wheat yield and nitrogen uptake (Watanabe and Kurihara 1982).**

| Treatment (location) | C:N | 3 weeks' N mineralization rate[a] (%) | N application rate (g/pot) | | Grain yield (g/pot) | N uptake (mg/pot) |
|---|---|---|---|---|---|---|
| | | | Compost | $(NH_4)_2SO_4$ | | |
| No N | – | – | 0.0 | 0.0 | 7.3 | 111 |
| $(NH_4)_2SO_4$ | – | – | 0.0 | 0.4 | 22.9 | 424 |
| $(NH_4)_2SO_4$ | – | – | 0.0 | 0.6 | 23.8 | 575 |
| Beppu | 31.7 | –154 | 0.2 | 0.4 | 16.8 | 293 |
| Saga | 23.4 | –161 | 0.2 | 0.4 | 15.8 | 261 |
| Nagasaki | 30.9 | –158 | 0.2 | 0.4 | 13.8 | 209 |
| Ito 2 | 25.3 | –151 | 0.2 | 0.4 | 14.7 | 224 |
| Ito 3 | 13.2 | 4 | 0.2 | 0.4 | 21.3 | 407 |
| Hojo | 23.9 | –101 | 0.2 | 0.4 | 17.6 | 280 |
| Toyohashi 1 | 21.7 | 5 | 0.2 | 0.4 | 20.1 | 369 |
| Toyohashi 2 | 12.6 | 7 | 0.2 | 0.4 | 20.1 | 355 |
| Kanuma | 14.6 | 20 | 0.2 | 0.4 | 20.6 | 369 |

[a] Negative figure shows N immobilization.

water treatment plants in fermentation, food processing, pulp, and gelatine factories. Minimum nutrient content is 5.5% for N alone or 4.5% for N, 1% for P, and 1% for K.

- Sludge fertilizer — sludge obtained by aeration or fermentation, or both, of waste water at industrial plants, of sewage, of human feces, and of animal waste, and then processing this sludge.
- Compost — materials composted from organic waste such as straw, rice hulls, grass, animal waste, sludge, etc.
- Lime-treated fertilizer — treated sludge, human feces, animal wastes, and fruit-processing dregs. Minimum alkalinity is 25% on an oven-dry basis.
- Incinerated sludge — material obtained by incinerating sludge fertilizer and lime sludge. Minimum alkalinity is 25% on an oven-dry basis.
- Fermented dry feces — sludge obtained by anaerobic treatment of human feces.
- Treated human feces — chemically and biologically treated human feces except for lime-treated sludge.

In 1980, Japan produced the following amounts of these fertilizers:

| *Kind* | *Metric tons* |
|---|---|
| Dried activated sludge | 27,649 |
| Sludge fertilizer | 297,463 |
| Compost | 650,202 |
| Lime-treated fertilizer | 10,255 |
| Incinerated sludge | 9,102 |
| Fermented dry feces | 3,741 |
| Treated human feces | 15,489 |

*Chemical composition of sludges.* Data presented by Yoshida (1976) are sufficiently extensive to evaluate nutrient concentrations in dried activated sludge generated in 26 food-processing plants. The nutrient concentrations ranged from 3.48 to 11.41% for N on a dry matter basis (mean 7.29%), from 1.70 to 8.62% for P (mean 4.45%), and from 0.06 to 2.06% for K (mean 0.65%). There was a negative linear relationship between the N concentration and the ash concentration. Nitrogen content generally was lower in sludge dewatered with inorganic flocculents than in sludge treated with organic polyelectrolyte flocculents. According to Kurihara and Fugii (1974), 80-90% of total N in dried activated sludges is included in the protein fraction, and the inorganic N is negligible. However, there is no consistent trend in the amino acid composition of tested sludges.

Activated sludges decompose relatively easily in soil, and thus most of their N is mineralized within 1 month. However, the mineralization rate of N vaned among tested activated sludges and ranged from 40 to 60%. This value is equal to or lower than that of rape seed oil cake, which is a popular organic fertilizer in Japan. The reason for the lower N release in soils is not clear, but an important factor in determining the mineralization of activated sludges is the drying condition. When sludge was dried at more than 175° C for 1 hour, the mineralization rate decreased surprisingly because of change in protein structure (Yoshida 1976), and the mineralization rate of air-dried or freeze-dried activated sludges was lower than that of heat-dried sludge (110°C, 1-2 hours) (Kurihara and Watanabe 1976).

Table 5 shows the nutrient content of sewage sludges. Another analysis concerning N form in sewage sludges showed that its N can be mostly acid hydrolyzable; the distribution of N into amino acid, hexamine, ammonium-amide, and unidentified fractions ranged from 40 to 43%, 2 to 7%, 13 to 15%, and 40 to 43%, respectively. The high hydrolyzable and unidentified N contents in sewage sludges are characteristic when compared with those of soil and manure (Kono 1978).

Nitrogen and K concentrations in feces sludges are roughly equal to those in sewage sludges, but P concentrations are much higher. A recent analysis indicates that the P concentrations in feces sludges average about 8%.

The mineralization rate of N from sludges varies with many factors, including source, application rate, and soil and environmental conditions. Data obtained by Ebihara et al (1979) are in Table 6. The mineralization rate at 30° C for 3 weeks ranged from 32 to 55% for feces sludges and 16 to 30% for sewage sludges, except sewage sludge 2. When this sludge, having a C-N ratio of 10.2, was applied to soils, N supplied by $(NH_4)_2SO_4$ was immobilized. This suggests that C in the sludge was decomposed rapidly by soil organisms, but that N release occurred to a lesser extent. Finally, the yield of Chinese cabbage was related to the mineralization of added sludges (Table 6).

**Table 5. Chemical composition of sewage sludges in Japan (Yamazone 1979).**

| | Nutrient content[a] (%) | | | | | pH (115) | EC (71) |
|---|---|---|---|---|---|---|---|
| | N (123) | P (123) | K (123) | Ca (117) | Fe (96) | | |
| Range | 0.7-7.6 | 0.1-3.2 | 0.1-2.8 | 0.2-31.5 | 0.3-14.0 | 4.8-12.9 | 0.1-18.3 |
| Median | 2.8 | 1.1 | 0.2 | 9.7 | 4.0 | 8.4 | 4.7 |
| Mean | 3.1 | 1.2 | 0.3 | 9.0 | 4.5 | 4.9 | 4.9 |

[a] Number in parentheses represents number of samples

**Table 6. Relationship between nitrogen mineralization rate of various sludges and seedling growth (Ebihara et al 1979).**

| Source | C:N | Total N (%) | 3 weeks' N mineralization (%) | Dry wt of Chinese cabbage | |
|---|---|---|---|---|---|
| | | | | mg/pot | index |
| Sewage sludge 1 | 5.5 | 4.16 | 30 | 780 | 85 |
| Sewage sludge 2 | 10.2 | 2.19 | –32 | 69 | 8 |
| Sewage sludge 3 | 6.1 | 3.44 | 16 | 654 | 71 |
| Sewage sludge 4 | 4.6 | 3.41 | 27 | 834 | 91 |
| Sewage + feces sludge | 8.9 | 1.76 | 20 | 449 | 49 |
| Feces sludge 1 | 8.7 | 2.34 | 34 | 797 | 87 |
| Feces sludge 2 | 7.3 | 2.62 | 32 | 815 | 89 |
| Feces sludge 3 | 7.9 | 2.53 | 38 | 922 | 100 |
| Feces sludge 4 | 7.2 | 2.79 | 55 | 1026 | 112 |
| $(NH_4)_2SO_4$ | – | – | – | 918 | 100 |
| No N | – | – | – | 346 | 38 |

Concentrations of Ca, Fe, and A1 in sludges vary widely. Sludges treated with a mixture of lime and $FeC1_3$ usually contain more than 10% CaO and 4% Fe, and thus the pH of these sludges is more than 7. Therefore, lime sludges can be used in those agricultural applications in which lime is needed.

The Association for Utilization of Sewage Sludge Resource (1980) has evaluated several chemical components of sewage sludges in relation to the composting process (Table 7). Generally speaking, nutrient concentrations increase with composting time because of the formation and loss of $CO_2$, but N does not always increase because of the $NH_3$ volatilization. Table 7 may also be used for monitoring the degree of maturity of composted sludges.

*Bark compost.* About 80 bark composting plants in Japan having capacities of 50-2,000 t/month produce about 300 thousand tons annually. Open windrow and bin systems are usually used, and the process includes size reduction, mixing raw material with some fermentation accelerators, piling, turning, and finally screening. Although the main raw material is bark, which is heaped outdoors for several years, sawdust, wood chips, and sludge (scum) generated at waste water treatment plants in the pulp industry are also raw or supplemental materials. Since bark and other wood wastes have high C-N ratios and at the same time break down very slowly, poultry manure, a N source such as urea or superphosphate, and sludge are added to adjust

**Table 7. Range of some properties of mature sewage sludge composts (Association for Utilization of Sewage Sludge Resource 1980).**

| Property | Raw sludge + rice hulls | Digested sludge + rice hulls | Raw sludge + bark |
|---|---|---|---|
| Moisture (%) | 48 -52 | 41 -55 | 40 -56 |
| Ignition loss (%) | 48 -51 | 56 -63 | 69 -70 |
| Total C (%) | 23 -25 | 28 -32 | 34 -37 |
| BOD (mg/g) | 5 -8 | 17 -23 | 11 -17 |
| Total N (%) | 1.2- 1.3 | 1.6- 1.8 | 3.3- 4.0 |
| pH | 6.2- 6.5 | 6.0- 6.6 | 6.6- 6.8 |

the C-N ratio and to supply nutrients to microorganisms. Special inoculums are occasionally added, but there is no clear evidence that they accelerate the composting process or improve the final product.

Generally, a safe allowance for high-rate composting of wood waste is 3-5 months under aerobic conditions.

Kawai (1981) proposed the following standard quality for bark compost:

| | |
|---|---|
| Organic matter | >70% |
| Total N | >1.2% |
| C-N ratio | <35 |
| Total P | >0.22% |
| pH | 5.5-7.5 |
| Cation exchange capacity | >70 meq/ 100 g |
| Moisture | 60 ± 5% |
| Seedling test | no abnormality |

## Determination of maturation degree

By maturity is meant the condition in which the composted material can be stored without creating a nuisance or can be applied to the soil without causing problems. The precise point at which maturation is sufficiently far advanced has yet to be agreed upon. Goleuke (1977) summarized the parameters for determining the degree of maturation: change in the C-N ratio, final drop in temperature, amount of decomposable and resistant organic matter in the material, rise in the redox potential, oxygen uptake, growth of the fungus *Chaetomium gracilis,* and the starch test. More recently in Japan, Inoko et al (1979) have proposed four methods for determining the maturity of municipal refuse compost.

*Paper chromatographic method (Inoko 1979).* Following the description by Hertelendy (1974), circular filter paper is immersed in 0.5% $AgNO_3$ solution and dried for use in chromatography of alkali extracts of municipal refuse compost samples. The chromatograms are divided into three zones: central zone of light pink to yellow, peripheral dark blue ring, and light pink to gray or brown zone, which lies between the other two. Jagged, brown parts appear in the peripheral zone only in samples having a low C-N ratio and low content of reducing sugar. This method is rapid (less than 30 minutes) and needs no special apparatus.

*Measurement of cation exchange capacity (CEC) (Harada and Inoko 1980a, b).* A finely milled 200-g compost sample is washed with 0.1 N HCl to replace exchangeable cations. After the excess HCl is washed off with distilled water, $Ba(OH)_2$solution of pH 7 is added to the treated sample and the mixture stands overnight. After filtration, the sample is washed with another $Ba(OH)_2$ solution and the released portion is titrated with standard NaOH using a potentiometer or a thymol blue pH indicator. A highly significant correlation ($r = -0.903$) between the CEC and the C-N ratio of municipal refuse composts was noted. Further analysis of various municipal refuse composts has led to the establishment of a CEC guideline: municipal refuse compost with a CEC greater than approximately 60 meq/100 g of ash-free material should be recommended to apply to crop land.

*Measurement of color change (Sugahara et al 1979).* The color of composting material changes to dark brown or grayish black with advancing maturity. Changes in color of municipal refuse material during composting are measured using a CIE 1931 Standard Colorimetric System. Stimulus Y (the degree of lightness) and chromaticity coordinate $(x,y)$ are determined with a color analyzer by measuring relative spectral reflectance. As a positive correlation is found between the stimulus value $Y$ and the C-N ratio, the former value seems to be used as a parameter for estimating the maturity of municipal refuse compost.

*Measurement of humus-like substances (Watanabe and Kurihara 1982).* The measurement method consists of extracting humus-like substances from the sample with 0.1 M $Na_4P_2O_7$ solution and determining the color of the extracted solution colorimetrically using a standard solution of purified humic acid. The absorbance is measured at 420 mu. The extraction rate of humus-like substances is calculated as follows:

$$\text{Extraction rate (\%)} = \frac{\text{amount of humus-like substance as C}}{\text{total C}} \times 100$$

The extraction rate of humus-like substances is linearly correlated with the C-N ratio and the mineralization or immobilization (or both) of N. When municipal refuse compost has an extraction rate of humus-like substances greater than 5%, it is sufficiently mature.

The compost process is generally divided into two parts — mechanical composting and windrow maturation or curing. Changes in the mentioned parameters are not noted to a large extent during the composting period. Therefore, an important handicap in the use of these methods is that they are not applicable for samples taken at the mechanical composting stage.

## PROBLEMS RELATED TO LAND APPLICATION OF WASTES AND PROCESSED WASTES

The concept of recycling of waste nutrients and organic matter back to agricultural land is feasible and desirable. However, certain constraints must be followed in waste utilization in agriculture. These constraints are expressed mainly in terms of permissible loading, both with respect to public health protection and to crop yield maximization. The major constraints pertain to 1) the presence of trace metals, 2) certain toxic organics in the waste, 3) the presence of pathogens, and 4) the feasibility of excess N release to the environment.

### Trace metals

Several excellent reviews of trace metal contamination in wastes, especially in sludge, were published recently (Page 1974, Council for Agriculture and Technology 1976, Pahren et al 1979). Page summarized the ranges of trace metal content in sludges from about 300 treatment plants from different regions in the USA, Canada, Sweden, and Great Britain as follows (in parts per million on a dry matter basis): Ag (5-150), As (1-8), B (6–1,000), Ba (150-4,000), Cd (1-1,500), Co (2-260), Cr (20-

41,000), Cu (50-11,700), Hg (0.1-56), Mn (60-3,900), Mo (2-1,000), Ni (10-5300), Pb (15-26,000), Sn (40-700), V (20-400), and Zn (72-49,000).

Except for Cr, variations in the concentrations of trace metals among the treatment plants in the four countries are reasonably comparable. Page also pointed out that sludges from strictly residential communities commonly contain concentrations of Cu exceeding 500 ppm and Zn exceeding 1,000 ppm. When excessive concentrations of one or more trace elements occur in sewage sludges, the source is probably industrial.

Less extensive data from a number of locations show that the concentrations of trace metals in sewage sludges are lower in Japan than in the previously mentioned countries, because of the very low concentration of trace metals in effluent discharged from industrial factories.

Blakeslee (1973) found no consistent trend in the trace metal content of raw sludge, secondary sludge, and filter cake, but Adachi et al (1981) indicated that trace metal concentrations are generally lower in unaerobically digested sludges than in activated sludges taken from the final clarifier in the same sewage treatment plant. Trace metal composition of feces sludge is similar to that of sewage sludges. Reports on trace metal concentrations in municipal refuse compost are rather sparse. Watanabe and Kurihara (1982) analyzed trace metal content in various municipal refuse composts from different locations in Japan (Table 8). Municipal refuse compost had much higher concentrations of Zn, Cu, Hg, and Pb than crop residue compost, but only slightly higher or approximately the same concentrations of Cd, Ni, Cr, and As. The Zn-Cd ratio ranged from 115 to 1,012 for municipal refuse compost and was less than 100 for crop residue compost. Other analytical data show that trace metal concentrations are closely related to amounts of unwelcome contaminants (Watanabe and Kurihara 1982). Trace element concentrations in municipal refuse compost prepared from domestic refuse (mainly garbage) collected by improved systems are the same as those in rice straw compost. These findings indicate that a reduction of trace metals in the product can be achieved by minimizing undesirable contaminants, that is, by improving the sorting system and by adopting a strict collection system for refuse. The latter approach seems more attractive and reasonable.

**Table 8. Content of trace elements in 21 municipal refuse composts and 6 crop residue composts (Watanabe and Kurihara 1982).**

| Element | Municipal refuse compost | | | Crop residue compost | | |
|---|---|---|---|---|---|---|
| | Range (ppm) | Mean (ppm) | CV (%) | Range (ppm) | Mean (ppm) | CV (%) |
| Zn | 77 -1670 | 641 | 60.5 | 48 -165 | 99 | 42.6 |
| Cd | 0.5- 6.0 | 2 | 66.7 | 1.3- 4.9 | 2.1 | 68.4 |
| Cu | 42 -1009 | 213 | 98.1 | 14 - 31 | 21 | 29.6 |
| Cr | 29 - 202 | 83 | 62.3 | 33 -120 | 67 | 53.8 |
| Ni | 4 - 49 | 27 | 46.3 | 14 - 39 | 25 | 34.0 |
| Pb | 64 - 911 | 232 | 104.3 | 15 - 34 | 24 | 32.5 |
| Hg | 0.4- 11.7 | 2 | 99.8 | 0.1- 0.7 | 0.26 | 90.8 |
| As | 0.1- 6.0 | 2 | 67.8 | 1.1- 5.2 | 2.7 | 54.3 |
| Zn:Cd | 115 -1012 | 341 | 70.0 | 25 - 97 | 56 | 48.7 |

### Organic compounds

There is little information regarding organic compounds in waste materials. The substances of widest concern are polychlorinated derivatives such as PCBs, insecticides, and herbicides. Pahren et al (1979) concluded that caution should be exerted before sludge containing more than 10 ppm is applied to the surface of grazing lands, where the sludge may be ingested.

Kurihara and Watanabe (1976) examined the effect of the addition to soil of polyacrylamide, a popular organic flocculent whose monomer is toxic to plants and humans, on plant growth in a greenhouse. No adverse effect was observed at a concentration 50 times higher than that in the soil, where sludge was applied at rates of 100 kg N/ha.

There is insufficient information to make definite judgments concerning the possible contamination of other hazardous organics in wastes; caution should therefore be exerted in applying them. To check these unknown organics, the germination test and the seedling test are recommended in Japan.

### Pathogens

Since the waste processing practiced currently in most sewage plants is not completely free of pathogenic organisms, sludge, including municipal refuse, should be handled with caution. The pathogenic organisms found in wastes can be classified into four groups—viruses, bacteria, protozoans, and intestinal worms. Methods for disinfecting wastes include pasteurization, heat-drying, lime treatment, and composting.

Pahren et al (1979) reviewed potential health risks associated with land application of municipal sludges and concluded the following:

- Pathogenic bacteria, viruses, and parasites found in waste water sludges raise the specter of potential public health problems because of plant or soil contamination.
- Densities of bacteria and viruses in raw waste water are greatly reduced in most conventional sludge treatment processes. Those reaching plants or soil have rather limited survival times and fairly quickly reach low titers. Reasonable area-entry limitations and site design should prevent serious epidemiologic problems from these classes of agents.
- Several parasite species normally possess free living phases in their life cycles that have resulted in greatly enhanced tolerance to adverse environmental factors. They are, therefore, capable of prolonged survival on plants or in soil. This suggests that parasitic loads in soil may be augmented by waste water sludge above naturally occurring background levels and may thus present a somewhat increased risk of transmission to humans.
- Despite the possibility of communicable disease transmission from land application of municipal sludges, a practice that has markedly accelerated in recent years, no epidemiologic evidence to date suggests that this practice has resulted in actual human illness where sludge has been properly applied.

There has been little recent study concerning health risks associated with land application of sludges in Japan, perhaps because of the infrequent application of raw or primary sludges without proper secondary treatment that reduces the density of pathogenic agents. Composting has recently been recommended for eliminating the pathogenic danger inherent in sludge utilization as well as for converting sludges into more easily handled and storable products.

In general, it appears that there is little evidence of the transmission of diseases to humans and animals by the spreading of sludges on land. To ensure surface and groundwater protection from pathogenic organisms that might survive the treatment period, runoff conservation practices are recommended for the management of sludge-applied sites (Grooms 1975; Department of the Environment and National Water Council, England 1977; USEPA 1977).

### Limiting the rate of application

Application rates of various sludges and other waste materials will be limited in many respects by regional agronomic practices and may be considered from two viewpoints: 1) use that is optimum for crop production, and 2) use of the soil simply as a disposal medium. However, the second viewpoint should not be recommended from the standpoint of environmental protection in agriculture.

Guidelines proposed by many countries (Chino 1980) are based upon fertilizer recommendations for N. Nitrogen is the fertilizer element applied in the greatest amounts to soil, and is found in sludges in substantial amounts. Therefore, there is good reason to base the application rate of sludges on their N content or availability.

Constraints have been placed on other constituents in wastes that may adversely affect crop production or may result in concentration in the edible part of the plant, affecting the health of humans and animals. Recently, guidelines for maximum permissible metal application have been developed in many developed countries. These have included recommendations based upon the maximum amount of a single metal that can be applied and upon the maximum amounts of Zn, Cu, and Ni that can be applied together.

*Nitrogen basis.* When sludges are added to soil, organic matter decomposes to release N available for crops. Although the precise rates for various climates, regions, and soil conditions have not been determined, the available data indicate that 15-40% of the organic N is mineralized in the year of application. Lesser percentages of the remaining N are mineralized in succeeding years. Keeney et al (1975) suggested 15% availability in the first year, 6% of the remaining N in the second, 4% in the third, and 2% in the fourth. In England the Department of Environment and National Water Council (1977) showed that availability of liquid digested sludges in the first year of application was 85% of the total N and that of dried digested sludges 33%.

Generally, amounts of sludges required to satisfy the N requirement of crops will range from 4 to 40 t/ha. Techniques to compute the amount of a particular sludge needed to supply a specific amount of available N were worked out by Keeney et al (1975) and Grooms (1975).

Nitrogen leaching below the root zones will be in the nitrate form, and eventually this nitrate may contaminate groundwater supplies. For this reason, it is advisable to gear sludge application to supply sufficient but not excessive N for crop requirements.

The limit of annual sludge application rates based on the N requirement for crops is generally lower than that calculated from the permissible loading rate for metals. The available N in the wastes is thus the limiting factor when the heavy metal content is normal.

*Metal basis.* When concentrations of certain metals build up in soil because of application of inorganic salts of these metals, the growth of a wide variety of crops is affected (e.g, Page 1974). For this reason, some guidelines in the application to agricultural land of wastes containing metals have suggested limits on the quantities of the metals, particularly Cu, Ni, Zn, and Cd, which can be safely applied.

An attempt to limit metals applied to soil in the form of sludges is based upon the Zn equivalent concept. This concept assumes that toxicities of Cu and Ni can be expressed in terms of some multiples of Zn, and that the toxicities of these metals to plants are additive. Information accrued since the introduction of this method shows that the toxicities of these elements are generally not additive and that the use of the equation greatly underestimates the amounts of sludge-borne metals that can be safely applied to neutral and calcareous soils. Furthermore, the equation is not applied uniformly over a broad spectrum of plant species (Council for Agricultural Science and Technology 1976).

It has also been suggested that rates of application of sludges should be limited by a Zn-Cd ratio in the sludges. This concept has two premises: First, the Zn-Cd ratio averages 500 for parent rocks and 100 for soils, which means that during weathering, Cd is not lost as rapidly as Zn. Second, regulation based upon the Zn-Cd ratio would result in Zn concentrations in soil high enough to damage plants before Cd could accumulate to a level in foods considered hazardous to animals and humans. More recent results show that this premise is often not correct and that many plants grown on neutral and calcareous soils will tolerate high levels of Zn in the soils and will still show an increase in the concentrations of Cd. In these soils, Cd limits can be based on safe annual and total rates of application. In acid soils, use of a combination of the Zn-Cd ratio in the sludge and the annual and total rates of application may be advisable.

If sludge applications are based initially on supplying the crop with adequate N and on safe annual applications of toxic metals and, subsequently, as metals accumulate with time, on permissible metal levels in soil, the life of the site will be extended and the food supply will be protected. The impact of heavy metals may be limited by using rational management methods intelligently.

*Guidelines for permissible application rate.* Goldstein (1977) reported the following application criteria for sludges applied to privately owned land, based on the recommendations of the US Department of Agriculture:

- No greater amount of sludge-borne metals may be applied than the amounts shown in Table 9.
- It is suggested that sludges having Cd contents greater than 25 mg/ kg (dry weight) should not be applied to land unless their Cd-Zn ratio is <0.015.
- Annual rates of sludge application on land should be the lower of the following values:
    1. N requirements of crop (inorganic N + 20% organic N)
        a. When incorporated — no more than 100% of the crop requirements for N.
        b. When surface applied — no more than 150% of the crop requirements for N.

**Table 9. Maximum cumulative sludge metal application for privately owned land (Gddstein 1977).**

| Metal | Max metal addition (kg/ha) at CEC[a] of | | |
|---|---|---|---|
| | 0-5 meq/100g | 5-15 meq/100g | > 15 meq/100g |
| Zn | 250 | 500 | 1,000 |
| Cu | 125 | 250 | 500 |
| Ni | 50 | 100 | 200 |
| Cd | 5 | 10 | 20 |
| Pb | 500 | 1,000 | 2,000 |

[a] Determined on unsludged soil by the method using pH 7 ammonium acetate for a weighted average to a depth of 15 cm.

2. Cd loadings on the land should not exceed 1 kg/ ha per year from liquid sludge and not more than 2 kg/ ha per year from dewatered sludge.

- A sludge having a Cd content greater than 1.5% of its Zn content should not be applied on a continuing basis unless there is an abatement program to reduce the quantities of Cd in the sludge to an acceptable level.
- These sludge additions should apply only to soil that is adjusted to pH 6.5 or greater when sludge is applied.

The British Government has also proposed guidelines for sludge application to land, the content of which is similar to Goldstein's, but in which the concept of Zn equivalent is adopted. A recommended maximum sludge application to normal arable land is 7.5 t/ha per year (dry basis) for the Zn equivalent and 7.2 t/ha for the available N, and thus the latter is the limiting factor (Department of the Environment and National Water Council 1977).

In Japan, there are still no officially recognized guidelines for the maximum limits of sludge application to agricultural land. However, Table 10 shows proposed guidelines for standard application rates of sludges to crops, based on the effectiveness of sludge N on crop growth and yield.

*Maximum concentration of trace elements in wastes.* Baker and Chesnin (1975) proposed metallic sludge guidelines as follows:

*HEAVY METAL LIMITS*

| | *ppm on a dry matter basis* |
|---|---|
| Zn | 1,500 |
| Cu | 750 |
| Pb | 500 |
| Cr | 500 |
| Ni | 150 |
| Cd | 50 |

In Baker's opinion, sewage not exceeding these concentrations is recommended for crop land for not more than 3 years at rates not to exceed 24.7 dry tons/ ha per year.

**Table 10. Standard application rate of sewage sludge for crops (Civil Engineering Association 1972).**

| crops | N requirement | N application rate (kg/ha) | Sludge application rate (dry t/ha) | |
|---|---|---|---|---|
| | | | Single | Successive |
| Wetland rice | Low | 100 | 4 | 2-3 |
| Sweet potato | Low | 100 | 10 | 5 |
| Wheat, barley, and root vegetables | Medium | 100-200 | 15 | 8 |
| Leaf and fruit vegetables and feed crops | High | 200-300 | 25 | 10 |

**Table 11. Maximum limits for concentrations of substances for special fertilizers from waste materials.**[a]

| Substance | Max metal concn on a dry basis (mg/kg) | Max concn in water extract (mg/l) |
|---|---|---|
| As | 50 | 1.5 |
| Cd | 5 | 0.3 |
| Hg | 2 | 0.005 |
| Pb | – | 3 |
| Organic P | – | 1 |
| $Cr^{+6}$ | – | 1.5 |
| $CN^-$ | – | 1 |
| Alkyl Hg | – | not detected |
| PCB | – | 0.03 |

[a] Following Japanese fertilizer law.

An ordinance for establishing maximum limits for concentrations of toxic substances in fertilizer materials is enforced in Japan. Established trace elements and maximum limits for concentrations are summarized in Table 11. The upper limits for Hg and Cd are quite low compared with the values proposed by Baker and Chesnin (1975) and several developed countries (Chino 1980).

Analytical data indicate that As concentrations in various wastes are far less than 50 ppm for this element except for sludges from hot spring areas, and that Cd concentrations are occasionally higher than 5 ppm in sludges generated at the treatment plant in industrial areas. On the other hand, Hg concentrations in the wastes are near and often exceed the limit of 2 ppm.

There are fewer data for trace elements in the water extract of wastes, but the available data show that they do not exceed the maximum concentrations.

## REFERENCES CITED

Adachi, D., N. Tanaka, A. Senoo, A. Yoshida, and K. Kurihara. 1981. Properties, especially heavy metal concentration of feces sludge [in Japanese]. Abstract of 1981 Meeting. Soc. Sci. Manure, Jpn. 27:146.

Association for Utilization of Sewage Sludge Resource. 1980. Guidelines for composing sewage sludge [in Japanese]. Tokyo, Japan. 123 p.

Baker, D. E., and L. Chesnin. 1975. Monitoring of soils for environmental quality and animal and human health. Adv. Agron. 27:304-374.

Bassam, N. E. L., and A. Thorman. 1980. Potentials and limits of organic wastes in crop production. Compost Sci./Land Utilization, (November/December):30-35.

Bastian, R. K. 1977. EPA construction grants program. Pages 110-123 *in* R. C. Loehr, ed. Municipal sludge management. Ann Arbor Publishers, Inc. Ann Arbor, Michigan. 12 p.

Blakeslee, P. L. 1973. Monitoring considerations for municipal wastewater effluent and sludge application to the land. U.S. Environmental Protection Agency, U.S. Department of Agriculture, Universities Workshop, 9-13, July 1973. Champaign, Urbana, Illinois.

Chino, N. 1980. Guidelines for the application of sludges to agricultural land in foreign countries [in Japanese]. Saisei to Riyo. 9:63-66.

Civil Engineering Association. 1972. Research report for 1971 on disposal, treatment and utilization of sewage sludge [in Japanese]. Tokyo, Japan. 145 p.

Council for Agricultural Science and Technology. 1976. Appraisal of potential hazards of the heavy metals to plants and animals. Application of sewage to crop land. Report No. 64. Iowa State University, Ames, Iowa. 11 p.

Date, N. 1982. Agricultural use of sewage sludge [in Japanese]. Nogyo to Engei (Agric. Hortic.). 57:202-210.

Department of Environment and National Water Council, England. 1977. Report of the working party on the disposal of sewage sludge to land. Standing Technical Committee reports, 5. London. 35 p.

Ebihara, T., K. Yamada, and S. Matsumura. 1979. Studies on application of sludge to agricultural land [in Japanese]. Bull. Gunma Agric. Exp. Stn. 19. 49 p.

Epstein, E., and G. B. Willson. 1975. Composting raw sludge, contribution from the Agricultural Environmental Quality Institute. Agricultural Research Service, USDA, Beltsville, Maryland. 32 p.

Golueke, C. G. 1977. Biological reclamation of solid wastes. Rodale Press, Emmaus, Pennsylvania.

Grooms, G. C. 1975. Ohio guidelines for land application of sewage sludge. Res. Bull. 1079. Ohio Agriculture and Development Center, Ohio. 8 p.

Harada, Y., and A. Inoko. 1980a. The measurement of the cation-exchange capacity of composts for the estimation of the degree of maturity. Soil Sci. Plant Nutr. 26: 127-134.

Harada, Y., and A. Inoko. 1980b. Relationship between cation-exchange capacity and degree of maturity of city refuse composts. Soil Sci. Plant Nutr. 26:353-362.

Harada, Y., A. Inoko, and T. Iwata. 1981. Maturing process of city refuse during piling. Soil Sci. Plant Nutr. 27:357-364.

Hertelendy, K. 1974. Paper chromatography, a quick method to determine the degree of humufication. IRCWD News. 7. 1 p.

Inoko, A. 1979. A rapid test for the check of maturity of city refuse compost using a paper chromatographic method [in Japanese]. Soil Sci. Manure, Jpn. 50:127-132.

Inoko, A., Y. Harada, and K. Sugahara. 1982. Agricultural use of municipal refuse compost with special reference to the degree of maturity [in Japanese, English summary]. Bull. Nat. Inst. Agric. Sci. Ser. B. 33. 165 p.

Inoko, A., K. Miyamatsu, K. Sugahara, and Y. Harada. 1979. On some organic constituents of city refuse composts produced in Japan. Soil Sci. Plant Nutr. 25:225-234.

Kawai, H. 1981. Bark compost. Hakuyusha, Tokyo, Japan. 116 p.

Keeney, D. R., K. W. Lee, and L. M. Walsh. 1975. Guidelines for the application of wastewater sludge to agriculture in Wisconsin. Tech. Bull. 88. Department of Natural Resources, Madison, Wisconsin. 8 p.

Kono, M. 1978. Comparison of organic nitrogen in sewage sludge and soil. Fukugo Hiryo. 6(2):14-21.

Kurihara, K., and K. Fugii. 1974. Studies on the use of industrial wastes as fertilizers [in Japanese]. Ann. Rep. Div. Fert., Natl. Inst. Agric. Sci. 173. 1 p.

Kurihara, K., and M. Watanabe. 1976. Factors affecting the N mineralization of activated sludges [in Japanese]. Ann. Rep. Div. Fert., Natl. Inst. Agric. Sci. 189. 2 p.

Kurihara, K., and M. Watanabe. 1976. Effect of polyacrylamide flocculents on plant growth [in Japanese]. Ann. Rep. Div. Fert., Natl. Inst. Agric. Sci. 189. 17 p.

Matsuzaki, T. 1973. Experiments on agricultural use of sludge [in Japanese]. Results on Soil and Fert. Res. 5. Agric. Res. Inst. Kanagawa Pref. 70 p.

Matsuzaki, T., and K. Wachi. 1979. Agricultural use of sewage sludge in Kanagawa Prefecture [in Japanese]. Pages 145-164 *in* Soil Sci. Manure. Sewage sludge — for recycling. Hakuyusha, Tokyo.

Nishizaki, H. 1981. Practices on municipal refuse composting. Composting system developed by the Agency of Industrial Science and Technology [in Japanese]. Pages 164-174 *in* A. Honda and S. Turu, eds. Waste composting technology. Sogogiken, Osaka, Japan.

Page, A. L. 1974. Fate and effects of trace elements in sewage sludge when applied to agricultural lands. Program Element 1B2043, US. EPA, Cincinnati, Ohio. 83 p.

Pahren, H. R., J. B. Lucas, J. A. Ryan, and G. K. Doston. 1979. Health risks associated with land application of municipal refuse. J. WPCF. 50:2588-2601.

Parr, J. F. 1975. Chemical and biological considereations for land application of agricultural and municipal wastes. Pages 227-252 *in* SIDA/FAO. Organic materials as fertilizers. Soils Bull. 27.

Sugahara, K., Y. Harada, and A. Inoko. 1979. Color change of city refuse during composting process. Soil Sci. Plant Nutr. 25:197-208.

Suzuki, T. 1981. Practices on municipal refuse composting. Toyohashi City system [in Japanese]. Pages 175-180 *in* A. Honda and S. Turu, eds. Waste composting technology. Sogogiken, Osaka, Japan.

Tsuru, S. 1981. Microflora in composting [in Japanese]. Pages 51-53 *in* A. Honda and S. Turu, eds. Waste composting technology. Sogogiken, Osaka, Japan.

USEPA (US. Environmental Protection Agency). 1977. Municipal sludge management, environmental factors. Technical Bulletin. Federal Register 42.211 p.

Watanabe, M., and K. Kurihara. 1982. Physicochemical characteristics of municipal refuse compost for agricultural use [in Japanese, English summary]. Bull. Natl. Inst. Agric. Sci. Ser. B. 33. 85 p.

Yamazone, F. 1979. Sewage sludges as fertilizer [in Japanese]. Pages 45-55 *in* Soil Sci. Manure. Sewage sludge — for recycling. Hakuyusha, Tokyo, Japan.

Yoshida, T. 1976. Utilization of activated sludges from industrial wastewater as fertilizers [in Japanese]. Yosui to Haisui. 18: 194-200.

## DISCUSSION

ROSALES: You made mention that sludge having a Cd content greater than 1.5% of its Zn content should not be applied on a continuing basis unless the quantity of Cd is reduced. What steps do you follow in reducing the Cd content?

*KURIHARA:* Sludges from residential communities commonly show lower Cd concentration (less than 5 ppm) than those from industrial areas, and thus the source of cd is mainly industrial input. To reduce the Cd concentration in sewage sludges, chemical or biological treatments of waste water before discharging it into the sewage system are necessary. These treatments can also reduce the content of other heavy metals in sludges.

LARSON: Are the ashes from sewage sludge incinerators used on agricultural land in Japan?

*KURIHARA:* Yes, they are produced and used as soil conditioners. The production amounted to about 9,000 t in 1981. Analyticaldata show that they contain available Si and Ca (alkalinity). Recently the consumption has decreased because of high concentrations of heavy metals.

# GREEN MANURES AS SOURCES OF NUTRIENTS IN RICE PRODUCTION

N. T. Singh

Green manuring has been practiced in India in different forms, like burying a legume crop in situ before planting the next crop, simultaneous cultivation of a green manure and a main crop, and adding leaves and cuttings of annual and perennial plants and trees growing elsewhere before or after planting a crop. Of the various benefits credited to green manuring, increases in available plant nutrients and in the organic matter content of the soil have been studied in both short- and long-term experiments. The green manures used in these studies have included cultivated annual legumes, cultivated or wild perennial legumes, wild annual legumes, and other plants like water hyacinth, *Ipomea, Calotropis procera,* and *Cannabis.* Of the green manure crops cultivated in situ, *Sesbania* and sunnhemp have been found suitable for rice in a large number of trials. An 8-week crop of these green manures may add 100 kg N/ha in the form of top growth besides benefits accruing through their well-established root system. Cowpea and cluster bean are more drought tolerant than *Sesbania* and fare better under restricted soil water conditions.

On an equivalent N basis, green manures compare quite well with chemical fertilizers even though it is difficult to make such comparisons. Most experiments therefore deal with the extent of N substitution with green manuring. The results are as varied as the experimental conditions, but N substitution of from one-half to two-thirds of the usual dose of 120 kg N/ ha has often been recorded. Burying *Sesbania* 1 day before planting rice has yielded as much as 90 kg N/ ha. Raising of a green manure and fixing of atmospheric N through fertilizer factories require tremendous amounts of energy. Some studies show that, through green manures, atmospheric N can be fixed with less than one-half the energy used on chemical fixation. Green manures have a place in rice production where the time available between two crops is too short to raise a pulse crop. Green leaf manuring, where the green matter is either grown on field boundaries or cut from forests, can be profitably practiced in rice culture.

The importance of green manuring in increasing soil productivity has been recognized from early times in countries like India and China. Varahamihira (500

---

Department of Soils, Punjab Agricultural University, Ludhiana 141004, India.

A.D.) reported that even before 500 B.C. sesamum was buried in the soil at the flowering stage to improve the productivity of garden lands (Kadke 1965). Green manuring has been practiced in different forms, like burying a legume crop in situ before seeding the next crop, simultaneous cultivation of a green manure and the main crop, and addition of leaves and cuttings of annuals and perennial plants and trees that have grown elsewhere before or after planting a crop. The benefits credited to green manuring include increases in available plant nutrients and organic matter content and improvement in the microbiological and physical properties of the soil. The magnitude of these improvements and their persistence under subtropical and tropical conditions have been studied in a number of short- and long-term experiments, many of which, unfortunately, were not designed to answer specific questions about green manures. Their data have thus escaped critical analysis. Singh (1962) reviewed the subject but failed to find a final answer on the modus operandi of green manures in tropical climates.

Many factors have obstructed wider acceptance of green manuring in rice culture. Because of lack of irrigation facilities, the green manures may compete with the main crop for monsoon rains. In some experiments, the soils were deficient in P, so the green manure crops showed a low turnover of N. And earlier cultivars were less responsive to the application of high doses of plant nutrients. Even then, 20-30% of several rice-growing areas of India were planted to green manured rice at mid-century. The use of green manures received a further setback with the increase in cropping intensity and the low cost and ready availability of fertilizers in the last several decades; but with the advent of high yielding cultivars, increases in the cost of

**Table 1. Characteristics of some green manures.**

| | Green matter (t/ha) | Moisture (%) | N content (% dry wt) |
|---|---|---|---|
| Cultivated annual legumes | | | |
| *Cassia mimosoides* | 4.7 | 74 | 2.99 |
| *Crotalaria juncea* | 16.5 | 73 | 3.01 |
| *Cyamopsis tetragonoloba* | 7.0 | 60 | 3.53 |
| *Indigofera ani1* | 6.8 | 74 | 3.66 |
| *Sesbania aculeata* | 14.8 | 78 | 2.67 |
| *S. speciosa* | 7.8 | 78 | 2.43 |
| *Vigna unguiculata* | 10.0 | 85 | 2.63 |
| *V. radiata var aureus* | 7.7 | 82 | 2.96 |
| *V. trilobus* | 5.3 | 79 | 2.47 |
| Perennial legumes | | | |
| *Cassia hirsuta* | 5.0 | 81 | 2.52 |
| *Desmodium gyroides* | 1.4 | 72 | 3.35 |
| *Gliricidia maculata* | 3.0 | 75 | 3.46 |
| *Sesbania punctata* | 3.7 | 73 | 2.42 |
| *Tephrosia candida* | 2.3 | 67 | 3.20 |
| Wild annual legumes | | | |
| *Aeschynomene americana* | 8.9 | 78 | 3.14 |
| *Calopogonium mucunoides* | 4.5 | 74 | 3.02 |
| *Cassia tora* | 5.2 | 71 | 2.13 |
| *Cassia occidentalis* | 4.3 | 78 | 2.80 |
| *Lathyrus sativus* | - | 82 | 4.67 |
| *Tephrosia purpurea* | 3.5 | 70 | 3.46 |

fertilizers, and the concern for pollution and conservation of energy, green manures have again become important to researchers and farmers.

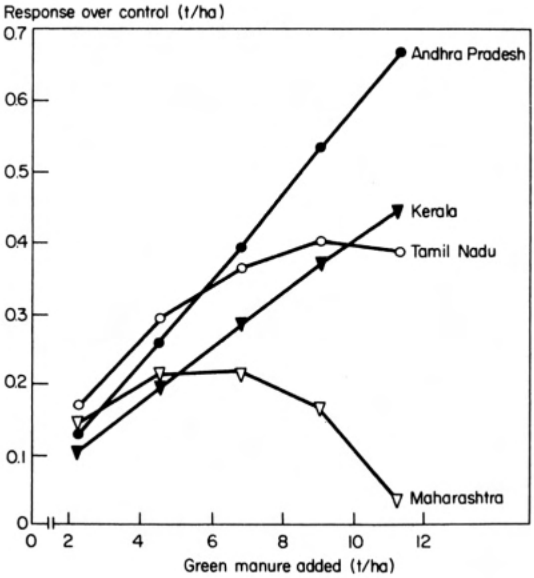
## NATURE OF GREEN MANURES

The foremost quality of a green manure should be its ability to yield large quantities of green matter in a short period. A legume with leafy growth, the ability to suppress weeds, and a well-developed deep root system forms the best green manure. Leguminous green manures commonly used in different parts of the world can be grouped as cultivated annual legumes, cultivated or wild perennial legumes, and wild annual legumes. Vachhani and Murty (1964) and Panse et al (1965) listed a large number of green manure crops, some of which appear in Table 1. Of the annual cultivated legumes, sunnhemp *Crotalaria juncea* and *Sesbania cannabina (Sesbania aculeata)* have been most widely used for rice. Sunnhemp is less tolerant of salinity and excess water than *Sesbania,* cluster bean *Cyamopsis tetragonoloba* is fairly drought tolerant, and cowpea *Vigna* spp. is valued both as a food crop and a green manure crop (Singh et al 1981). *Sesbania speciosa,* which can grow as a perennial plant, has slow initial growth but is more drought tolerant than *S. aculeata* (Patnaik et al 1957). Leaves and cuttings of perennial plants grown along field borders or elsewhere are used at the time of planting or somewhat later. Wild legumes, which are self-sown, are collected from nearby fields and forest areas and used as green manures. Singh (1971) added 0.35 t/ha each of several wild legumes as green manures in standing rice crops and found that *Tephrosia pumila* and *Aeschynomene americana* were more useful than the others.

Besides legumes, several other plants have been used as green manures. Water hyacinth grows wildly in standing water and contains about 2% N on a dry weight basis. Sea weeds, with 1-2% N, are used for manuring crops in coastal areas. *Calotropis procera,* a wild plant in dry areas, yields 20-25 kg green leaves/plant. *Ipomea cornea* (grown along field boundaries as a hedge), mango leaves, and *Cannabis sativa* (a wild-growing intoxicant) have also found use as green manures (Mirchandani and Khan 1952).

## COMPARATIVE EFFICIENCY OF GREEN MANURES

The value of a green manure crop depends not only upon the green matter or N it accumulates per unit time but also on its growing season. An efficient green manure must contain maximum nutrients at harvest immediately preceding the growing season of the main crop. Efficiency can be properly compared only for those legumes whose best growth periods correspond exactly. Panse et al (1965) compiled the result sof 65 trials comparing different green manures used in rice culture. Most trials included only sunnhemp, *Sesbania,* and *Vigna* spp. Sunnhemp showed a better response than *Sesbania* in low rainfall areas, but both were better than other green manures. Under good moisture conditions *Aeschynomene americana* showed a higher response than *Sesbania.* Indigenous tall-growing rice cultivars were used, and their average responses to varying doses of green manure are shown in Figure 1. The responses varied in different areas, and the average response was 0.24 t/ha. In



**1.** Average response of rice to application of green manure.

southern India the responses were of relatively higher magnitude. Uppal (1955) reported that among *Sesbania,* sunnhemp, and cluster bean, *Sesbania* was the best green manure for rice in alkali soils. Singh (1963) found that, even in normal rice soils, *Sesbania* has been preferred over its near rival sunnhemp because of its ability to withstand prolonged moist conditions. Bhardwaj et al (1981) compared the efficiency of sunnhemp, *Sesbania,* and *Ipomea* as green manures in rice-wheat rotation. When these green manures were added to the soil, the N equivalents were 74.5, 49.9, and 25.3 kg/ ha, which were reflected in the rice yields of 4.96, 4.66, and 4.22 t/ha, respectively, compared with 3.40 t/ha without green manuring. Rice yields were significantly higher with Sunnhemp and *Sesbania* than with no green manure. *Ipomea* had a significant effect only on the yield of the subsequent wheat crop.

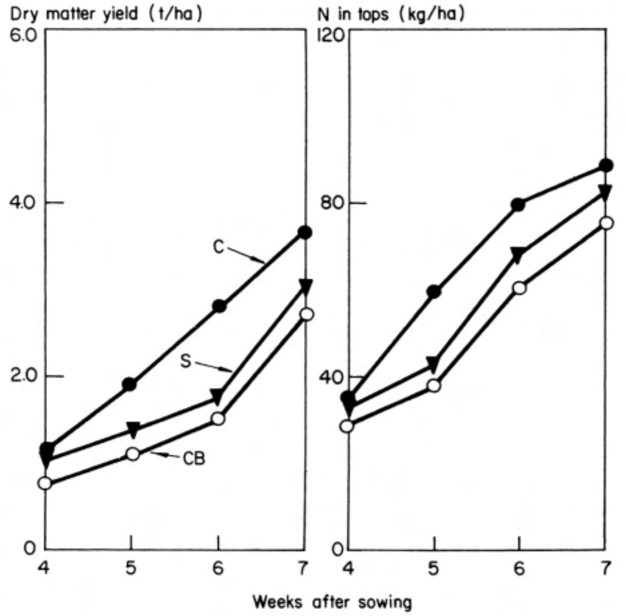
*Sesbania* is less tolerant of atmospheric and soil drought than cowpea (Table 2).

**Table 2. Dry matter and nitrogen yield of 7-week-old green manures.**

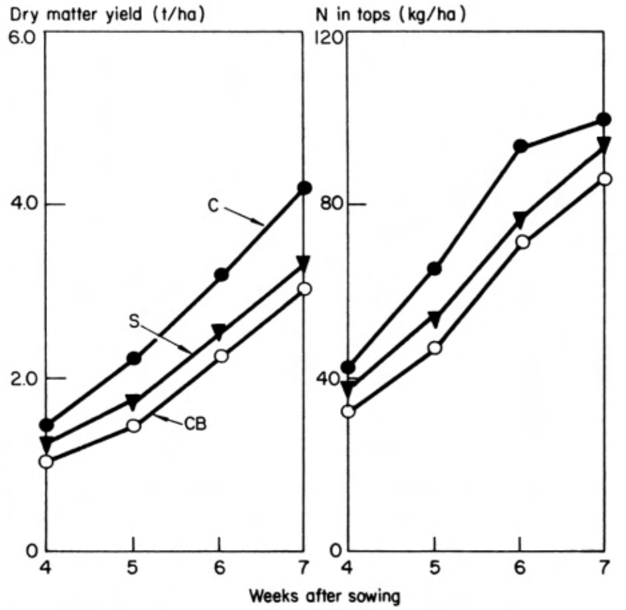
| Green manure | Dry matter (t/ha) | | | N (kg/ha) | | |
|---|---|---|---|---|---|---|
| | 1976 | 1977 | 1978 | 1976 | 1977 | 1978 |
| Cowpea | 4.0 | 4.9 | 4.4 | 97 | 104 | 95 |
| Cluster bean | 2.9 | 3.6 | 3.0 | 89 | 98 | 85 |
| *Sesbania* | 3.1 | 4.8 | 3.8 | 79 | 94 | 78 |
| Mean | 3.3 | 4.4 | 3.7 | 88 | 99 | 89 |
| C. D. (0.05): | | | | | | |
| Green manure | | 0.21 | | | 3.3 | |
| Year | | 0.23 | | | 4.4 | |
| G × Y | | 0.36 | | | 5.7 | |

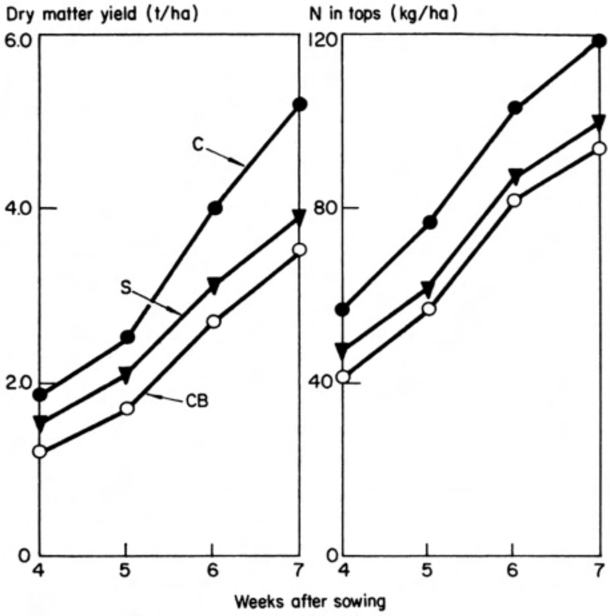
Because of dry weather in 1976 and 1978, *Sesbania* showed a larger reduction in dry matter and N yield than cowpea and cluster bean. In 1977, when weather during the growth period was milder, the dry matter yield of *Sesbania* almost equalled that of cowpea. Singh et al (1981) studied the response of these green manures to irrigation based on different ratios of irrigation water depth (IW) to open pan evaporation (PAN,-E) during the irrigation interval (Fig. 2, 3, 4). An increase in irrigation interval

**2.** Cumulative dry matter yields and N in tops of cowpea (C), cluster bean (CB), and *Sesbania* (S). Irrigated at 0.5 IW/PAN-E. 3-yr average.



**3.** Cumulative dry matter yield and N in tops of cowpea (C), cluster bean (CB), and *Sesbania* (S). Irrigated at 0.7 IW/PAN-E. 3-yr average.





**4.** Cumulative dry matter yield and N in tops of cowpea (C), cluster bean (CB), and *Sesbania* (S). Irrigated at 1.0 IW/PAN-E, 3-yr average.

(low IW/PAN-E) severely curtailed growth of all green manures. Cowpea gave the highest and cluster bean the lowest yield of dry matter and N under all the soil moisture regimes. With a favorable irrigation schedule (1.0 IW/PAN-E), cowpea yielded almost 120 N/ha. The water-use efficiency of cowpea was the highest under all irrigation schedules (Table 3), followed by that of cluster bean and then *Sesbania.* Thus cowpea may take preference over *Sesbania* under drought conditions.

Gaul et al (1976) reported on the irrigation needs of *Sesbania.* Its consumptive use was 65.7 cm and the crop responded to as many as 15 irrigations. Despite its high water requirement, *Sesbania* is a good accumulator of N. The N fixed by the nodule bacteria may be used by the host plant or it may be excreted into the soil. Khare and Rai (1968) compared the effect of P on N fixation by leguminous crops and found that maximum N was excreted by *Sesbania,* followed by soybean, cowpea, and green gram. A net use of soil N occurred with sunnhemp. It follows that the contribution of *Sesbania* to soil N is actually more than what is added as roots and tops. *Sesbania* is also more efficient in mining P from lower soil depths (Subbiah and Mannikar 1964).

## GREEN MANURES VERSUS CHEMICAL FERTILIZERS

It is difficult to compare the relative efficiency of green manures with chemical fertilizers, even on an equivalent nutrient basis. A more rational way is to discover the extent to which green manures could substitute for nutrient elements derived from fertilizers to obtain equivalent crop yields. Earlier studies seem to have more often missed this aspect. For example, in long-term experiments started in 1908 at Pusa in Bihar, India, fertilizers were added to match the NPK content of farm

**Table 3. Effect of irrigation frequency on cumulative water expense of green manures.**

| Irrigation at IW/PAN-E[a] | Water expense (cm) | | | Water expense efficiency (kg N/ha per cm) | | |
|---|---|---|---|---|---|---|
| | Cowpea | Cluster bean | *Sesbania* | Cowpea | Cluster bean | *Sesbania* |
| 1.0 | 35.6 | 36.7 | 37.5 | 3.31 | 2.67 | 2.49 |
| 0.7 | 31.0 | 32.4 | 34.0 | 3.17 | 2.86 | 2.53 |
| 0.5 | 28.7 | 30.2 | 32.0 | 3.06 | 2.74 | 2.36 |

[a] Irrigation water depth/open pan evaporation.

manure, but no such consideration was given to green manure. The results of the initial 22 years, however, showed that in maize and oats, sunnhemp green manure, along with the application of P in a quantity equal to that in farm manure, gave more yield than farm manure, green manure, or fertilizers alone.

Sometimes it is wrongly assumed that green manures do not need any fertilization. In a number of long-term experiments, green manures have responded significantly to fertilizer P by showing increased fresh weight and N content as well as increased rice yield (Table 4).

Bhardwaj et al (1981) studied the possible use of green manures like sunnhemp, *Sesbania*, and *Ipomea* to decrease reliance on fertilizer N in rice - wheat rotations. They obtained larger rice yields by green manuring with sunnhemp than by applying 60 kg N/ ha as fertilizer. With *Ipomea* green manure, the rice yield was equal to that obtained with 30 kg N/ ha. Chatterjee et al (1979) reported that green leaf manure of *Sesbania* and *Ipomea* applied before transplanting rice released more N than farm manure and yielded as much rice as with 40 kg/ ha of fertilizer nitrogen. According to Tiwari et al (1980), 40 kg N/ ha along with green manuring compared well with the application of 120 kg N/ ha without green manuring in the availability of nutrients in the soil, their uptake, and rice yield. A5-year study showed that rice yield with 20 kg N/ha applied as *Sesbania* green manure was equal to that obtained with the application of 30 kg N as $(NH_4)_2SO_4$ (Vachhani and Murty 1964).

The response of rice to green manure depends upon the time of its application. Because of succulence and a narrow C-N ratio, a large part of green manure N is released as nitrates and tends to leach down with water in the course of planting rice. This leads to variations in the extent of N substitution obtained in different experiments comparing green manures and chemical fertilizers. The experiments conducted from 1955 to 1958 at Cuttack in India showed that for 8-week-old

**Table 4. Effect of phosphorus application on green matter and nitrogen addition in soil through *Sesbania* green manure.**

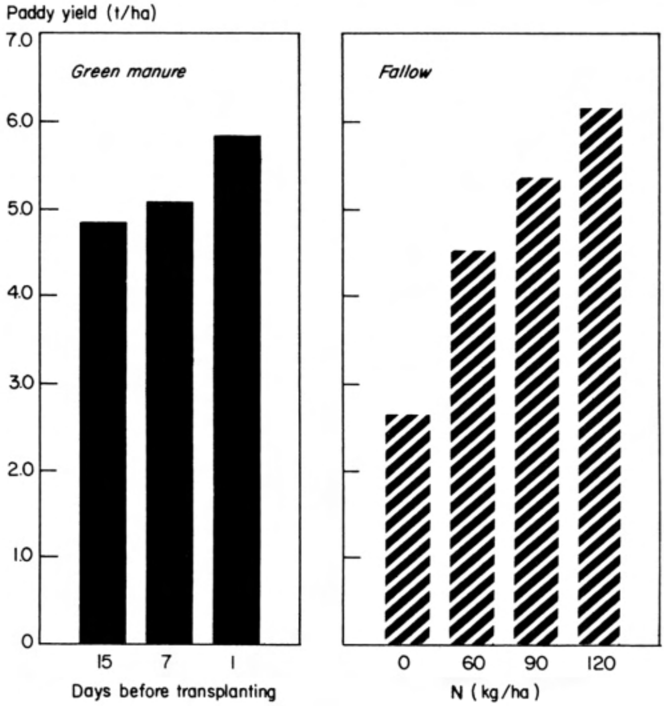
| Treatment | Green wt (t/ha) | Dry wt (t/ha) | N added (kg/ha) | Rice yield (t/ha) |
|---|---|---|---|---|
| *Sesbania* without P | 17.9 | 4.0 | 88 | 4.2 |
| *Sesbania* with P | 20.8 | 4.2 | 105 | 4.9 |

*Sesbania* the rice yield decreased as the interval between burying green manure and planting rice increased from zero to 8 weeks (Panse et al 1965). The reverse was true for 12-week-old green manure, as the older crop became woody and needed almost 8 weeks to decompose (Vachhani and Murty 1964). The effect of plant age at the time of incorporation on the release of organic P by *Sesbania* and Indian clover *Melilotus alba* was studied by Singh and Rai (1973). Maximum increase in organic P in the soil occurred on the 30th day of decomposition of a 60-day crop, but it took 60 days for 75- to 90-day-old crops to attain this maximum.

A large number of experiments conducted by Meelu and his associates (Bery and Meelu 1981, Meelu and Rekhi 1981) showed that burying *Sesbania* 1 day before transplanting rice gave significantly more yield than a time interval of 1-2 weeks. In the former case, the rice yields were higher than those obtained with the application of 90 kg N/ha (Fig. 5). These experiments were conducted on soils of fairly good permeability, showing appreciable leaching of nitrates. Green manures, when buried just before transplanting rice, act as slow-release fertilizers and also create reducing conditions, which help in mobilizing several other nutrient elements.

## GREEN MANURES AS A SOURCE OF PLANT NUTRIENTS

There is no dispute about the role of green manures as sources of organic matter and N. Their capacity to mobilize soil P and other nutrients is also more or less



**5.** Effect of time of incorporation of green manure on rice yield.

universally recognized. Green manures are readily accepted when the added green matter grows elsewhere, as in the case of green leaf manuring; but a problem arises with in situ green manures when these compete with some other crop for space, time, water, and other inputs. In earlier studies, one crop was sacrificed to grow a green manure for a second crop, and the loss of the one crop was on occasion made good by an increased yield of the second crop. In many experiments, the second crop was not otherwise fertilized, which made the comparison unjustified.

In situ green manures must grow for 8-10 weeks before planting rice. This is only possible with an assured water supply. In areas where rice is rainfed, growing green manure with the onset of monsoon rains makes it impossible to plant rice; or the planting is so delayed that yield losses are not compensated for through the nutrient contribution of the green manure. Because of these constraints, the green manured rice area is less than 40% even in pockets known to practice green manuring. Patel (1964) observed that in tracts where green manuring is competitive with main crops it is irrational to recommend it.

A valid question concerns the rationale behind seeding a green manure in areas of assured water supply when a pulse can be grown. Pulses provide much-needed protein for human consumption in developing countries, and the residues can still be turned under to serve as manure. Meelu (1981) reported that burying residues of green gram after picking the pods resulted in substantial economy of N in rice. On the other hand, Jadhav et al (1979) extracted a part of the leaf protein of *Sesbania* and sunhemp and buried the residues in the soil. The resulting wheat yield per kilogram of N supplied by the residue was greater than that obtained when the whole plant was used as green manure.

In areas with an assured water supply and an available span of 2-3 months between the two main crops, green manures can compete with pulse crops. The competition favors green manures when good short-duration pulses are not available and when the farmers lack the resources to grow pulses as catch crops on large tracts. Proper fertilization of green manures, especially with P, can yield a good crop and save considerable fertilizer N (Table 4).

Another important consideration is the energy used in raising a green manure to harvest atmospheric N. Chemical fixation of N requires about four times more energy than that needed to harvest a green manure like cowpea (Table 5). Such a comparison may not in itself be valid because green manures may absorb a part of the soil N. This aspect, as well as the total effect of green manures in a crop rotation, is accounted for in Table 6. The total energy input for raising rice and wheat crops

**Table 5. Energy input for raising green manure crops compared to chemical fixation.**

| Green manure crop | Energy input ($10^2$ kW-h/ha) | | | | |
|---|---|---|---|---|---|
| | Irrigation water | Cultural practices | Seed | Total input | For fixing 1 kg N |
| Cowpea | 3.2 | 1.1 | 1.4 | 5.7 | 0.05 |
| Cluster bean | 3.3 | 1.1 | 2.0 | 6.4 | 0.07 |
| *Sesbania* | 3.4 | 1.1 | 2.0 | 6.5 | 0.07 |
| Chemical fixation | – | – | – | – | 0.20 |

**Table 6. Effect of green manuring on energy-use efficiency from rice - wheat rotation.**

| Rotation | Yield (t/ha) | | N requirement for nearly equivalent yield (kg/ha) | Energy ($10^3$kW·h/ha) | | Energy-use efficiency |
|---|---|---|---|---|---|---|
| | Rice | Wheat | | Input | Output | |
| Rice - wheat | 6.0 | 3.9 | 120 + 90 | 7.5 | 32.7 | 4.3 |
| *Sesbania* - rice - wheat | 6.0 | 3.7 | 0 + 90 | 5.7 | 32.3 | 5.6 |

was more than that for raising these crops in rotation with *Sesbania* as green manure. The difference stemmed from the high energy input in the form of fertilizer N in rice - wheat rotation without green manure. The energy output in the form of produce was almost equal. Even with a modest figure of one-half N substitution with a green manure, the energy-use efficiency remains higher. Green manures are thus more economical in energy use than fertilizer factories, provided the green manures do not compete with the main crop.

Green manures, particularly *Sesbania,* adapt very well during reclamation of alkali soils, where rice is invariably preferred as the first crop (Uppal 1955). Singh (1969) reported that decomposition products of *Sesbania* helped in the removal of exchangeable Na from soils. Inclusion of *Sesbania* as a green manure in rice - clover, rice - sugarbeet, and rice - barley rotations gave greater returns than its exclusion during reclamation of salt-affected soils (Singh 1963). The role of green manures as a source of plant nutrients may therefore be viewed along with their other attributes.

## REFERENCES CITED

Bery, V., and O. P. Meelu. 1981. Substitution of nitrogen through green manure in rice. Indian Farming. 31 (2):3-4.

Bhardwaj, S. P., S. N. Parsad, and G. Singh. 1981. Economizing N by green manures in rice wheat rotation. Indian J. Agric. Sci. 51(2):86-90.

Chatterjee, B. N., K. J. Singh, A. Pal, and S. Maiti. 1979. Organic manures as substitutes for chemical fertilizers on high yielding rice varieties. Indian J. Agric. Sci. 49(3):188-192.

Gaul, B. L., I. P. Abrol, and K. S. Dargan. 1976. Note on the irrigation needs of *Sesbania aculeata* Poir for green manuring during summer. Indian J. Agric. Sci. 46(9):436-438.

Jadhav, B., N. S. Takele, and R. N. Joshi. 1979. Green manure crops as a source of leaf protein. Indian J. Agric. Sci. 49(5):371-373.

Kadke, J. R. 1965. Hastening decomposition of incorporated green manures. Indian J. Agron. 10(4):443-446.

Khare, N. K., and M. M. Rai. 1968. Effect of symbiotic fixation of N by leguminous crops. J. Indian Soc. Soil Sci. 16:111-114.

Meelu, O. P. 1981. Integrated use of fertilizers and manures in cropping sequence. Indian Farming. 31(7):75-79

Meelu, O. P., and R. S. Rekhi. 1981. Fertilizer use in rice based cropping system in northern India. Fert. News 26:16-22.

Mirchandani, T. J., and A. R. Khan. 1952. Green manuring. Indian Council of Agricultural Research Bulletin. 37 p.

Panse, V. G., T. P. Abraham, and C. R. Leelavathi. 1965. Green manuring of crops. Indian Council of Agricultural Research Bulletin No. 2. 84 p.

Patel, G. C. 1964. Economic implications of green manuring. Indian J. Agron. 9:128-132.

Patnaik, S., A. S. Ramarao, and J. S. Nanda. 1957. *Sesbania speciosa* comes to Orissa. Indian Farming. 7:20.

Singh, A. 1962. Studies on the modus operandi for green manures on tropical climates. A critical review of literature. Indian J. Agron. 7:59-75.

Singh, N. T. 1963. Effect of sugarbeet cultivation in the reclamation of saline alkali soils in Punjab. MS. thesis, Punjab Agricultural University, Ludhiana, India.

Singh, N. T. 1969. Changes in sodic soils incubated under saturated environments. Soil Sci. Plant. Nutr. 15:156-160.

Singh, R. G. 1971. Prospectus of utilizing wild legume as green manures in a paddy-wheat rotation. Alahabad Farmer 45:489-495.

Singh, S., and R. N. Rai. 1973. Effect of soil, superphosphate and age at burial legume and changes in inorganic and organic phosphorus during their decomposition. J. Indian Soc. Soil Sci. 21:271-276.

Singh, N. T., R. Singh, and A. C. Vig. 1981. Yield and water expense of cowpea, cluster bean and *Sesbania* as summer green manures in semiarid regions of Punjab. Indian J. Agric. Sci. 51:417-421.

Subbiah, B. V., and N. D. Mannikar. 1964. Selection of green manure crops for uptake of subsoil phosphorus studies with $P_{32}$. Indian J. Agric. Sci. 34:21-27.

Tiwari, K. N., S. P. Tiwari, and A. N. Pathak. 1980. Studies on green manuring of rice in double cropping system in a partially reclaimed saline sodic soil. Indian J. Agron. 25:137-146.

Uppal, H. L. 1955. Green manuring with special reference to *Sesbania aculeata* for treatment of alkaline soils. Indian J. Agric. Sci. 25:211-217.

Vachhani, M. B., and K. S. Murty. 1964. Green manuring for rice. ICAR Research Report Series No. 17. Indian Council of Agricultural Research, New Delhi. 50 p.

## DISCUSSION

BHATTI: What is the appropriate calendar of green manuring of *Sesbania* (its sowing and green manuring schedule) in a wheat - rice rotation system in the Punjab (India), particularly when IRRI-types of early cultivars are involved?

*SINGH:* The first week of May is a convenient time for the farmer to grow a green manure. The crop is buried in the soil when 8 weeks old and rice is tranplanted within the next few days, i.e., the first week of July (even late June).

BHATTI: Have you calculated the economics of N supply considering cultivation, irrigation, seed, and so forth?

*SINGH:* Yes, if irrigation water cost is small and idle farm labor is employed, it is economical to grow a green manure.

BHATTI: What green manure crops besides *Sesbania* could be considered suitable in the wheat-rice rotation, and how do they compare with *Sesbania?*

*SINGH:* Sunnhemp is another good green manure. We also recommend cowpea, which does very well under low moisture supply. Under relatively dry conditions both these green manures fare well as compared with *Sesbania.*

YOSHIDA: Is green manuring economically feasible or not? Farmers may not be willing to purchase seeds and spend more time to grow green legumes.

*SINGH:* Green leaf manuring is economically feasible. In the case of raising in situ green manures, farmers can use idle time between two crops and grow a green manure provided irrigation water is available. They can raise their own seed, as is the common practice.

YOSHIDA: Nitrogen economy with green manuring may not be as good as we expect; the rhizobium-legume symbiotic relationship may not be as effective as you think. It may take up more soil N rather than enriching N from the atmosphere. What is your comment?

*SINGH:* I agree with you, but even if the rhizobia do not fix all the N presented in the paper the green manures mop up soil N released through mineralization following the harvest of the previous crop. This soil N would otherwise be lost through leaching. So green manures act as fixers of atmospheric N and scavengers of soil N and thus provide sufficient N for the next rice crop.

LARSON: If green manures and other crop residues are added to growing rice fields, do they lower the temperature of the water and root zone, and if so does the lowered temperature reduce plant growth?

*SINGH:* Green leaf manures are usually trampled into the soil in growing rice fields. Water and soil temperatures during the rice season are usually in such a range that a possible lowering of 1-2°C in temperature does not affect plant growth.

# USE OF GREEN MANURES IN NORTHEAST ASIA

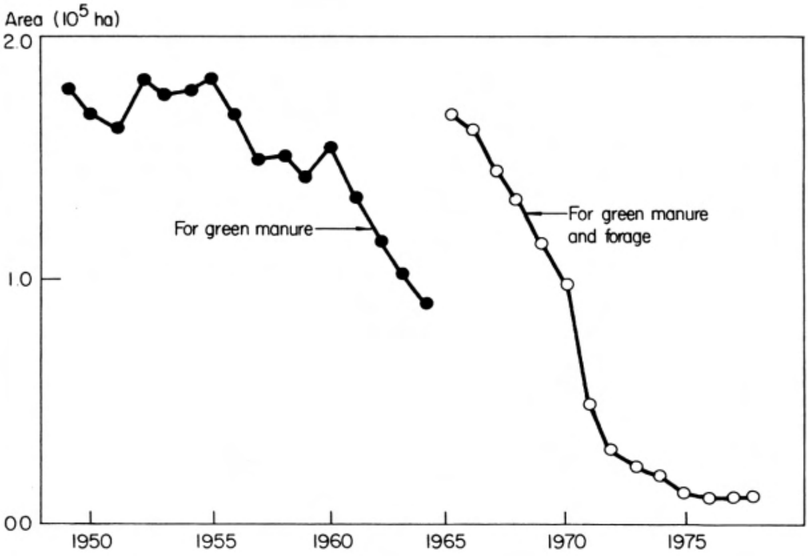
Iwao Watanabe

In Japan, the major green manure crop in wetland fields used to be *Astragalus sinicus,* which was grown from autumn to spring, but its cultivation decreased sharply in the late 1960s because of its technical disadvantages as a N source and the socioeconomic situation. As this plant grows, its biomass increases, but its C-N ratio also increases and the availability of N decreases. The optimum timing for harvest and incorporation of *A. sinicus* was determined to be the beginning of maximum flowering. Excess incorporation was deleterious to rice growth because of excess organic matter and lodging caused by excess N. A higher application was recommended in southern Japan (15 t/ha, fresh weight) than in northern Japan (10 t/ha). Unlike in the tropics, a delay in flooding of about 1 week after incorporation was recommended. Lysimeter experiments showed that the addition of green manure accelerated Fe and Mn leaching.

In Northeast Asia (Korea and Japan), green manure crops were formerly grown extensively before the main rice season. In China, they are still being grown. The major green manure crops for wetland rice are *Astragalus sinicus* L. (in Japan, *genge* or *renge;* in China, *suyunying* or *huatsau;* in English, Chinese milk vetch), soybean, *Medicago denticulata,* and *Vicia sativa* (common vetch). Among them, *A. sinicus* was most widely used. It is sown from middle August to middle October among the standing rice crop and harvested from middle May to early June, depending on the region. Soybean is sown from middle March to early April among the standing wheat crop (Okuda 1953). Before World War II, the maximum area of *A. sinicus* cultivation was 3 × $10^5$ ha. Next to *A. sinicus* was soybean, but its area was much less. Figure 1 shows the extent of *A. sinicus* cultivation in wetland fields in Japan since 1950. Until 1964, the statistics described the area of cultivation separately for green manure and forage, but since then only the combined statistics have been reported. The area of cultivation of these crops has decreased sharply since 1970. The soybean area was one-fourth that of *A. sinicus* in 1948 and one-sixtieth of that in 1969.

---

The International Rice Research Institute, Los Baños, Laguna, Philippines.



**1.** Extent of *Astragalus sinicus* cultivation in wetland fields in Japan.

## NITROGEN CONTENT AND YIELD

The average N content and yield of green manures (Table 1) are greatly dependent upon the harvesting time, which in turn is dependent on the cropping season of wetland rice. As the green manure crop grows, its biomass increases, but the C:N and fiber and lignin contents, which greatly affect its decomposition, also increase, resulting in less decomposable material (Table 2). In *A. sinicus* at 30° C, 70% of total N was mineralized in 4 weeks (Anonymous 1963). As the N content decreases or the C:N increases, the decomposability of green manure decreases. But the decomposability is governed not simply by the C:N. With the same C:N, plants with higher lignin content or with lower soluble N content decompose more slowly (Yoshida and Sato 1934). Generally, a C:N of about 10 is preferable for green manure. The N content varies according to the parts of the plant. The flower and leaf blade have higher N contents than the root, culm, or petiole. Therefore, as the plant approaches maturity, its N content decreases (Table 2). There must therefore be an optimum time for harvest. For *A. sinicus,* the early period of maximum flowering was considered optimum (Anonymous 1963).

**Table 1. Yield and nitrogen contents of green manure crops.**[a]

| Species | Fresh wt (t/ha) | Water (%) | N content (% fresh wt) | Total N (kg/ha) |
|---|---|---|---|---|
| *Astragalus sinicus* | 37.5 – 19.0 | 89 | 0.35 | 131 – 65 |
| Soybean | 11.0 – 30.0 | 80 | 0.58 | 174 – 64 |
| *Medicago denticulata* | 5.6 – 0.3 | 80 | 0.63 | 35 – 18 |

[a] Source: Okuda (1953).

**Table 2. Change of yield and N content during the growth of** *Astragalus sinicus.*[a]

| Date | Growth stage | Yield | | | N (% of dry wt) | C:N |
|---|---|---|---|---|---|---|
| | | Fresh wt (t/ha) | Dry wt (t/ha) | Total N (kg/ha) | | |
| 25 April | Start of flowering | 23.0 | 2.53 | 108 | 4.28 | 9.5 |
| 2 May | Maximum flowering | 36.3 | 3.27 | 122 | 3.73 | 10.6 |
| 9 May | " | 40.9 | 4.50 | 156 | 3.45 | 12.5 |
| 16 May | " | 47.0 | 4.32 | 138 | 3.20 | 13.0 |
| 23 May | Maturity | 34.4 | 4.67 | 123 | 2.63 | 15.3 |

[a] Source: Anonymous (1963).

The amount of N applied to a field increases with the incorporation of green manure. But the beneficial effects of green manure appear only within certain limits. Incorporation of too much green manure accelerates anaerobic fermentation of organic matter after flooding, and depresses rice growth at earlier growth stages. The retarded growth at earlier stages results in excessive uptake of N at later growth stages. Excessive growth then brings about lodging and renders the rice plants susceptible to insect pests and diseases. Table 3 shows the recommended rate of *A. sinicus* incorporation in various regions of Japan.

## EFFECT OF GREEN MANURE INCORPORATION ON SOIL FERTILITY

It was long believed that green manure applied to fields increases soil fertility by supplying N and organic matter. The long-term application of *A. sinicus* at the Toyama Agriculture Experimental Station, Hokuriku District, from 1930 to 1944 raised questions about the accumulation of humus and N in rice fields through green manure application. The results are shown in Table 4. An annual application of 45 t/ha (fresh weight) could not stop the depletion of organic matter and N from the soil, although in the plot that received green manure, the soil had a somewhat higher humus and N content than the control. The amount of organic matter remaining in the soil after 14 years of application was only 6% of that applied. Not much

**Table 3. Recommended rate of** *Astragalus sinicus* **in various regions in Japan.**[a]

| Prefecture[a] and conditions | | Rate (t fresh *A. sinicus*/ha) | |
|---|---|---|---|
| | | Optimum rate | Upper limit |
| Iwate | | 11.3 | 18.8 |
| Akita | | 7.5 | 11.3 |
| Yamagata | | 9.4 – 11.3 | 18.8 |
| Fukushia | | 11.3 | 15 |
| Niigata – | sandy | 11.3 – 15 | 15 – 18.8 |
| | loam | 9.4 – 11.3 | |
| | clay | 7.5 – 9.4 | |
| Nagano | | 15 | 18.8 |
| Toyama – | well drained | 15 | 30 |
| | ill drained | 11.3 | |
| Ishikawa | | 11.3 – 15 | 22.5 |
| Fukui – | early rice | 13 – 15 | 18.8 |
| | late rice | 15 – 16.8 | |

[a] Source:Yamazaki (1957). Arranged from north to south.

**Table 4. Change in humus and nitrogen contents of soil after 14 years' application of *Astragalus sinicus* at 46 t/ha per year.** [a]

| | Humus | | Nitrogen | |
|---|---|---|---|---|
| | t/ha | Diff. | t/ha | Diff. |
| Start | 34.4 | | 2.61 | |
| After 14 years | | | | |
| Control | 25.0 | – 9.4 | 1.84 | – 0.77 |
| *A. sinicus,* | | + 5.6 | | + 0.56 |
| 45 t/ha per yr | 30.6 | – 3.8 | 2.40 | – 0.21 |
| Total applied | 94.5 | | 2.51 | |

[a] Source: Yamazaki (1957).

accumulation of organic matter from green manure can therefore be expected (Yamazaki 1957).

Konishi and Yamazaki (1955) conducted lysimeter experiments to see the effect of green manure application on the leaching of mineral elements from various soils. Leaching of Fe, Mn, and P was accelerated by the application of *A. sinicus.* Leaching of Ca was not affected by the application of *A. sinicus* but was increased by the increasing volume of leachate. The increasing volume of leachate also increased the leaching of K, Si, and Mg, but the leaching of these elements was accelerated as well by the application of green manure. Thus, Yamazaki (1957) warned that continuous application of *A. sinicus,* particularly in well-drained soils, may induce degradation (leaching of Fe, Mn, and Si from the plowed layer) of wetland soils. The surveys of soils in Toyama Prefecture wherein *A. sinicus* had been continuously applied showed that these soils had lower contents of acid soluble Fe and reducible Mn than the soils to which *A. sinicus* had not been applied. The acceleration of the leaching of Fe and Mn was ascribed to accelerated reduction in flooded soil. Motomura (1961) found that leaf extracts from *A. sinicus* could solubilize Fe from the soil. This process may be partly related to the acceleration of Fe leaching by green manure.

## APPLICATION TECHNIQUES

After the negative effects of green manure were recognized, improved application methods were sought to avoid rice yield instability due to excessive application. Delayed flooding, liming, and drainage were considered possible measures. When flooding was delayed, green manure was decomposed aerobically after incorporation, and easily decomposable organic matter decreased during the dry period. Thus, delayed flooding can eliminate excessive reduction after flooding. Prolonged aerobic decomposition was, however, offset by the risk of nitrification of N from the green manure, resulting in a decrease in available N. Researchers at the Toyama Agriculture Experimental Station (Anonymous 1963) recommended a 5-day interval between incorporation and flooding at a time when the soil temperature is about 15° C.

The combination of lime with green manure at 5 kg lime for every 100 kg fresh green manure had long been recommended. Yamazaki (1957) reexamined the effect of liming and failed to find consistency. Lime as a basal dressing sometimes mitigated the harmful effects of organic acids on rice at earlier growth stages. On the other hand, liming stimulated the decomposition of applied and native soil N, resulting in excessive growth of rice at the later stages, particularly when the dose of green manure was excessive. It was concluded that liming as a means of mitigating damage was not as effective as delayed flooding (Anonymous 1963).

Drainage or midseason drying was found to be quite effective in mitigating rice damage caused by excessive reduction after the application of green manure. Irrigation was delayed until slight cracks appeared in the soil for about a week. Root development was stimulated by the drainage, and soil Eh increased. Drainage at the tillering stage or at the panicle initiation stage increased rice yields. However, excessive drainage caused N losses, which offset the positive effects.

Basal application of a small amount of chemical N fertilizer increased rice yields by increasing earlier tiller development, which was rather depressed because of the inhibitive action of anaerobic decomposition and the slow release of N. The dose of chemical N should be about 20 kg/ ha, and should not be applied when the biomass of *A. sinicus* is more than 25 t/ha.

## DISADVANTAGES OF GREEN MANURE

No doubt, green manure crops like *A. sinicus* were cheap sources of N to rice farmers for centuries and made great contributions to rice yields in earlier times when chemical N fertilizers were unknown or insufficient. However, green manures have many disadvantages as fertilizers:

- It is difficult to estimate the amount of N applied and the variation from year to year.
- Rice growth damage, particularly at earlier growth stages, occurs. The higher N supply from green manure is offset by the risk of growth damage due to anaerobic decomposition.
- Rice yields are quite often subjected to instability, particularly as a result of unpredictable weather. The slow release of N and growth depression at earlier stages, particularly in-cooler years, induces excessive growth at later stages, which is detrimental to yield, particularly in cooler years.
- Rather than increasing soil fertility, there is evidence that green manures accelerate the degradation of wetland soils.

Thus, with the increase in availability of cheaper chemical N fertilizers and the tendency toward earlier transplanting, which competed with the prerice growth of green manure crops, the cultivation of green manure crops rapidly faded away in Japan. However, the experiences and research achievements of the past concerning the use of green manures are still valid in situations where the availability of chemical N fertilizers is limited.

## REFERENCES CITED

Anonymous. 1963. Studies of improving fertilizer efficiency of green manure, renge, to wetland rice. Report of special project (Soil and Fertilizer) no. 5 [in Japanese]. Agricultural Research Council in Ministry Agric. Forest Fishery and Toyama Prefectural Agricultural Experimental Station.

Konishi, C., and K. Yamazaki. 1955. Studies on the behavior of mineral nutrients in the paddy field manured with renge (1) Lysimeter test [in Japanese, English summary] J. Hokuriku Agric. 3: 1–61.

Motomura, S. 1961. Dissolution of iron compounds in soils by milk vetch extract. Soil Sci. Plant Nutr. 7:55-60.

Okuda, A. 1953. Hiryogaku gairon (Introduction to fertilizer science) [in Japanese]. Yokendo Tokyo, p. 253 .

Yamazaki, K. 1957. Renge rice culture [in Japanese]. Toyama Agric. Technol. 4(5):1-31.

Yoshida, R., and M. Sato. 1934. Effect of nitrogen fertilizer to the decomposition of green manure in soil [in Japanese]. Agric. Hortic. 9:1927-1941.

# DECOMPOSITION OF ORGANIC MATTER IN WETLAND RICE SOILS

# ANAEROBIC DECOMPOSITION OF ORGANIC MATTER IN FLOODED RICE SOILS

Iwao Watanabe

Anaerobic decomposition of organic matter in various anaerobic environments such as anaerobic sludges, rumens, aquatic sediments, and flooded rice soils has similarities — accumulation of volatile fatty acids (VFA), principally acetic, propionic, and butyric, and the subsequent decrease of VFA with concomitant increase of $CH_4$ and sulfide. In soils, anaerobic decomposition of organic matter is coupled with sequential reduction of electron-accepting agents such as $NO_3^-$, $Mn^{+4}$, $Fe^{+3}$, $SO_4^{-2}$, and $CO_2$. The extent of the reduction is regulated by the balance between the oxidizing and reducing capacities of the soil.

The formation and metabolism of gaseous products ($H_2$, $CH_4$, and $C_2H_4$), $NH_4^+$, VFA, nonvolatile acids, alcohols, amines, volatile compounds, and phenolic acids are described. $H_2$ and 2,3-butanediol are characteristic metabolites of carbohydrate fermentation in paddy soils. Ammonium, volatile S compounds, amines, and isovaleric acid are unique metabolites from proteins. Increased temperature decreases the accumulation of VFA in organic matter-amended soils by stimulating the formation of $CH_4$. The effects of percolation and rice plant roots on anaerobic decomposition and pedogenic process are described.

## FLOODED RICE SOILS AS ANAEROBIC ENVIRONMENTS

During most of the growing cycle of wetland rice, the soil is flooded. Because oxygen movement is 10,000 times slower in water than in air, the oxygen supply from the air cannot meet the oxygen demand of aerobic organisms in the soil. That results in the development of anaerobic conditions. Microbial and biochemical changes are accompanied by a stepwise reduction of the soil — a lowering of the oxidation-reduction potential. Thus, characteristic anaerobic metabolites accumulate in the reduced rice soils.

Anaerobic environments such as anaerobic digestion sludges, rumens, silages, lake and ocean sediments, and paddy soils have many common characteristics. Their patterns of anaerobic metabolism are quite similar, as follows:

- The accumulation of volatile fatty acids (VFA), mainly acetic, propionic, and butyric acids;

---

The International Rice Research Institute, P.O. Box 933, Manila, Philippines.

- The formation of $CH_4$ and sulfide, after the accumulation of VFA; and
- Ammonium is a stable product of N metabolism and nitrate is easily denitrified (Pearsall and Mortimer 1939, Wolin 1979, Toerien and Hattingh 1969).

Much valuable information would be obtained through studies on anaerobic environments such as anaerobic sludges, rumens, and aquatic sediments.

A few reviews on the biochemistry and microbial ecology of paddy soils are available (Ponnamperuma 1972; Yoshida 1975, 1978; Watanabe and Furusaka 1980). Paddy soils differ in many aspects from other aquatic environments. These differences may be summarized as follows:

- The system is not continuous. Rumen and, to a lesser extent, anaerobic sludge are continuous in material input and output. But in paddy soil, organic matter is incorporated during land preparation either as green manure, crop, or weed residues and stubble, and roots are left after the harvest. Weeds, algal biomass, and root exudation (sloughed-off tissues) are inputs during rice growth.
- The system is heterogenous. The reduced cultivated layer of flooded rice soil is sandwiched between aerobic layers — oxidized surface soil and subsoil beneath the plow pan layer. Within the reduced layer there are patches of aerobic sites. The rice root excretes $O_2$ and oxidizes the reduced substances, and paddy soil worms (tubificids) have an aeration function (Kikuchi et al 1977). On the other hand, there are more reduced sites around organic debris (Wada 1975). Farming operations such as weeding and water management disturb the soil.

Thus, anaerobic metabolites are oxidized at the soil surface and in the rhizosphere of rice. This oxidation must be taken into consideration to understand thedynamics of organic and inorganic metabolites during the decomposition of organic matter in flooded rice soil.

## SEQUENTIAL REDUCTION

Biological oxidation of organic matter is initiated from dehydrogenation of the substrate. In the absence of $O_2$ as a terminal oxidant, deprived H (NADH and NADPH) is oxidized anaerobically by inorganic substances like $NO_3^-$ and denitrification metabolites ($NO_2^-$, $N_2O$), $Mn^{+4}$, $Fe^{+3}$, $SO^{-2}$, and $CO_2$. NADH (NADPH) is also oxidized by the intermediates of carbohydrate or amino acid catabolism, resulting in the accumulation of fermentation products.

Takai et al (1956) studied the biochemical and microbiological changes in the anaerobic metabolism of paddy soils and presented the idea of sequential reduction (Takai and Kamura 1969), which takes place roughly in the sequence predicted by thermodynamics (Ponnamperuma 1955). The reduction proceeds from the reactions with higher Eh 7 (Eh at pH 7) to those with lower Eh 7. Takai divided the reduction processes into two major steps — facultatively anaerobic and obligately anaerobic. These two steps correspond roughly to premethanogenic processes or acid formation and methanogenic processes in anaerobic digestion (Toerien and Hattingh 1969). In the first step, reduction of $NO_3^{-1}$, $Mn^{+4}$, and $Fe^{+3}$ takes place in that order; in the second step, sulfate reduction and $CH_4$ formation by strictly anaerobic bacteria take place in that order. The details of these sequential reduction processes are not described in this review. Takai (1961) presented the hypothesis that the ratio of the final C products of organic matter decomposition inanaerobic soil — $CO_2$:$CH_4$ — is regulated by the ratio of oxidizing capacity to reducing capacity. The amount of reducible $O_2$, $NO_3^{-1}$, $Mn^{+4}$, and $Fe^{+3}$ corresponds to the oxidizing (electron-accepting) capacity, because these compounds act as the oxidants during the facultatively anaerobic step. Takai took $NH_3$ formation as the index of reducing (electron-donating) capacity, because ammonium is formed during anaerobic incubation from the easily decomposable organic matter. Table 1 shows that the higher the oxidizing capacity relative to reducing capacity, the higher is the $CO_2$-$CH_4$ ratio. Asami and Takai (1970) found that the addition of amorphous iron oxide in anaerobically incubated soil depressed the accumulation of VFA and $CH_4$. This result supports the idea mentioned above. Thus sesquioxide acted as a buffer to reduction to methanogenic processes.

## DYNAMICS OF METABOLITES

By 1935, the major metabolites of the anaerobic decomposition of organic matter were known (Subrahmanyan 1929; Acharya 1935 a,b,c,d) and were reviewed by Acharya (1935a). Acharya studied the decomposition of rice straw with soil inoculant and mineral elements under anoxic conditions and found the following:

- Acetic and butyric acids, $CO_2$, and $CH_4$ are the major products.
- The decomposition proceeds in two different stages, the first involving the formation of organic acids and the second their conversion into gaseous products.
- Anaerobic conditions require less N for microbial growth than aerobic conditions.
- Protein-rich organic matter produces more butyric acid than carbohydrate-rich material.

Although Acharya (1935a) used plant residues with a small amount of soil inoculant, his earlier observations on organic metabolism were later confirmed in organic unamended and amended paddy soils by many researchers.

Trace quantities of anaerobic decomposition products were recently detected and analyzed through gas chromatography and sensitive detectors (Wang et al 1967a, Laskowski and Broadbent 1970, Banwart and Bremner 1974). These products, though small in quantity, may have significance as plant growth regulators, environmental pollutants, agents for pedogenesis, and indicators of bacterial metabolism.

Adamson et al (1975) and Francis et al (1975) made surveys of volatile organic compounds evolved from anaerobic glucose or glucose + amino acid amended soil. The compounds were analyzed by gaschromato-mass spectrometry. Aldehydes, ketones, alcohols, VFA, esters, and dimethyl monosulfides and disulfides were detected, but volatile compounds explained only a small percentage of the added C in glucose.

In the following section, the metabolisms of ammonium, hydrogen, hydrocarbons, VFA, nonvolatile fatty acids, alcohols, amines, volatile S compounds, and phenolic acids are described.

**Table 1. Oxidizing and reducing capacities of various soils and $CO_2$:$CH_4$.**[a]

| Soil | Fertility | Organic matter metabolism | Oxidizing capacity (m1 $O_2$/100 g) | | | | | | Reducing capacity = $NH_4^+$ formed | | Relative capacity | $CO_2$:$CH_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $O_2$ | $NO_3^{-1}$ | Reducible Mn | Reduced Fe | Total (ml) | (%) | (mg/100 g) | (%) | | |
| Mimakigahara | High | Aerobic | 2.4 | 0.6 | 4.3 | 56 | 63.3 | 100 | 8.8 | 100 | 100 | 100 |
| Nagano Experimental Station | | (Facultatively anaerobic) | 2.4 | 1.0 | 0.7 | 63 | 67.1 | 106 | 17.4 | 198 | 54 | 30 |
| Ichikuwada | | | 3.8 | 1.2 | 0.3 | 63 | 68.5 | 108 | 16.7 | 190 | 57 | 37 |
| Aichi Experimental Station | | | 1.1 | 1.2 | 0.2 | 29 | 22.5 | 36 | 13.0 | 148 | 24 | 19 |
| Aichi-Ariake | | | 3.8 | 1.4 | 2.1 | 35 | 42.3 | 67 | 25.8 | 293 | 23 | 17 |
| Yashiroda | | | 3.4 | 1.9 | 0.9 | 70 | 76.2 | 120 | 39.4 | 448 | 27 | 14 |
| Sanage | | Anaerobic | 1.4 | 0.8 | 0.2 | 4.2 | 6.6 | 10 | 7.8 | 89 | 11 | 11 |
| Teruji | Low | (Strictly anaerobic) | 2.7 | 1.0 | 0.4 | 7.0 | 11.1 | 18 | 16.8 | 191 | 9 | 7 |

[a] Source: Takai (1961). [b] $\frac{\text{Oxidizing}}{\text{reducing}} \times 100.$

## Ammonium

Ammonium, a final and stable product of the anaerobic decomposition of organic N compounds, is derived from deamination of amino acids and aminosugars, decomposition of purines, and hydrolysis of urea. Although in highly reduced soils, nitrate is converted to ammonium (Buresh and Patrick 1981) through the dissimilatory process by *Clostridium* (Caskey and Tiedje 1979), organic N compounds are major sources of ammonium in flooded soils. Inorganic N is released in larger quantities from soil organic N in flooded or anaerobic conditions than in moist dryland or aerobic conditions (Broadbent and Reyes 1971, Asami 1971). Because mineralization of N organic compounds is accompanied by simultaneous immobilization of mineral N, and under anaerobic conditions less ammonium is required for the synthesis of cell material (less immobilization) because of the inefficient cell synthesis of anaerobic metabolism (Acharya 1935c), it was thought that the higher mineralization rate in flooded soil is due to depressed immobilization in this condition (Broadbent and Nakashima 1970, Ponnamperuma 1972).

Asami (1971) studied simultaneous mineralization and immobilization in flooded and aerobic (dryland) soils. In the absence of externally added glucose, the immobilization of inorganic N was slightly higher (1.2 times) in aerobic conditions than in flooded conditions, but the mineralization of soil N was distinctly higher (1.9 times) in flooded soil. In the presence of glucose, the immobilization of inorganic N in aerobic conditions was twice as large as that in flooded conditions, while mineralization in both conditions was not affected much by the addition of glucose. These results mean that the difference in immobilization between aerobic and flooded soils is not great when the supply of organic substrate is limited. These experiments also suggest that other factors besides depressed immobilization may be involved in the faster and larger mineralization in flooded soils.

In aerobic soils, moisture stress may limit the access of microorganisms to decomposable organic matter indigenous in soil and depress the organic matter decomposition.

Externally added organic matter decomposes only slightly faster in flooded soil than in aerobic soils (Shioiri and Mitsui 1935). The C:N of organic matter required for net mineralization was about 12, not greatly different between the two soil conditions (Shioiri and Mitsui 1935). In view of the experimental results of Greenwood and Lees (1960) showing slower deamination of amino acids in anaerobic conditions, the hydrolysis of protein may be the limiting factor in mineralization of organic N.

## Hydrogen

Harrison and Aiyer (1915) found the formation of $H_2$ in swampy rice soil and its oxidation in surface soil. Just after flooding air-dried soil or soil amended with carbohydrate, a large volume of $H_2$ is evolved, and Eh and pH values drop sharply. At the maximum, 1 mol glucose accumulated 2 mol $H_2$ (Sato and Yamane 1966). $H_2$ is produced by the anaerobic bacteria, Enterobacteriaceae and *Clostridium.* Because Takeda and Furusaka (1975b) found that in soil amended with glucose, *Clostridium* was not predominant, $H_2$ evolution just after the addition of glucose is probably due to the action of Enterobacteriaceae. $H_2$ uptake is observed in both facultatively and strictly anaerobic stages, and $H_2$ supports the reduction of iron (Saito, personal communication). $H_2$ may be used for iron reduction after $H_2$ evolution in glucose-amended soil. In the strictly anaerobic stage, $H_2$ is used actively by $CH_4$-forming bacteria (Zeikus 1977) and sulfate-reducing bacteria (Furusaka 1968).

### Methane and alkanes

Methane is a final product of the anaerobic decomposition of organic matter. Studies on the mechanism of $CH_4$ formation in paddy soil are more limited than studies on other anaerobic systems. The substrate of $CH_4$ formation is a major interest in methanogenesis. Labeled C and the inhibition technique (Cappenberg 1974, Cappenberg and Prins 1974, Laskowski and Broadbent 1970) clarify the substrate relation of methanogenesis. These techniques have suggested that acetic acid is the major substrate for $CH_4$ in anaerobic soil. Takai (1970) reported the preferential formation of $CH_4$ from the methyl $^{14}C$ of acetate in flooded soil, and the proportion of $CH_4$ derived from $CO_2$ added to flooded soil ranged from 10 to 25%. As mentioned above, the $CO_2$:$CH_4$ of the final decomposition products is dependent upon soil characteristics.

Goodlass and Smith (1978) tried to detect alkanes ($C_3$, $C_4$), but these are detected only in aerobic conditions from the amended plant material.

### Ethylene

Recently, the formation of $C_2H_4$ in anaerobic soil caught the attention of soil biochemists and plant pathologists, because $C_2H_4$ is a plant hormone and is suspected to be the regulating agent for plant pathogenicity and root growth (Smith and Russel 1969, Smith 1976, Primrose 1979). The mechanism, percursors, and organisms responsible for $C_2H_4$ formation in soil are still in great dispute. But it is most likely that $C_2H_4$ is accumulated under anaerobic conditions because of the inability of the $C_2H_4$ formed to be oxidized (Smith and Cook 1974). The addition of organic matter stimulates $C_2H_4$ formation (Yoshida and Suzuki 1975, Goodlass and Smith 1978). Methionine is known as a percursor of $C_2H_4$ formation (Lieberman et al 1965), but plant residues high in protein did not form more $C_2H_4$ than less proteinaceous organic matter (Yoshida and Suzuki 1975). Sutherland and Cook (1980) also disputed methionine as a percursor of $C_2H_4$ in anaerobic soil. Nakano and Kuwatsuka (1979b) showed that the $C_2H_4$ evolved after the addition of rice straw originated partly abiologically from straw and was probably stored in the straw either as $C_2H_4$ or as its percursors, and that the biological formation of $C_2H_4$ in flooded soils follows abiological formation.

Smith et al (1978) presented data that $Fe^{+2}$ induced $C_2H_4$ abiologically in anaerobic soil; however, $C_2H_4$ was formed before the accumulation of $Fe^{+2}$. Therefore, it is suspected that only a part of $C_2H_4$ formation may be coupled with $Fe^{+2}$ formation. The amount of $C_2H_4$ formed from straw was 14 µl/g straw for 4 days (Nakano and Kuwatsuka 1979a) and 1.5 µl/kg soil per day from paddy soil without organic amendments (Yoshida and Suzuki 1975). The $C_2H_4$ released from paddy soil was less than 1.5 ml/m$^2$ per day in most soils (Watanabe, unpublished). This value was obtained during acetylene reduction assay (in control assays without acetylene). The addition of dead plant material produces more $C_2H_4$ than the addition of fresh material (Nakano and Kuwatsuka 1979a). $C_2H_4$ is stable in anaerobic soil, except that it is lost through the rice plant (Lee and Watanabe 1977).

## Volatile fatty acids

Table 2 shows the amount of VFA found in flooded soils that were amended with plant material.

In most cases, acetic acid is predominant, followed by propionic acid and butyric acid. The concentration of acetic acid was about 10 mmol/kg soil when legume leaves were added. The relative abundance of butyric acid among VFA was higher from green manure than from gramineous plant residue (Fujii et al 1972a), higher with higher amounts of green manure, and higher in more reductive soils (Takai et al 1956, Takijima and Sakuma 1961, Motomura 1962). Takeda and Furusaka (1975b) also found that butyric acid was formed more from peptone-amended soil than from glucose-amended soil. In particular, in peptone-amended soil, the presence of branched fatty acids (iso-valerate and iso-butyrate) was noted. Because *Clostridium* isolated from paddy soil (except *C. tertium*) utilized only amino acids as energy sources and produced acetic and butyric acids as well as branched fatty acids, and the branched fatty acids are the products of the Stickland reaction (oxidation-reduction reactions between amino acid molecules), Takeda and Furusaka (1975a,b) ascribed the presence of branched fatty acids to the activity of *Clostridium,* which preferentially grows on amino acids. None of the facultative anaerobes (mostly Enterobacteriaceae) could produce branched fatty acids.

Many kinds of Enterobacteriaceae, *Clostridium,* and sulfate-reducing bacteria can produce acetic acid, presumably from pyruvic acid and lactic acid. Acetic acid is a major FVA presumably because it is decomposed more slowly than its precursors. Goto and Onikura (1967a) showed that lactic acid is decomposed more quickly in reduced soil (4 me/ kg soil per day) than acetic acid (0.3 me/ kg per day). Cappenberg and Prins (1974) also presented data showing a more rapid turnover of lactate (28.9/ hour) than acetate (0.35/ hour) in lake mud. The oxidation of FVA (mostly acetic acid) was coupled with Fe reduction (Kamura and Takai 1961, Asami and Takai 1970). When the relative volume of oxidizing capacity is lower, VFA remains oxidized because of a shortage of oxidizing capacity and accumulates during Fe reduction. On the other hand, when the oxidizing capacity exceeds the reducing capacity, VFA oxidation is fully coupled with Fe reduction, and VFA accumulates only after the Fe reduction process finishes.

Lactate serves as the substrate for sulfate-reducing bacteria (Furusaka 1968, Cappenberg 1974). The recent discovery of sulfate-reducing bacteria that utilize acetate (Widdel and Pfennig 1977) necessitates a reexamination of the role of acetate in sulfate reduction. Recently, Sorensen et al (1981) suggested acetate as an energy-supplying substrate for sulfate reduction in marine sediments. The addition of 20 mM molybdate inhibited sulfate reduction and increased acetate content. The molybdate inhibition technique needs to be applied in paddy soils.

**Table 2. Amount of volatile fatty acids (VFA) in flooded soils amended with plant material.**

| Kind and amount of plant material[a] | Soil | Temperature (°C) | VFA me/100 g soil (days) Acetic | Propionic | Butyric | Total | Analytic[b] | Authors |
|---|---|---|---|---|---|---|---|---|
| Rice straw 1 g DW/100 g | Kyushu Japan | 27.5 | 1.4 (14) | 0.13 (28) | 0.12 (14) | 1.62 (14) | Water-soluble. LC | Goto and Onikura (1967a) |
| Wheat straw 1 g DW/10 | ” | ” | 0.92 (14) | | 0.13 (14) | 1.05 (14) | | |
| Italian rye grass 1 g DW/100 g | ” | ” | 0.59 (14) | | 0.035 (14) | 0.63 (14) | | |
| Compost 1 g DW/ 100 g | ” | ” | 0.064 (14) | | 0.010 (14) | 0.083 (14) | | |
| *Sesbania* leaf 25 g FW/100 g | Maahas | 25 | 2.92 (5) | 0.41 (5) | 0.28 (3) | | Acidic soluble. GC | Chandrasekaran and Yoshida (1973) |
| | Libon, Philippines | ” | 4.38 (3) | 0.13 (5) | 0.48 (5) | | | |
| Rice straw 24 t/ha (pot) | Kyushu | Greenhouse with plant | 0.26 (10) | | 0.11 (10) | 0.39 (10) | Water soluble. LC | Goto and Onikura (1967b) |
| 12 t/ha | | | 0.13 (10) | | 0.018 (10) | 0.17 (10) | | |
| *Astragalus sinicus* dry powder 0.3 g/l00 g | Chiba sandy | 25 | 0.94 (7) | | 0.39 (4) | 1.27 (7) | Water soluble. LC | Takijima and and Sakuma (1961) |

Continued on opposite page

**Table 2. continued.**

| Kind and amount of plant material[a] | Soil | Temperature (°C) | VFA me/100 g soil (days) | | | | Analytic[b] | Authors |
|---|---|---|---|---|---|---|---|---|
| | | | Acetic | Propionic | Butyric | Total | | |
| 0.35 g/l00 g | Nagano silt | " | 0.89 (14) | 0.10 (14) | | 1.11 (14) | | |
| 0.52 g/100 g | Tochigi Ando | " | 1.60 (7) | 0.15 (14) | | 2.00 (7) | | |
| 0.69 g/l00 g | Iwanuma peaty | " | 2.90 (4) | 0.31(7) | | 3.60 (4) | | |
| *Astragas* dry powder | | | | | | | | |
| 1.5 g/l00 g | Sanage, Japan | 30 | 2.2 (7) | 0.11 (7) | | | Water soluble. LC | Takai (1958) |
| Peanut leaf powder | | 16 | 1.68 (15) | 0.26 (15) | 0.300 (15) | 2.27 (15) | Water soluble.<br>steam distillation | Mitsui et al (1959b) |
| 1.3 g DW/100 g | | 35 | 0.0 (15) | 0.06 (15) | 0.001 (15) | 0.06 (15) | LC | |
| *Crotalaria* leaf | | | | | | | | |
| 5 g FW/100 g | TSES | 30 | 1.8 (7) | trace | trace | | Alkali extraction.<br>Acid ether extraction. | Wang et al (1967b) |
| | Sialung | " | 2.16 (7) | " | " | | | |
| Sugar cane leaf | Yuehmi | " | 1.70 (7) | " | " | | GC | |
| 1.5 g DW/100 g | TSES | " | 0.200 (14) | " | " | | | |
| | Sialung | " | 0.39 (7) | " | " | | | |
| | Yuehmei | " | 0.43 (14) | " | " | | | |

[a] DW = dry weight, FW = fresh weight. [b] LC = silica gel liquid chromatrography, GC = gas-liquid chromatography.

Hayashi and Furusaka (1979) found that the population of *Propionibacterium* was 10 times higher than the population of *Clostridium,* and they presented evidence that lactate is a precursor of propionic acid fermentation (Hayashi and Furusaka 1980).

### Nonvolatile fatty acids

The presence of nonvolatile fatty acids such as fumaric, succinic, and lactic acids in paddy soils has been reported (Takai et al 1956, Takijima and Sakuma 1961, Lynch 1980), but in concentrations much smaller (1,000 times) than those of VFA. Wang et al (1967b) detected malonic, tartaric, and malic acids in alkali extracts, but the effect of anaerobiosis differed according to kinds of acids and soils; there was no consistent tendency.

### Alcohols

Wang and Chuang (1967) detected 200-1,500 µmol kg alcohols (methanol > ethanol > N-propanol) in sugarcane leaf-amended flooded soils. From *Crotalaria* leaf-amended soils, more alcohols were formed, and n-butanol (10 mmol/ kg) was predominant. Lynch (1977) detected 50-120 mg ethanol/35 g straw during the decomposition of wheat straw, but it accumulated slightly more in anaerobic conditions than in aerobic conditions.

In glucose-amended soil, facultative anaerobes (Enterobacteriaceae and *Bacillus)* become dominant (Takeda and Furusaka 1975b), and many of them form acetoin (Voges-Proshauer reaction) and 2,3-butanediol. Kubota and Furusaka (1981) could detect 2,3-butanediol (40 µg/g soil), acetoin, ethanol, and butanol in glucose-amended soils and in a soil rich in organic matter. However, the amount of 2,3-butanediol was much smaller (30 µg/ kg soil) in wetland soils than in soils tested in the laboratory (Kubota and Furusaka 1982).

### Amines and volatile sulfur compounds

Fujii et a1 (1972a) detected amines (putresine, cadaverine, trimethylamine, ethylamine, n-propylamine, and isobutylamine) during anaerobic decomposition of clover powders (maximum 280 g putresine/g clover) and smaller amounts of tertiary amines from rice straw. But the concentration detected was not harmful to rice seedling growth (Fujii et a1 1972b).

Asami and Takai (1963) could detect an amount (several ppm) of methylmercaptan ($CH_3SH$) in an ill-drained organic matter-rich paddy soil; the addition of green manure increased the amount up to 100 µg/g organic matter.

A sensitive gas chromatographic technique with a flame photometric detector was used to detect volatile S compounds (Banwart and Bremner 1974). Volatile S compounds from unamended and sulfate-treated soils are principally $CH_3SCH_3$ and, to a lesser extent, COS, $CS_2$, $CH_3SH$, and $CH_3SSCH_3$. More S was volatilized in flooded soil conditions than in aerobic conditions (Banwart and Bremner 1967a,b).

Addition of organic compounds like sewage sludges, animal manure, and plant material enhanced the release of volatile S compounds (Banwart and Bremner 1976b). $CH_3SCH_4$ and $CH_3SSCH_3$ were the major products from sludges, and

$CH_3SH$ and $CH_3SCH_3$ from plant material. The ratio of volatilized S to the S content of the added materials was 3% or less. Minami et al (1981) also studied volatilization of S compounds from paddy soils. Glucose + sulfate addition only slightly increased volatilization of COS, $CS_2$, $CH_3SCH_3$, and $CH_3SSCH_3$ over unamended soil. Rice straw increased the volatilization of all S compounds detected.

It is therefore likely that major, not entire, sources of volatile S compounds are S-containing amino acids. The formation of volatile S compounds from sulfate was detected only to a smaller extent. From cystine-amended paddy soil, major volatile S compounds were $H_2S$ and COS, while from methionine, major products were $CH_3SSCH_3$ and $CH_3SH$. Thedifference of metabolites is understandable from their chemical nature (S-S- in cystine vs $CH_3S$- in methionine).

## Phenolic compounds

Chou and Lin (1976) and Chou and Chiou (1979) claimed that phenolic acids could be the causative agents of poor rice growth attributed to left-over crop residues in the second crop of rice. However, they and Wang et al (1967a, b) extracted phenolics by alkaline solution or alcohol, their contents being around $10^{-5}$ M. Because water-soluble phenolics are presumably much smaller and the toxicity of phenolic acid in aquatic solution is on the order of $10^{-5}$ M (Takijima 1963), the actual importance of phenolic compounds in flooded soils as toxicants needs to be reexamined.

Shindo and Kuwatsuka (1975) and Kuwatsuka et al (1977) reported experiments on the behavior of phenolic compounds in dryland and flooded soils. In most cases, they also used alkaline extracts to determine phenolic acids. During moist or submerged incubation of rice straw, the total amount of phenolic acids present in straw as an ether-extractable form rapidly decreased (half life about 30 days at 30°C). Phenolic acids disappeared a little more slowly in flooded conditions than in moist conditions (Shindo and Kuwatsuka 1975). Chemical interchanges between phenolic acids were suggested. In both conditions, the decrease of *p*-coumaric and ferulic acids was accompanied by an increase of *p*-hydroxybenzoic and vanillic acids, respectively.

The disappearance of phenolic compounds from flooded soil is not likely to be due solely to decomposition, but may be due to condensation, because ring cleavage is generally coupled with oxygenation and requires aerobic conditions. Oxidation ($CO_2$ formation) of labeled salicylic acid was lower after flooding than that of aliphatic acids (Tate 1979).

Contrary to general belief in the slower breakdown of the phenol ring in anaerobic conditions, Clark and Fina (1952) and Fina et al (1978) found anaerobic cleavage of the benzene ring of benzoic acid and methane formation in enriched anaerobic sludge.

Wang et al (1967b) detected *p*-hydroxybenzoic, vanillic, *p*-coumaric, and ferulic acids in alkaline extracts, but dynamics during the incubation of soil with organic matter did not show much difference between aerobic and anaerobic conditions.

Lynch (1980) detected a small amount of these kinds of phenolic acids ($10^{-5}$–$10^{-6}$ M) in an extract of the anaerobic decomposition of *Agropyron repens* rhizomes. This extract showed strong growth-inhibiting activity and contained about 30 mM VFA, so he attributed the growth-inhibiting action to VFA.

## CARBOHYDRATE AND PROTEIN DECOMPOSITION

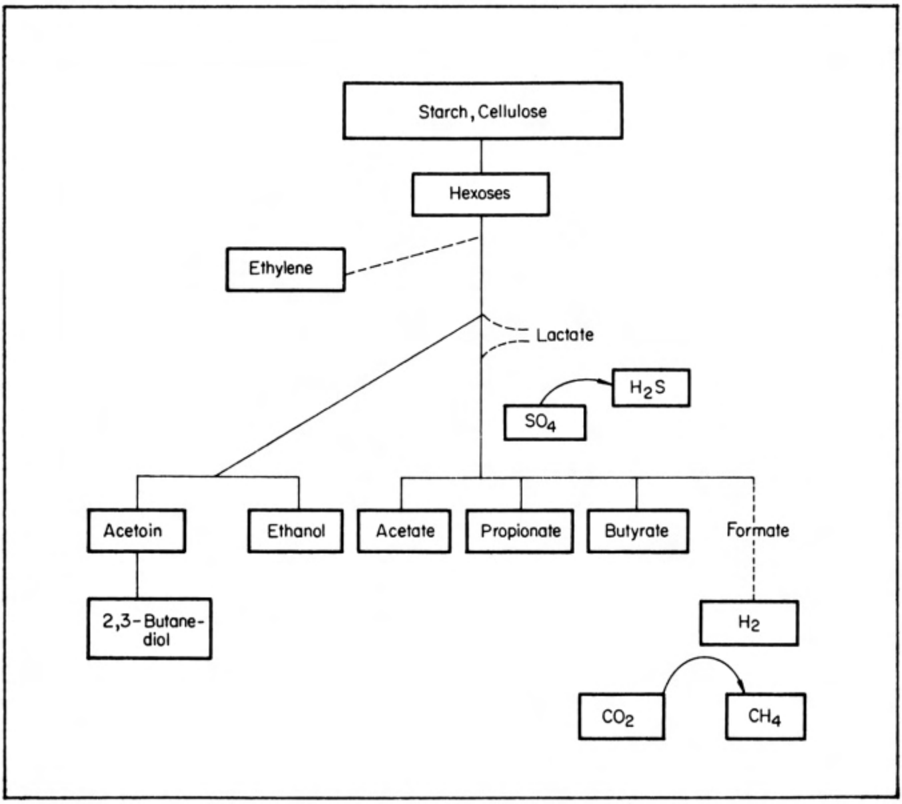
To summarize the anaerobic metabolism of organic matter decomposition in paddy soils, metabolic schema of carbohydrates and protein — major plant components — are shown in Figures 1 and 2.

### From carbohydrates

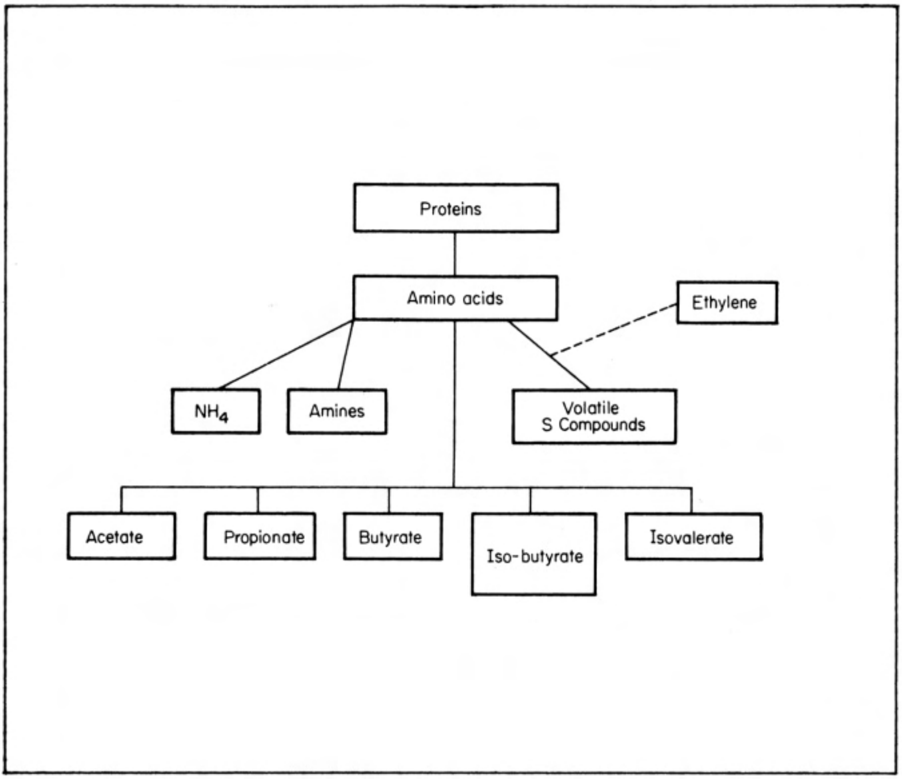
Pyruvate may be the metabolite from which various fermentation products are formed (Wood 1961). Lactate is likely to be the percursor of acetic acid. $H_2$ and 2-3-butanediol are characteristic metabolites when carbohydrates are decomposed anaerobically. Ethylene may be formed from both carbohydrates and amino acids (likely to be methionine).

### From proteins

Proteins are hydrolized to amino acids, from which ammonium, amines, sulfide, volatile S compounds, and ethylene are formed. Branched fatty acids (mainly iso-valeric acid) are also unique products from amino acids. Butyric acid is formed in larger quantities from amino acids than from carbohydrates.



1. Metabolism of carbohydrates in flooded soil.



**2.** Metabolism of amino acids in flooded soil.

## FACTORS AFFECTING ANAEROBIC ORGANIC DECOMPOSITION

Kind of organic matter and kind and volume of oxidizing agent are important factors affecting anaerobic decomposition which have already been described in the preceding sections. Temperature, percolation, and the presence of plants will be discussed as important cultural factors affecting decomposition.

### Temperature

Mitsui et al (1959a) pointed out that the growth-retarding action of organic matter amendments to rice was more pronounced in cooled pots (cooled soil temperature) than in uncooled pots. Mitsui et al (1959b) attributed to organic acids the greater damage by green manure at lower soil temperature. At lower temperature more VFA was accumulated. Lower VFA content at higher temperature was also observed by Goto and Onikura (1967a). Cho and Ponnamperuma (1971) expressed a similar view.

Sato and Yamane (1966) studied the effect of temperature (10°-35° C) on organic acid accumulation and $H_2$ and $CH_4$ formation from glucose-amended soil. With increasing temperature, organic acid and $H_2$ persisted for a shorter time and more $CH_4$ was formed. Koyama (1963) also pointed out the effect of high temperature on

$CH_4$ formation. Therefore, in organic matter-amended soil, an elevated temperature causes more $CH_4$ formation than the decomposition of organic matter; the result is less and shorter accumulation of VFA. Because in soil without organic matter, the release of readily decomposable organic matter is rate limiting and high temperature also accelerates the decomposition of native soil organic matter (Harada 1959), the net effect of higher temperature may be a higher VFA content, contrary to observations on soil amended with organic matter (Inubushi, personal communication).

## Percolation

Most highly productive paddy soils in Japan are characterized by fairly good internal drainage (15 mm/day) and low water table. To clarify the effect of water percolation on the chemistry and microbiology of flooded soils, Takai et al (1974) conducted laboratory experiments. Submerged soils with varying contents of readily decomposable organic matter were percolated either with water that was saturated with ambient air or with deoxygenated water. Comparisons were made with a stagnant water treatment. It was assumed that changes in chemical and microbial properties brought about by percolation were determined by the amount of readily decomposable organic matter in soil. If the soil contained an excess of readily decomposable organic matter, the supply of $O_2$ and removal of water-soluble substances brought about by percolation were conducive to enhanced microbial activities, increased formation of $Fe^{+2}$ and $NH_4^+$, and decreased Eh of the soil. It was assumed that the removal of excess organic matter that inhibited microbial activity may have enhanced microbial transformation. The nature of the organic matter that was thought to depress microbial activity was not known.

In soil lower in readily decomposable organic matter, percolation increased soil Eh and decreased $Fe^{+2}$ content by removing available organic substrates. It is likely, however, that the removal of excess organic matter by percolation would also mitigate the harmful action to rice roots (Mitsui et al 1959a). Takijima (1963) observed that the percolation of peaty soils increased the development of the rice root system and that in glucose-amended soil, the percolation rather increased organic matter decomposition and $Fe^{+2}$ formation. He also presumed that instability of rice yield, often observed just after percolation improvement of peaty soil, was attributable to enhanced organic matter decomposition by percolation.

Anaerobic percolation accelerates leaching or eluviation of Fe and Mn to the subsoil, leading to the formation of an eluviated horizon. The addition of organic matter stimulates this process (Konishi and Yamazaki 1955). Three mechanisms explain the reductive leaching of Fe and Mn: 1) formation of $Fe^{+2}$ and $Mn^{+2}$ during anaerobic respiration (Ottow and Glathe 1973) and their leaching, 2) solubilization of Fe and Mn and their partial reduction due to the compounds present in organic amendments (Motomura 1961), and 3) formation of organic compounds in anaerobic conditions, which reduce $Fe^{+3}$ and $Mn^{+4}$ (Okazaki et al 1981). Leachates from flooded soil columns contained organic matter with varying molecular weight, which had the capacity to reduce $Fe_2O_3$ and to be trapped by $Al_2O_3$. Aldehydes were found among the lower molecular weight substances as Fe-reducing compounds (Okazaki et al 1981).

**Table 3. Decomposition of straw in paddy fields, 1981.**[a]

| | Korea (20°-25°C) | | Philippines (28°-30°C) | | | | China (22°-33°c) | | | | Thailand (28°-30°c) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Suweon | | Los Baños | | Luisiana | | Fuchou | | Wanli | | Bangkhen | | Klong luang | |
| | Days | OM | Days | OM | Days | OM | Days | OM | Days | OM | Days | OM | Days | OM |
| | 10 | 58 | 10 | 57 | 11 | 58 | 11 | 57 | 10 | 57 | 10 | 56 | 10 | 43 |
| | 20 | 49 | 20 | 46 | 20 | 52 | 21 | 42 | 20 | 46 | 20 | 45 | 20 | 41 |
| | 30 | 42 | 30 | 37 | 32 | 42 | 31 | 39 | 30 | 42 | 30 | 35 | 30 | 31 |
| | 40 | 35 | 41 | 37 | 42 | 38 | 40 | 32 | 40 | 34 | 40 | 27 | 40 | 24 |
| | 60 | 31 | 49 | 29 | 49 | 33 | 60 | 26 | 60 | 29 | 60 | 21 | 60 | 19 |
| | 80 | 17 | 57 | 28 | 57 | 31 | 80 | 20 | 80 | 22 | 80 | 14 | 80 | 15 |
| | | | 68 | 27 | 68 | 27 | | | | | | | | |
| | | | 77 | 23 | 78 | 22 | | | | | | | | |
| | | | 103 | 22 | 105 | 27 | | | | | | | | |
| Decomposition rate (%/day) (± s. d.)[b] | 1.3 ± 0.16 | | 1.3 ± 0.12 | | 1.4 ± 0.04 | | 1.3 ± 0.08 | | 1.2 ± 0.08 | | 1.9 ± 0.1 | | 1.6 ± 0.1 | |

[a] I. Watanabe, T. Aziz, W. Ventura, W. Cholitkul, C. C. Liu, and S. K. Lee (unpublished). Initial organic matter (OM) content was 0.84 g/g straw. Values are 100 X g OM/bag. [b] s. d. = standard deviation.

## Presence of rice plants

The rice root has $O_2$-releasing and oxidizing ability. Because of this ability, some metabolites may be directly absorbed or oxidized by rice roots or indirectly by microorganisms living in the rhizosphere. Takijima (1961) reported that the presence of rice plants stimulated the disappearance of VFA from water culture amended with VFA.

Acetic acid added externally is metabolized by rice roots (Mitsui and Kumazawa 1961). The role of microorganisms in acetate metabolism in the rhizosphere is unknown.

Yoshida and Suzuki (1975) found that $C_2H_4$ is decomposed in the rhizosphere of wetland rice plants. Because the sterile rice root is unable to decompose $C_2H_4$, microorganisms in the rhizosphere are likely to be involved in $C_2H_4$ metabolism. The oxidizing ability and presumably the detoxifying activity of rice roots are dependent upon the nutrition of the plant. Poorly nourished rice plants, particularly those deficient in N, trigger the reduction of the rhizosphere (Okajima 1960).

## Perspective

More is known about anaerobic decomposition in aquatic environments such as anaerobic sewage treatment plants, rumens, and aquatic sediments than in paddy soils. This knowledge includes the kinetics of the metabolites, simulation models (Pohland 1971), and the ecology of the responsible microorganisms. The introduction of techniques used in these studies like the turnover of labeled metabolites, computer simulations, inhibition techniques, immuno-fluorescent techniques to identify microorganisms, and so on is urgently needed in the study of anaerobic decomposition in paddy soils. To understand the possible toxicity or stimulation that organic matter causes in rice plants, the quantitative determination of metabolites *in situ* is necessary, particularly in the presence of rice plants.

To discover the decomposition rates and the mode of action on rice, which may differ in varying environmental conditions, international collaboration among the many rice-growing countries is necessary. Recently, IRRI organized collaborative research on the decomposition of rice straw in various Asian countries. Straw was put in plastic net bags and buried in soil. Bags were taken out periodically and the organic matter content of the straw was determined (Table 3); there were no great differences in decomposition rates among various sites. This is an example of the kind of work that should be done through international collaboration.

## REFERENCES CITED

Acharya, C. N. 1935a. Studies on the anaerobic decomposition of plant materials. I. The anaerobic decomposition of rice straw *(Oryza sativa).* Biochem. J. 29:528-541.

Acharya, C. N. 1935b. Studies on the anaerobic decomposition of plant materials. II. Some factors influencing the anaerobic decomposition of rice straw *(Oryza sativa).* Biochem. J. 29:953-960.

Acharya, C. N. 1935c. III. Comparison of the course of decomposition of rice straw under anaerobic, aerobic and partially aerobic condition. Biochem. J 29:1116-1120.

Acharya, C. N. 1935d. IV. Decomposition of plant substances of varying composition. Biochem. J. 29:1459-1467.

Adamson, J. A., A. J. Francis, J. M. Duxbery, and M. Alexander. 1975. Formation of volatile organic products in soil under anaerobiosis. I. Metabolism of glucose. Soil Biol. Biochem. 7:45-50.

Asami, T. 1971. Immobilization of added inorganic nitrogen and mineralization of soil organic in paddy soil incubated under submerged or upland condition [in Japanese]. J. Sci. Soil Manure, Jpn. 42:74-80.

Asami, T., and Y. Takai. 1963. Formation of methyl mercaptan in paddy soils. Part 2. Soil Sci. Plant Nutr., Tokyo. 9:65-69.

Asami, T., and Y. Takai. 1970. Relation between reduction of free iron oxide and formation of gases in paddy soil [in Japanese]. J. Sci. Soil Manure, Jpn. 41:48-55.

Banwart, W. L., and J. M. Bremner. 1974. Gas chromatographic identification of sulfur gases in soil atmosphere. Soil Biol. Biochem. 6: 113-115.

Banwart, W. L., and J. M. Bremner. 1976a. Volatilization of sulfur from unamended and sulfate treated soils. Soil Biol. Biochem. 8: 19-22.

Banwart, W. L., and J. M. Bremner. 1976b. Evolution of volatile sulfur compounds from soils treated with sulfur containing organic material. Soil Biol. Biochem. 8:439-443.

Broadbent, F. E., and T. Nakashima. 1970. Nitrogen immobilization in flooded soils. Am. Soc. Soil Sci. Proc. 34:218-221.

Broadbent, F. E., and O. C. Reyes. 1971. Uptake of soil and fertilizer nitrogen by rice in some Philippine soils. Soil Sci. 112:200-205.

Buresh, R. J., and W. H. Patrick, Jr. 1981. Nitrate reduction to ammonium and organic nitrogen in an estuarine sediment. Soil Biol. Biochem. 13:279-283.

Cappenberg, T. E. 1974. Interactions between sulfate-reducing and methane-producing bacteria in bottom deposits of a fresh-water lake. II. Inhibition experiments. Antonie van Leeuwenhoek. 40:297-306.

Cappenberg, T. E., and R. A. Prins. 1974. Interaction between sulfate-reducing and methane-producing bacteria in bottom deposits of a fresh-water lake. III. Experiments with 14C-labeled substrates. Antonie van Leeuwenhoek. 40:457-469.

Caskey, W. H., and J. M. Tiedje. 1979. Evidence of clostridia as agents of dissimilatory reduction of nitrate to ammonium in soils. J. Soil Sci. Soc. Am. 43:931-936.

Chandrasekaran, S., and T. Yoshida. 1973. Effect of organic acid transformations in submerged soil on growth of the rice plant. Soil Sci. Plant Nutr. 19:39-45.

Cho, D. Y., and F. N. Ponnamperuma. 1971. Influence of soil temperature on the chemical kinetics of flooded soils and the growth of rice. Soil Sci. 112:184-194.

Chou, C. H., and S. J. Chiou. 1979. Auto intoxification mechanism of *Oryza sativa.* II. Effect of culture treatments on the chemical nature of paddy soil and rice productivity. J. Chem. Ecol. 5:839-859.

Chou, C. H., and H. J. Lin. 1976. Phytotoxic effects of decomposing rice residue. J. Chem. Ecol. 2:353-367.

Clark, F. M., and L. R. Fina. 1952. The anaerobic decomposition of benzoic acid during methane fermentation. Arch. Biochem. Biophys. 36:26-32.

Fina, L. R., R. L. Bridges, T. H. Coblenz, and F. F. Roberts. 1978. The fate of carbon four and identification of propionic acid. Arch. Microbiol. 118:169-172.

Francis, A. J., J. M. Duxbury, and M. Alexander. 1975. Formation of volatile organic products in soils under anaerobiosis. II. Metabolism of amino acids. Soil Biol. Biochem. 7:51-56.

Fujii, K., M. Kobayashi, and E. Takahashi. 1972a. Amines in the mixture of plant residue and sand incubated under aerobic and waterlogged condition [in Japanese]. J. Sci. Soil Manure, Jpn. 43:160-164.

Fujii, K., M. Kobayashi, and E. Takahashi. 1972b. Effect of organic acids and amines on growth of rice seedlings [in Japanese]. J. Sci. Soil Manure, Jpn. 43:211-217.

Furusaka, C. 1968. Studies on the activity of sulfate reducers in paddy soil [in Japanese]. Bull. Inst. Agric. Res. Tohoku Univ. 19:101-184.

Goodlas, G., and K. A. Smith, 1978, Effect of organic amendments on evolution of ethylene and other hydrocarbons. Soil Biol. Biochem. 10:201-205.

Goto, S., and Y. Onikura. 1967a. Organic acid in paddy soil. I. The production of organic acids in waterlogged soil in the presence of organic matter under laboratory condition [in Japanese, English summary]. Bull. Kyushu Agric. Exp. Stn. 12:235-249.

Goto, S., and Y. Onikura. 1967b. Organic acid in paddy soil. II. The production of organic acids in the presence of rice straw in relation to the growth and yield of rice plant using pot culture technique [in Japanese, English summary]. Bull. Kyushu Agric. Exp. Stn. 13:173-186

Greenwood, D. J., and H. Lees. 1960. Studies on the decomposition of amino acids in soils. II. The anaerobic metabolism. Plant Soil. 12:69-80.

Harada, T. 1959. The mineralization of native organic nitrogen in paddy soils and the mechanism of its mineralization [in Japanese, English summary]. Bull. Nat. Inst. Agric. Sci. B9:123-199

Harrison, W. H., and P. A. S. Aiyer. 1915. The gases of swamp rice soils. II. Their utilization for the aeration of the roots of crops. Mem. Dep. Agric. India Chem. Ser. 4:1-7.

Hayashi, S., and C. Furusaka. 1979. Studies on *Propionibacterium* isolated from paddy soils. Antonie van Leeuwenhoek. 45:565-574.

Hayashi, S., and C. Furusaka. 1980. Enrichment of *Propionibacterium* in paddy soil by addition of various organic substances. Antonie van Leeuwenhoek. 46:313-320.

Kamura, T., and Y. Takai. 1961. The microbial reduction mechanism of ferric iron in paddy soils, Part I [in Japanese]. J. Sci. Soil Manure, Jpn. 32:135-138.

Kikuchi, E., C. Furusaka, and Y. Kurihara. 1977. Effects of tubificids (*Branchiura sowerbyi* and *Limnodrilus socialis*) on the nature of submerged soil ecosystem, Jpn. J. Ecol. 27:163-170.

Konishi, C., and K. Yamazaki. 1955. Studies on the behavior of mineral nutrients in paddy field manured with renge (1) Lysimeter test [in Japanese, English summary]. J. Hokuriku Agric. 3:1-16.

Koyama, T. 1963. Gaseous metabolism in lake sediments and paddy soils and the production of atmospheric methane and hydrogen. J. Geophys. Res. 63:3971-3973.

Kubota, M., and C. Furusaka. 1981. Formation of 2, 3-butanediol, acetoin, ethanol, and butanol in paddy soils [in Japanese]. J. Sci. Soil Manure, Jpn. 52:149-154.

Kubota, M., and C. Furusaka. 1982. Formation of 2, 3-butanediol in paddy field soils [in Japanese]. J. Sci. Soil Manure, Jpn. 53:247-248.

Kuwatsuka, S., S. Shindo, and K. Tsutsuki. 1977. Behaviour of phenolic substances in the decaying process of plant materials. Pages 731-736 *in* Proceedings International Soil

Environment Fertility Management in Intensive Agriculture. Society Soil Manure, Tokyo, Jpn.

Laskowski, D. A., and F. E. Broadbent. 1970. Effect of chlorinated aliphatic acids on gas and volatile fatty acid and production in anaerobic soil. Soil Sci. Soc. Am. Proc. 34:72-76.

Lee, K. K., and I. Watanabe. 1977. Problems of the acetylene reduction technique applied to water-saturated paddy soils. Appl. Environ. Microbiol. 34:654-660.

Lieberman, M., A. T. Kinushi, L. W. Mapson, and D. A. Wardale. 1965. Ethylene production from methionine. Biochem. J. 97:449-459.

Lynch, J. M. 1977. Phytoxicity of acetic acid produced in the anaerobic decomposition of wheat straw. J. Appl. Bacteriol. 42:81-87.

Lynch, J. M. 1980. Organic acid from the anaerobic decomposition of *Agropyron repens* rhizomes. Phytochemistry, 19:1846-1847.

Minami, K., K. Oyama, and S. Fukushi. 1981. Volatile sulfur compounds evolved from paddy soils treated with organic materials [in Japanese]. J. Sci. Soil Manure, Jpn (J. Soil Sci. Plant Nutr.) 52:375-380.

Mitsui, S., and K. Kumazawa. 1961. Metabolism of organic acids in rice plant root [in Japanese]. J. Sci. Soil Manure, Jpn. 32:433-439.

Mitsui, S., K. Kumazawa, and N. Mukai. 1959a. The growth of the rice plant in poorly drained soil as affected by the accumulation of volatile organic acids. Part I [in Japanese]. J. Sci. Soil Manure, Jpn. 345-348.

Mitsui, S., K. Kumazawa, and T. Hishida. 1959b. The growth of the rice plant in poorly drained soils as affected by the accumulation of volatile organic acids. Part 2 [in Japanese]. J. Sci. Soil Manure, Jpn. 30-411-413.

Motomura, S. 1961. Dissolution of iron compounds in soils by milk vetch extract. Soil Sci. Plant Nutr. 7:55-60.

Motomura, S. 1962. Effect of organic matter on the formation of ferrous iron. Soil Sci. Plant Nutr. 8:20-29.

Nakano, R., and S. Kuwatsuka. 1979a. Ethylene and methane formation in soil incubated with plant materials [in Japanese]. J. Sci. Soil Manure, Jpn. 50:61-66.

Nakano, R., and S. Kuwatsuka. 1979b. Mechanism of ethylene formation from rice straw in soil in early incubation period [in Japanese]. J. Sci. Soil Manure, Jpn. 50:499-503.

Okajima, H. 1960. Studies on the physiological function of the root system in rice plant, viewed from nitrogen nutrition [in Japanese, English summary]. Bull. Agric. Res. Inst. Tohoku Univ. 12:1-49.

Okazaki, M., H. Wada, and Y. Takai. 1981. Reducing organic substances responsible for removal of Fe(III) and Mn(IV) from surface horizon of lowland rice soil. Pages 235-250 *in* Proceedings of Symposium on Paddy Soil. Inst. Soil Sci. Acad. Sin. Springer-Verlag, Berlin.

Ottow, J. C. G., and H. Glathe. 1973. Pedochemie und Pedomikrobiologie hydromorpher Boden. Chemie der Erde. 32:1-44.

Pearsall, W. H., and C. H. Mortimer. 1939. Oxidation-reduction potentials in waterlogged soils, natural water and muds. J. Ecol. 27:485-501.

Pohland, F. G., ed. 1971. Anaerobic biological treatment processes. Am. Chem. Soc. Washington, D.C. 196 p.

Ponnamperuma, F. N. 1955. The chemistry of submerged soils in relation to the growth and yield of rice. PhD thesis, Comell University, Ithaca, New York.

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Primrose, S. B. 1979. Ethylene and agriculture: The role of microbe. J. Appl. Bact. 46: 1-25.

Sato, K., and I. Yamane. 1966. The effect of temperature on the decomposition of glucose in flooded soil [in Japanese]. J. Sci. Soil Manure, Jpn. 37:547-551.

Shindo, H., and S. Kuwatsuka. 1975. Behavior of phenolic substances in the decaying process of plants. II. Changes of phenolic substances in the decaying process of rice straw under various conditions. Soil Sci. Plant Nutr. 21:215-225.

Shioiri, M., and S. Mitsui. 1935. Chemical composition and decomposition of algae and aquatic weeds grown in paddy soils [in Japanese]. J. Sci. Soil Manure, Jpn. 9:261-268.

Smith, A. M. 1976. Ethylene in soil biology. Ann. Rev. Phytopathol. 14:53-73.

Smith, A. M., and R. J. Cook. 1974. Implication of ethylene production by bacteria for biological balance of soil. Nature (London), 252:703-705.

Smith, K. A., and R. S. Russel. 1969. Occurrence of ethylene, and its significance in anaerobic soil. Nature (London). 222:769-771.

Smith, A. M., D. J. Milham, and W. L. Morison. 1978. Soil ethylene production specially triggered by ferrous iron. Pages 327-336 *in* M. W. Loutit, ed. Microbial ecology. Springer-Verlag, Amsterdam.

Sorensen, J., D. Christensen, and B. B. Jorensen. 1981. Volatile fatty acids and hydrogen as substrates for sulfate reducing bacteria in anaerobic marine sediment. Appl. Environ. Microbiol. 42:5-11.

Subrahmnayan, V. 1929. Biochemistry of waterlogged soils I(III). Decomposition of carbohydrate with special reference to formation of organic acids. J. Agric. Sci. 19:627-648.

Sutherland, J. B., and R. J. Cook. 1980. Effect of chemical and heat treatments on ethylene production in soil. Soil Biol. Biochem. 12:357-362.

Takai, Y. 1958. Determination of organic acids contamination in paddy soil (Part I). Determination by silica-gel chromatography and separation by either extraction [in Japanese]. J. Sci. Soil Manure, Jpn. 28:435-438.

Takai, Y. 1961. Reduction and microbial metabolism in paddy soils (3) [in Japanese]. Nogyo Gijitsu (Agric. Technol), 19:122-126.

Takai, Y. 1970. The mechanism of methane fermentation in flooded paddy soil. Soil Sci. Plant Nutr. 16:238-244.

Takai, Y., T. Koyama, and T. Kamura. 1956. Microbial metabolism in reduction process of paddy soils. Soil Plant Food. 2:63-66.

Takai, Y., and T. Kamura. 1969. The mechanism of reduction in waterlogged paddy soil. Folia Microbial. 11:304-313.

Takai, Y., H. Wada, H. Kagawa, and K. Kobo. 1974. Microbial mechanism of effect of water percolation on Eh, iron, and nitrogen transformation in the submerged paddy soils. Soil Sci. Plant Nutr. 20:33-45.

Takeda, K., and C. Furusaka. 1975a. Studies on the bacteria isolated anaerobically from paddy field soils. III. Production of fatty acids and ammonia by *Clostridium* species. Soil Sci. Plant Nutr. 21:113-118.

Takeda, K., and C. Furusaka. 1975b. Studies on the bacteria isolated anaerobically from paddy field soil. IV. Model experiments on the production of branched fatty acids. Soil Sci. Plant Nutr. 21:119-127.

Takijima, Y. 1961. Absorption and decomposition of butyric and acetic acid added to soil in relation to root growth depression [in Japanese]. J. Sci. Soil Manure, Jpn. 32:193-197.

Takijima, Y. 1963. Studies on behavior of the growth inhibiting substances in paddy soils with special reference to the occurrence of root damage in peaty paddy fields [in Japanese, English summary]. Bull. Natl. Inst. Agric. Sci. B13: 117-252.

Takijima, Y., and H. Sakuma. 1961. Production of organic acids in waterlogged soil-treated with green manure. (Chinese milk vetch) and its relation to growth inhibition of rice seedlings [in Japanese]. J. Sci. Soil Manure, Jpn. 32:559-564.

Takijima, Y., H. Sakuma, and M. Chiba. 1961. Accumulation of organic acids in soil in the presence of sucrose and its relation to growth inhibition of rice seedlings [in Japanese]. J. Sci. Soil Manure, Jpn. 32:390-394.

Tate, R. L., III. 1979. Effect of flooding on microbial activities in organic soils: Carbon metabolism. Soil Sci. 128:267-273.

Toerien, D. F., and W. H. J. Hattingh. 1969. Anaerobic digestion. The microbiology of anaerobic digestion, Water Res. 3:385-408.

Wada, H. 1975. Micropedological approach to the study of dynamics of paddy soils. Jpn. Agric. Res. Q. 9:24-29.

Wang, T. S. C., and T. T. Chuang. 1967. Soil alcohols and their dynamics and their effects upon plant growth. Soil Sci. 104:40-45.

Wang, T. S. C., S. Y. Cheng, and H. Tung. 1967a. Extraction and analysis of soil organic acids. Soil Sci. 103:360-366.

Wang, T. S. C., S. Y. Cheng, and H. Tung. 1967b. Dynamics of soil organic acids. Soil Sci. 104:138-143.

Watanabe, I., and C. Furusaka. 1980. Microbial ecology of flooded rice soils. Pages 125-168 *in* M. Alexander, ed. Advances in microbial ecology, Vol. 4, Plenum Publishing Co., New York.

Widdel, F., and N. Pfennig. 1977. A new anaerobic, sporing, acetate, oxidizing, sulfate reducing bacterium, *Desulfotomaculum acetoxidans.* Arch. Microbiol. 33:275-282.

Wolin, M. J. 1979. The rumen fermentation: A model for microbial interactions in anaerobic ecosystems. Pages 49-77 *in* M. Alexander, ed. Advances in microbial ecology, Vol. 3. Plenum Publishing Co., New York.

Wood, W. A. 1961. Fermentation of carbohydrates and related compounds. Pages 59-150 *in* Gunsalus, I. C. and R. Y. Stanier, eds. Bacteria. Vol. 2. Academic Press, New York.

Yoshida, T. 1975. Microbial metabolism of flooded soils. Pages 83-122 *in* E. A. Paul and A. D. MacLaren, eds. Soil Biochemistry, Vol. 3, Marcel Dekker, New York.

Yoshida, T. 1978. Microbial metabolism in rice soils. Pages 445-464 *in* The International Rice Research Institute. Soils and rice. Los Baños, Philippines.

Yoshida, T., and M. Suzuki. 1975. Formation and degradation of ethylene in submerged rice soils. Soil Sci. Plant Nutr. 21:129-135.

Zeikus, J. G. 1977. The biology of methanogenic bacteria. Bacteriol. Rev. 41:514-541.

## DISCUSSION

YOSHIDA: Regarding the heterogeneity of the wetland soil environment, have you considered the significance of the aerobic-anaerobic interface near the rhizosphere of the rice crop under submerged conditions?

*WATANABE:* The significance of the rhizosphere is only qualitatively recognized. Methane and $C_2H_4$ are oxidized in the root zone, but their oxidizing ability has not been quantified.

YOSHIDA: Please comment on the evolution of $NH_3$ and $N_2O$ in rice soils.

*WATANABE:* Ammonia is lost by volatilization during the daytime when the pH of the flood water increases due to the photosynthetic activity of algae. A part of the $NH_3$ is lost through the plant. Nitrous oxide is probably lost during nitrifcation (Freney, Denmead, Watanabe, and Craswell. 1981. Aust. J. of Agric. Res. 32:37-45).

CHAUDHRY: You have mentioned the production of chelating agents during anaerobic decomposition. What is the effect on oxalates and other such organic chelating substances formed during the decomposition of organic matter?

*WATANABE:* See the text and the paper by Okazaki et al (1981).

WAIN: Have you made any studies on the physiological effects of $C_2H_4$ on the growth and development of rice roots?

*WATANABE:* No, I have not. The paper by Cannell and Lynch describes this problem.

WAIN: Does Mn toxicity arise in rice plants growing in flooded soils?

*WATANABE:* Manganese becomes toxic under certain conditions. When the Mn content in rice plants is higher than 2,500 ppm Mn toxicity can be suspected. But the toxicity is affected by many factors—the nutritional condition of the rice plants, the oxidizing capacity of the soil, and so on (see Ottow, Benkiser, and Watanabe. *Tropical Agricultural Research Series* 15:167-179. 1982).

# MINERALIZATION OF ORGANIC NITROGEN, PHOSPHORUS, AND SULFUR IN SOME PADDY SOILS OF CHINA

Zhao-liang Zhu, Chong-qun Liu, and Bai-fan Jiang

In field experiments with different cropping systems, N uptake by rice plants grown on no-N plots, the majority of which were in intensive cropping systems, was derived from the mineralization of soil N, and ranged from 35 to 139 kg N/ ha, depending on soil type and properties and on the accumulated effective temperature in the plowed layer from transplanting to maturity. The priming effect of chemical fertilizer N may largely be a result of biological interchange between fertilizer N and soil N. Growth of rice plants increased the apparent mineralization of soil N, especially in the middle and late growth stages, and thus induced a higher $n$ value in the equation $Y = k[\Sigma(T-T_o)]^n$. Most of the mineralizable N of organic manures, except straw, was released within 1 month after incorporation and submergence. The high lignin content of azolla delayed the release of N from it. Variation in content of total N, organic P, and organic S, as well as the ratios of organic C to organic P and organic C to organic S of paddy soils in different regions of China are discussed. Changes in organic P content during composting and in total S content of organic manures are also presented.

The mineralization of organic N, P, and S, is an important part of the transformation of nutrients in paddy soils. Since N is the principal constraint in rice production, its mineralization in paddy soils has been studied extensively for a long time and has recently been reviewed by Broadbent (1979). Less work has been done on the mineralization of P and S in paddy soils, largely because analytical methods are far from complete (Dalal 1977) and the mineralization of organic P and S is less important than that of organic N in rice production. This paper presents a brief discussion of the mineralization of N, P, and S in paddy soils of different agroclimatic zones in China on the basis of available data.

---

Institute of Soil Science, Academia Sinica, P.O. Box 821, Nanking, China.

## NITROGEN

### Organic matter and nitrogen content of paddy soils

The contents of both organic matter and N in both dryland and paddy soils are commonly higher in the black soil zone of Northeast China than in other regions (Institute of Soil Science, Academia Sinica 1978), due mainly to the higher content of organic matter before reclamation and to the relatively shorter duration of reclamation. In the North China Plain the contents of both organic matter and N in soil are rather low. However, the organic matter content of soil tends to be higher in the south of this region, which may be explained to a certain extent by the difference in cropping systems and by the higher annual average rainfall and temperature in the south. In the area along the middle and lower Changjiang River, for example, a double cropping system of rice and winter crop prevails, and in recent years a triple cropping system of rice - rice - winter crop has been practiced. In Central and South China, the same triple cropping system prevails. According to Xi (1981), in the past 10 years or so the organic matter content of the paddy soils of Shanghai suburbs has been increasing because of a change from double cropping to triple cropping.

### Nitrogen-supplying capacity of paddy soils

Results from plot and microplot experiments on paddy soils using the $^{15}N$ tracer technique have shown that the soil contributes about half to three-fourths of the N accumulated in the above-ground parts of rice plants at maturity (Chu et al 1978, Hsi et al 1978, Guo et al 1980, Li et al 1982). The proportion of N absorbed from the soil is considerably higher in single-cropped rice with a longer growing period than in double-cropped early rice with a shorter growing period (Chu et al 1978), indicating that the soil N supply occupies a key position in rice production, especially in rice plants with a longer growing period.

**Table 1. Nitrogen uptake in above-ground parts ($N_p$) of rice plants grown on no-N plots in field experiments.[a]**

| | Location | Experiments (no.) | Np (kg N/ha) | | Np/Ns[b] (%) | |
|---|---|---|---|---|---|---|
| | | | Range | Mean | Range | Mean |
| Double-cropped early rice | Tai Lake Region[c] | 34 | 45- 90 | 66 | 0.9-3.3 | 1.8 |
| | Zhejiang | 24 | 35-116 | 68 | 0.9-2.8 | 1.9 |
| Double-cropped late rice (2d crop on no-N plot) | Tai Lake Region[c] | 18 | 15- 57 | 34 | 0.3-2.0 | 0.99 |
| | Guangdong[c] | 5 | 31- 59 | 50 | 1.2-2.9 | 2.2 |
| Double-cropped early rice - late rice | Tai Lake Region[c] | 16 | 64-139 | 101 | 1.3-4.8 | 3.0 |
| Single-cropped rice | Tai Lake Region | 3 | 97-119 | 107 | 3.0-3.5 | 3.3 |

[a] Compiled from unpublished data of Z. L. Zhu and G. X. Cai, Institute of Soil Science, Academia Sinica; Z. P. Pan, Institute of Agricultural Sciences, Suzhou District, Jiangsu Province; Y. H. Wang, Institute of Soil and Fertilizer, Shanghai Academy of Agricultural Sciences; M. Z. Zhou, Institute of Soil and Fertilizer, Zhejiang Academy of Agricultural Sciences; and Y. Y. Yang, Institute of Soil Science, Guangdong Province. [b] $N_S$ = total N in 20-cm soil layer. [c] Nitrogen in rice seedlings at transplanting was deducted.

In field experiments, the amount of N accumulated at maturity in the aboveground parts of rice plants grown on a no-N plot may be taken as the approximate N-supplying capacity of the soil (Table 1). In double-cropped early rice, the N uptake and the percentage of accumulated N in the total N reserves in the top 20 cm of soil in the Tai Lake Region (including Suzhou District and the Shanghai suburbs) in the northern subtropical zone are quite similar to those in Zhejiang Province (situated mainly in the mid-subtropical zone) and also to those of field experiments conducted in Japan (Yanagisawa and Takahashi 1964). In regions in the southern subtropical zone, however, no comparison can be made for lack of available data.

Double-cropped late rice grown as the second crop on a no-N plot accumulates much less N than the preceding early rice. The average N uptake, particularly the amount of accumulated N compared to the total N reserves of the top 20 cm of soil, was much higher in experiments conducted in Guangdong in the southern subtropical zone than in the Tai Lake Region. This may be partly attributed to the higher temperatures in the former region.

Although less information is available on single cropped rice, it may be inferred from available data that in the Suzhou District, both N uptake at maturity and the amount of accumulated N compared to the total N reserves in the top 20 cm of soil are remarkably higher in a no-N plot than in double-cropped early rice or late rice in the locality, and are quite similar to the sum of N uptake of double-cropped early rice and late rice grown continuously on the same no-N plot. This phenomenon may be closely related to the fact that the duration of field growth for single-cropped rice is much longer than that of double-cropped rice in every season, and that the accumulated effective temperature is higher in the former (Chu et al 1978).

Even in a group of experiments carried out simultaneously in the same region, the N uptake of rice plants at maturity in the no-N plots differed as widely as several times with soils of the same type, because of the varying total N content of the soil. Nevertheless, even when judged from the amount of N uptake of rice plants compared to the total N reserves of the top 20 cm of soil in the no-N plot, the variation is still great, the coefficient of variation being as high as 30% (Zhu 1982). The reasons for this are many-sided; they include the microbial susceptibility of soil organic N itself and a series of factors affecting N mineralization. Furthermore, the N taken up by the rice plants from the soil below the plowed layer may vary.

### Mineralization capacity of nitrogen in paddy soils

The N mineralization capacity of some paddy soils of China was estimated using air-dried soil in sealed incubation in submerged conditions at 30°C for 2 weeks; the results are summarized in Table 2.

In the Tai Lake Region, paddy soils are derived from alluvial-lacustrine deposits, with a mineralization range of 8-160 mg N/kg soil and an average of 80 mg N/kg, making up 0.8-7.6% of the total N of soil, and 4.4% on the average. There is a highly significant correlation between mineralized N and total N.

There is a significant negative correlation between mineralization percentage and soil pH (ranging from 5.6 to 8.5), $r = -0.542$ ($n = 68$, significant at the 1% level), and a remarkable positive correlation between mineralization and amorphous iron oxide (0.27-2.19%), $r = 0.461$ ($n = 59$, significant at the 1% level). The positive correlation of mineralization percentage with amorphous iron oxide may be

**Table 2. Nitrogen mineralization of paddy soils.**[a]

| Region | Samples (no.) | Mineralized N |  |  |  | Correlation vs coefficient (mineralized N vs total N) |
|---|---|---|---|---|---|---|
|  |  | mg/kg soil |  | % of total N in soil |  |  |
|  |  | Mean | S. D. | Mean | S. D. |  |
| Tai Lake | 68 | 80.3 | 36.6 | 4.38 | 1.48 | 0.689[b] |
| South to Changjiang River, South China, and Southeast China | 67 | 83.5 | 54.0 | 4.86 | 2.36 | 0.693[b] |

[a] Source: Z. L. Zhu and G. X. Cai, Institute of Soil Science, Academia Sinica, unpublished data. Air-dried soils were incubated at 30°C for 2 weeks under sealed and submerged conditions. [b] Significant at the 1% level.

attributed to the extent of dry and wet alternation in the soil as well as to the soil drainage conditions. The percentage of N mineralization is higher in paddy soils of this region developed under well-drained conditions than in those developed under poorly drained conditions (Cai et al 1981).

In Central, South, and Southwest China, paddy soils are of various types, with wide differences in N mineralization. However, the average results show that they are only slightly different from paddy soils in the Tai Lake Region. Also, there is a significant positive correlation between the N mineralized under incubation and the total N in the soil.

## Factors affecting nitrogen mineralization in paddy soils

Air-drying raises N mineralization prominently. After harvest of the winter crop, farmers plow under dryland conditions and let the ridged fields dry, which has different effects on different soil types (Shen et al 1959). This practice helps accelerate the formation of nitrate N. After submergence, the nitrate N may be lost, resulting in a drop in production (Huang et al 1957).

In Southern China, liming is a rather common practice in paddy fields. One of its effects is the speeding of organic matter decomposition. In an experiment, with incubation under submerged conditions, the mineralized N in the liming treatment was 53.5 mg N/ kg soil, on the average, compared with 42.0 mg N/ kg soil for the treatment without lime (an average increase of 11.5 mg N/kg soil); this amounted to an increase in mineralization percentage from 3.51 to 4.39 (an average increase of 0.88%; $n$ = 13; Z. N. Zhang and Z. L. Zhu, Institute of Soil Science, unpublished data).

For soils of the same type, structure is also an important factor affecting the mineralization of soil N in field conditions. Investigations conducted on well-drained paddy soils in the Tai Lake Region showed that in fertile soil, where there are fewer soil clods apt to become either loosely broken or soft after being submerged in water, the N mineralized from the soil is more, while in less fertile soil, where there are many soil clods difficult to break or soften after submergence, the N mineralized from the soil is less, despite the similarity in total N content (Zhu et al 1979, Xu and Xu 1981). For this reason, the majority of farmers repeatedly plow and harrow poorly structured soil. These differences in N mineralization might be explained by differential penetration of water into the soil clods and by the resultant ease with which enzymes can spread into contact with organic matter to decompose it.

The promotion by chemical fertilizer N of mineralization of soil N, called the priming effect, is a many-sided process. Results from an experiment on seven fresh soil samples in pots showed that the differences between the increase in mineralized N due to the priming effect of N fertilizer and the immobilized N of the fertilizer were all within the error of estimation. Thus it is believed that the priming effect of N fertilizer is the result of biological interchange between fertilizer N and soil N, without considerable increase of total available N for the use of the rice plant (Cai et al 1981). A similar viewpoint was expressed by Koyama (1975), and the same result was also obtained from field investigations by Yoshida and Padre (1977). Moreover, under incubation conditions, the additional mineralization of soil N through the application of N fertilizer is either equivalent to or even less than the amount of immobilized fertilizer N (Asami 1971, Maeda and Shiga 1978, Yoshino and Dei 1978). In addition to biological interchange, N fertilizer may improve rice growth and its root activity under field conditions, thus enabling the plant to absorb soil N to a greater extent. However, because there is a restriction placed on root expansion in the plow pan of well-developed paddy soils, the increase in soil N absorbed through root expansion may be rather insignificant; hence it cannot be regarded as the important mechanism of the priming effect. Besides, organic manures generally have a positive priming effect on the mineralization of soil N, but the increase in mineralized N is much less than the N entering the soil through organic manures (Gu and Wen 1981). These results indicate that the priming effect of chemical N fertilizer will not lead to a lowering of N-supplying capacity of the soil over a long time. And the residual N of organic manures will help maintain and even increase the N-supplying capacity of soils.

### Nitrogen mineralization pattern of paddy soils

Temperature is a key factor affecting the rate of mineralization of soil N. Through a field investigation carried out in a no-N plot of well drained paddy soil in Suzhou District, Jiangsu Province, it appears that the period of the highest rate of mineralization of soil N is middle July to late August (Chu et al 1978). This has been further proved through pot experiments (Cai et a1 1981).

The N mineralized from soil ($Y$) is a function of the accumulated effective temperature ($X$) in the soil, $Y = kX^n$. The n-value reflects soil type and properties (Yoshino and Dei 1977). In field conditions, the mineralization pattern of soil N is influenced by temperature fluctuations during the rice-growing season as well as the drying of paddy soil and the extent of harrowing.

A simple way to investigate the pattern of N mineralization of paddy soils is to use sealed incubation of fresh and air-dried soil samples (Yoshino and Dei 1977). In 2-4 weeks of incubation, the mineralization rate of air-dried soil was much higher than that of fresh soil, but later the rates become equal (Onikura et al 1975). To eliminate the effect of soil-drying on N mineralization pattern, air-dried soil should be subject to preincubation for a specific period. Some authors have proposed a period of 2 weeks or so for preincubation; however, for certain soils, other periods may be preferable (Yoshino and Dei 1977, Cai et al 1979), and it is therefore very difficult to set a standard preincubation period.

The N mineralization pattern of paddy soils in sealed incubation in submerged conditions was relatively the same as that in rice pot cultures but not always equivalent to that in rice fields. This may be due to the different extent of soil aggregation as well as to the capability of the rice plant to absorb part of the N from the soil below the plowed layer. The results of an investigation of N mineralization of fresh soil samples through sealed incubation under submerged conditions and pot culture (G. X. Cai and Z. L. Zhu, Institute of Soil Science, unpubl. data) indicated that under the same accumulated effective temperature, the N mineralized in the soil for growing single-cropped rice was higher than that in the soil under incubation, especially at the middle and late stages of growth. This was probably due to the promotion of mineralization of soil N by growing rice as well as to N fixation. Nevertheless, it is possible that there was a slight loss of mineralized N under sealed incubation. Results further indicated that the effect was the same for rice plants grown in different seasons (i.e., single-cropped rice and double-cropped early rice); the numerical values for $n$ and $k$ in the mineralization equation were similar. Thus, a number of problems are still involved in the transfer of the numerical values of $n$ and $k$, measured from the sealed incubation under submerged conditions, to field conditions. Hence the measurements should be made in a no-N plot in the field, and the numerical values of $n$ and $k$ measured in the field during the growth of single-cropped rice may be used for the double-cropped early rice, and vice versa.

## Nitrogen release from organic manures

The percentage recovery of N from organic manures by rice plants, which is related to the C:N and lignin content, was as follows in a one-season field experiment in paddy fields: leguminous green manures 25.3 ± 10.2% ($n$=10), farmyard manures 14.7 ± 8.8% ($n$=12), and waterlogged compost 15.0 ± 5.7% ($n$=15). Results in rice pot culture experiments were: leguminous green manures 42.2 ± 15.2% ($n$=10) and azolla 27.3 ± 15.8% ($n$=6). The application of leguminous green manures will produce an increase in rice yield of 11.7 ± 4.2/kg N applied ($n$=14) (Z. L. Zhu, compiled data). In field experiments, although green manures evidently affect the yield of double-cropped early rice, their residual effect on succeeding late rice is insignificant, but there is a definite residual effect on succeeding wheat (Gu and Wen 1981). Results from pot experiments have indicated that the N recovery of milk vetch applied to double-cropped early rice is 45.8%, as against 63.1% of that in $(NH_4)_2SO_4$, while the residual effect of N in the former is 8%, as against 4% of that in the latter (Z. N. Zhang and Z. L. Zhu, Institute of Soil Science, unpubl. data).

The C:N of azolla is not higher than that of milk vetch, but the N recovery of azolla by rice plants is significantly lower than that of milk vetch (Shi et al 1978). Studies with green manures labeled with $^{15}N$ have shown that milk vetch is characterized not only by the highest N recovery by the existing rice crop but also by the highest N availability ratio in the crops of the second and the third seasons as well as in the period of sealed incubation in submerged conditions after the third season. Azolla has the lowest N recovery by existing rice plants and the lowest availability ratio because it has a higher content of lignin (Shi et al 1980).

Pot experiments on rice using *Crotalaria* labeled with $^{15}N$ indicate that *Crotalaria,* once applied to the soil, has a N loss much lower than $(NH_4)_2SO_4$, while the residual N in the soil is much higher; hence one of the important effects of green manures is to maintain the N-supplying capacity of soil (Huang et al 1981).

Nitrogen release is subject to the influence of soil properties. In rice pot experiments, the decomposition rate of organic manures is slower in heavy, clayey soil than in clay loamy soil (Table 3). However, the percentages of N release were 17 ± 5% for waterlogged compost, 13 ± 4% for buffalo dung, and 37 ± 10% for milk vetch in paddy soils derived from five kinds of parent materials in submerged conditions (Institute of Soil Science 1978), indicating that N release from organic manures depends primarily upon their own C:N and chemical composition.

The release rate of N from organic manures is generally rapid during the first month after submergence and then gradually becomes steady (Table 3; Institute of Soil Science 1978, Shi et al 1978). The pattern of N release from azolla differs somewhat in that the release rate is relatively slower just after submergence and becomes faster at a later period, probably because of the higher content of lignin (Shi et al 1978).

Rice straw induces the immobilization of N soon after being applied to the field; remineralization follows after a certain period of time. The C:N of rice straw has a wide range, and the duration of immobilization and subsequent remineralization depends largely on the N content, as well as the addition of N fertilizer and the temperature. In rice pot experiments, the N immobilization occurred within about 52 days after the straw was incorporated and submerged. But on the 82d day of the experiment, the N supply was still lower in the straw-amended pot than in the control (Table 3). Therefore, the application of a straw with a wide C:N would not increase the yield of existing rice plants, but might positively affect that of succeeding crops. In a microplot experiment in which rice straw (N 0.94%) labeled with $^{15}N$, in combination with urea, was applied to paddy soils derived from red earth, the recovery of straw N by rice plants reached 22-23% in one season (Mo and Qian 1981). According to Yoshida and Padre (1975), it was the straw that stepped up the biological immobilization of $^{15}N$-labeled $(NH_4)_2SO_4$ and reduced the N loss from it. A pot experiment with *Crotalaria* and $(NH_4)_2SO_4$ showed by cross-labelling techniques that *Crotalaria* helped bring about immobilization of $(NH_4)_2SO_4$, which, in turn, helped promote N release from the former (Huang et al 1981). When organic

**Table 3. Percentage release of nitrogen from organic manures 32-82 days after submergence in pot experiments.**[a]

| Soil | Organic manure | N release (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 32days | 42days | 52days | 62days | 71days | 82days |
| Clay loam | Pig manure | 20.0 | 15.0 | 22.3 | 24.4 | 23.4 | 24.9 |
| | Vetch | 45.3 | 46.0 | 48.4 | 52.4 | 55.8 | 60.7 |
| | Rice straw | –34.5 | –38.5 | –35.5 | –23.5 | –20.2 | – 8.5 |
| | Vetch + rice straw | 26.2 | 27.9 | 32.6 | 33.6 | 38.7 | 41.1 |
| Heavy clay | Vetch + rice straw | 15.6 | 16.9 | 18.7 | 22.4 | 25.4 | 28.7 |

[a] Source: Institute of Soil Science, Academia Sinica (1978). Ground organic manure was mixed with air-dried soil and submerged on 4 June 1964. Rice seedlings were transplanted on 23 June. The sum of N in the whole plant and the $NH_4^+$-N in the soil were calculated and considered as the N supply. The difference in N supply between organic manure-amended pots and the control was divided by the N added as organic manure to calculate the percentage release of N from organic manure.

manure is applied along with N fertilizer, the N uptake pattern for rice plants tends to become steady and long lasting, while the apparent recovery of fertilizer N by rice plants sometimes decreases, especially when N fertilizer is applied in combination with straw (Institute of Soil Science 1978, Huang et al 1981).

## PHOSPHORUS

### Organic phosphorus content of paddy soils

To the south of the Changjiang River, paddy soils of the plowed layer have an organic P content of 0.005-0.030%, making up 20-60% of the total P in soil and 40% or so, on the average (Table 4). There was a remarkable positive correlation between the content of organic P and that of total P, $r$ = 0.744 ($n$ = 33, significant at the 1% level). The highest content of organic P was found in paddy soils in Guangdong and Guangxi provinces, probably because, among the samples used for investigation, a considerable number were derived from the weathered residues of limestone and contained abundant organic matter, while in the red-earth zone of Zhejiang, Jiangxi, and Hunan provinces, the content of organic P in paddy soil was lower, probably because of the lower content of P in its parent materials (Quaternary red clay, Tertiary red sandstone, etc.). Different soils in the same region differ widely in content of organic P, which depends on factors such as parent materials, texture, soil water regime, and history of applying phosphatic fertilizer and organic manures.

A distinct positive correlation exists between the content of organic P and that of organic matter in soil, $r$ = 0.600 ($n$ = 71, significant at the 1% level). In paddy soils, the ratio of organic C to organic P tended to be wider in the middle and lower Changjiang River regions and the Qiantangjiang River Valley of the northern subtropical zone and in the Yunnan-Guizhou Plateau, which has similar climatic conditions; the ratio was narrower in the middle, southern subtropical zone and in the tropical zone in south China. This appears contrary to the fact that the P content in soil organic matter decreases along with the increase of rainfall and annual average temperature, i.e., there is a tendency toward a wider organic C:organic P (Dalal l977). It seems that the organic C:organic P in paddy silks is also influenced by cropping systems. In the middle and lower Changjiang River Region and the Qiantangjiang River valley, for instance, both double cropping of rice - winter crop and triple cropping of rice - rice - winter crop exist concurrently, with a shorter period of submergence than in southern China, where triple cropping is practiced.

### Mineralization of phosphorus in organic manures during composting

Rice straw has a very low P content, with organic P making up 82% of the total P. Milk vetch has a higher content of P than straw, although organic P accounts for only 54% (Mo et al 1979). Pig manure is highest in P content, with organic P accounting for only 25.5% of the total. At the earlier stage of waterlogged composting of milk vetch and rice straw with N fertilizer, the inorganic P tended to become immobilized and then remineralized. After 120 days' waterlogged composting, the percentage of total P increased remarkably as a result of a decrease in the amount of dry matter. The percentage of organic P in milk vetch and pig manure declined as a result of mineralization, but after waterlogged cornposting of rice straw

**Table 4. Content of organic P and S in the plowed layer of paddy soil.** [a]

| Region | Organic P (%) | Organic P:total P (%) | Organic C: organic P | Organic S (%) | Organic S: total S (%) | Organic C: organic S |
|---|---|---|---|---|---|---|
| Middle and lower Changjiang River, Qiantangjiang River | 0.016 ± 0.005<br>($n = 14$) | 38 ± 9<br>($n = 14$) | 133 ± 86<br>($n = 14$) | 0.024 ± 0.005<br>($n = 12$) | 82 ± 3.9<br>($n = 12$) | 64 ± 5.1<br>($n = 13$) |
| South to Changjiang River | 0.013 ± 0.005<br>($n = 37$) | 41 ± 17<br>($n = 14$) | 101 ± 37<br>($n = 37$) | 0.022 ± 0.002<br>($n = 91$) | 92 ± 0.3<br>($n = 90$) | 62 ± 4.6<br>($n = 21$) |
| Yunnan-Guizhou Plateau, Sichuan | 0.015 ± 0.008<br>($n = 6$) | – | 144 ± 57<br>($n = 6$) | 0.026 ± 0.013<br>($n = 22$) | 90 ± 4.0<br>($n = 21$) | 47 ± 9.1<br>($n = 15$) |
| South China | 0.022 ± 0.008<br>($n = 14$) | 46 ± 7<br>($n = 5$) | 105 ± 46<br>($n = 14$) | 0.020 ± 0.009<br>($n = 8$) | 92 ± 2.4<br>($n = 8$) | 63 ± 26<br>($n = 4$) |

[a] Sources: Institute of Soil Science, Academia Sinica (1961); B. F. Jiang, Z. R. Wang, C. Q. Liu, G. A. Chen, and S. Q. Cao, Institute of Soil Science, Academia Sinica, unpublished data. Organic P by ignition method. Organic S = total S - sulfate S. Total S by combustion-iodimetric method. Sulfate S by $NaH_2PO_4$-HOAc extraction.

added with N, it changed insignificantly. Results of pot experiments indicated that on the basis of pig manure, wheat, rice, and millet gave a good yield response to N fertilizer, while the effect of phosphatic fertilizer was not so evident. On the contrary, on the basis of milk vetch, the yield response to N fertilizer would sometimes not be as high as that to phosphatic fertilizer. This conforms to the fact that there are different contents of N and P in different organic manures.

## SULFUR

### Organic sulfur content of paddy soils

In Southern China, the average content of total S in the plowed layer of paddy soils ranged from 0.0197 to 0.0255%; organic S accounted for 82-92% of the total sulfur on the average (Table 4). In the Tai Lake Region, the total S content of soil was higher and that of the available S was even notably higher than that of the paddy soils in the red-earth zone of Jiangxi Province. This may possibly be attributed to the large number of industrial cities in this region, which contribute to a high content of S in rain water and in irrigation water (Liu et al 1981). In the hilly and mountainous areas of Jiangxi Province, both the cold muddy paddy soil and the sandy paddy soil are known to be S deficient. There is a distinct positive correlation between the content of total S and that of organic matter, $r = 0.92$ (significant at the 1% level; Liu et al 1981). In paddy soils derived from the same parent material, the content of total S was 18-61% and that of organic S 14-59%, higher than in the corresponding dryland soils (C. Q. Liu, Institute of Soil Science, unpubl. data).

In S-deficient soils, the C:S in the organic matter is wider. For example, in the S-deficient soil in Jiangchuan County, Yunnan Province. the ratio is 111, on the average, as against 64 in the paddy soil of the Tai Lake Region.

In incubation in submerged conditions, S is not the end-product of the mineralization of organic S, and the S originally present in the soil before submergence is subject to reduction during incubation. In aerobic incubation of air-dried samples at 30° C and 60% WHC, within 10 weeks the mineralization of soil organic S ranged from 3.8 to 15.6%, with an average of 9.6% and a standard deviation of 3.7% ($n$ = 10) (C. Q. Liu, Institute of Soil Science, unpubl. data).

**Table 5. Sulfur content of organic manures.**[a]

| Organic manure | S content[b] (%) |
|---|---|
| Straw of cereal crops | 0.112 - 0.189 ($n$ = 88) |
| | 0.480[c] ($n$ = 1) |
| Straw of leguminous crops | 0.226 - 0.331 ($n$ = 31) |
| | 0.400 - 0.711[c] ($n$ = 7) |
| Straw of cruciferous crops | 0.348 - 0.920 ($n$ = 10) |
| Azolla | 0.38 - 0.841 ($n$ = 10) |
| Farmyard manures | 0.347 - 0.374 ($n$ = 4) |

[a] Sources: Liu, C. Q., Institute of Soil Science, Academia Sinica, unpublished data; Li et al (1982). [b] Determined by turbidimetric method after acid digestion. [c] Fertilized with superphosphate.

### Sulfur in organic manures

Among various kinds of straw, those of leguminous and cruciferous plants have the highest S content (Table 5), while those of graminaceous plants contain less. Sulfur content is higher in the straw applied with S-bearing fertilizer than in that applied without. Likewise, the straw of crops growing on soils rich in S such as the paddy soils in the Tai Lake Region contains a higher percentage of S than that growing on S-deficient soils such as the paddy soils in Jiangxi Province. In aerobic incubation of paddy soils at 30°C and 60% WHC, addition of rice straw with a S content of 0.142% depressed the rate of release of sulfate from soil organic S (C. Q. Liu, Institute of Soil Science. unpubl. data). It is generally believed that organic manures with a content of S higher than 0.15% will undergo S release in the process of decomposition (Biederbeck 1978). For this reason, with the exception of a part of graminaceous crops. the organic manures in other kinds of straw can supply crops with S released (Table 5).

## REFERENCES CITED

Asami, T. 1971, Immobilization and mineralization of nitrogen compounds in paddy soils. 4. Effect of plant residues on the immobilization and mineralization of nitrogen compounds in the paddy soil incubated under submerged or upland condition [in Japanese]. J. Sci. Soil Manure, Jpn. 42:97-102.

Biederbeck. V. O. 1978. Soil organic sulfur and fertility. Pages 273-310 *in* M. Schnitzer and S. U. Khan, eds. Soil organic matter. Elsevier Scientific Publishing Company, Amsterdam, Oxford, New York.

Broadbent, F. E. 1979. Mineralization of organic nitrogen in paddy soils. Pages 105-118 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Cai, G. X., S. L. Zhang, and Z. L. Zhu. 1979. On the experimental conditions for the determination of nitrogen mineralization pattern of paddy soil with sealed incubation under submerged condition [in Chinese]. Turang 6:234-240.

Cai, G. X., S. L. Zhang, and Z. L. Zhu. 1981. Characteristics of nitrogen mineralization of paddy soils and their effect on the efficiency of nitrogen fertilizer. Pages 793-799 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, and Springer Verlag, Berlin, Heidelberg, New York.

Chu, C. L., H. L. Liao, K. S. Tsai, and C. C. Yu. 1978. Soil nutrition status under “rice-rice-wheat” rotation and the response of rice to fertilizers in Suchow District [in Chinese, English summary]. Acta Pedol. Sin. 15:126-137.

Dalal, R. C. 1977. Soil organic phosphorus. Adv. in Agron. 29:83-117.

Gu, R. S., and Q. X. Wen. 1981. Cultivationand application of green manure in paddy fields of China. Pages 207-219 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, and Springer Verlag, Berlin, Heidelberg, New York.

Guo, Z. F., S. S. Chen, Y. S. Wang, and N. X. Tang. 1980. Investigation on the absorption, fixation and loss of fertilizer nitrogen in paddy field and increasing its efficiency [in Chinese]. Appl. At. Energy in Agric. 1:24-29.

Hsi, C. P., Y. C. Pien, A. C. Kuang, T. P. Liu, and M. Y. Liu. 1978. Studies on peak nutrient uptake of double-cropping rice and the method of basal dressing with volatile nitrogen fertilizer to the whole plowed layer [in Chinese, English summary]. Acta Pedol. Sin. 15:113-125.

Huang, D. M., and P. S. Chang. 1957. Transformation of nitrogen in paddy soils and yield of rice as affected by plowing under dry and waterlogged conditions [in Chinese, English summary]. Acta Pedol. Sin. 5:223-233.

Huang, D. M., J. H. Gao, and P. L. Zhu. 1981. The transformation and distribution of organic and inorganic fertilizer nitrogen in rice-soil system [in Chinese, English summary]. Acta Pedol. Sin. 18: 107-121.

Institute of Soil Science, Academia Sinica. 1961. Characteristics of nutrient supply of paddy soils. Pages 240-287 *in* Soil conditions for high yield of rice [in Chinese]. Science Press, Beijing.

Institute of Soil Science, Academia Sinica. 1978. Soil nitrogen. Pages 360-375 *in* Soils of China [in Chinese]. Science Press, Beijing.

Koyama, T. 1975. Practice of determining potential nitrogen supplying capacities of paddy soils and rice yield [in Japanese]. J. Sci. Soil Manure, Jpn. 46:260-269.

Li, S. Y., J. Y. Wang, and V. G. Kong. 1982. Studies on the characteristics of nitrogen supply in paddy soils. 2. Effect of fertilization on the soil nitrogen supply and grain yield of double cropped rice [in Chinese, English summary]. Acta Pedol. Sin. 19:13-21.

Li, Z. X., S. X. Zu, M. F. Mao, and T. A. Lumpkin. 1982. Study on the utilization of eight azolla species in agriculture. 1. An investigation of their utilization properties [in Chinese, English summary]. Sci. Agric. Sin. 1:19-27.

Liu, C. Q., G. A. Chen, and S. Q. Cao. 1981. Sulfur content and distribution in paddy soils of south China. Pages 628-634 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, and Springer Verlag, Berlin, Heidelberg, New York.

Maeda, K., and H. Shiga. 1978. Relationship between mineralization and immobilization of nitrogen influenced by various conditions of submerged soils. Soil Sci. Plant Nutr. 24:515-524.

Mo, S. X., Y. X. Lin, G. Z. Yu, Z. C. Luo, and Y. F. Xu. 1979. Transformation of nitrogen and phosphorus during composting of pig manure, milk vetch, and rice straw [in Chinese]. Turang Tongbao 5:21-25.

Mo, S. X., and J. F. Qian. 1981. Uptake of nitrogen by rice plant from straw manure, urea and soil. Pages 800-804 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, and Springer Verlag, Berlin, Heidelberg, New York.

Onikura, Y., T. Yoshino, and K. Maeda. 1975. Mineralization patterns of soil nitrogen during the growth period of rice plant [in Japanese]. J. Sci. Soil Manure, Jpn 46:255-259.

Shen, Z. P., D. M. Huang, G. Y. Bai, and X. T. Duan. 1959. Effect of drying of paddy soil in relation to soil properties [in Chinese, Russian summary]. Acta Pedol. Sin. 7:124-134.

Shi, S. L., L. L. Cheng, H. H. Lin, C. L. Shu, and C. H. Wen. 1978. Effect of azolla on the fertility of paddy soils [in Chinese, English summary]. Acta Pedol. Sin. 15:54-60.

Shi, S. L., Q. X. Wen, and H. Q. Liao. 1980. The availability of nitrogen of green manures in relation to their chemical composition [in Chinese, English summary]. Acta Pedol. Sin. 17:240-246.

Xi, Z. B. 1981. On the tendency of organic matter accumulation in paddy soil under triple cropping system in suburbs of Shanghai. Pages 502-508 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, and Springer Verlag, Berlin, Heidelberg, New York.

Xu, F. A., and X. Y. Xu. 1981. The effect of different structures of paddy soil on the nutrient absorption by early rice plants [in Chinese]. Acta Pedol. Sin. 18:199-202.

Yanagisawa, M., and J. Takahashi. 1964. Studies of the factors related to the productivity of paddy soils in Japan with special reference to the nutrition of rice plants [in Japanese, English summary]. Bull. Natl. Inst. Agric. Sci. Ser. B. 14:41-171.

Yoshida, T., and B. C. Padre, Jr. 1975. Effect of organic matter application and water regimes on the transformation of fertilizer nitrogen in a Philippine soil. Soil Sci. Plant Nutr. 21:281-292.

Yoshida, T., and B. C. Padre, Jr. 1977. Transformation of soil and fertilizer nitrogen in paddy soil and their availability to rice plants. Plant Soil 47:113-123.

Yoshino, T., and Y. Dei. 1977. Prediction of nitrogen release in paddy soils by means of the concept of effective temperature [in Japanese, English summary]. J. Cent. Agric. Exp. Stn. Jpn. 25:1-62.

Yoshino, T., and Y. Dei. 1978. Transformation of fertilizer nitrogen and its effect on the release of soil nitrogen in paddy soils [in Japanese, English summary]. J. Cent. Agric. Exp. Stn. Jpn. 28:91-113.

Zhu, Z. L., R. Y. Chen, Y. F. Xu, Y. H. Xu, and S. L. Zhang. 1979. The effect of forms and methods of placement of nitrogen fertilizer on the characteristics of the nitrogen supply in paddy soils [in Chinese, English summary]. Acta Pedol. Sin. 16:218-233.

Zhu, Z. L. 1982. Parameters for assessing the rate of application of nitrogen fertilizer in rice and wheat production [in Chinese]. Turang. (in press)

## DISCUSSION

WATANABE: The discrepancy between the N uptake by the plant and N-mineralization predicted by the incubation method was often ascribed to biological N-fixation. What is your estimate of the contribution of N-fixation in rice plant N uptake?

*ZHU:* This discrepancy may be attributed to many factors or processes, and the contribution of biological N-fixation during the growth of the rice plant is only one of them. On the basis of the data available it is difficult to make the estimation.

AMIEN: In your paper you mention paddy soil with pH 8.5. The pH of flooded soil is usually close to neutral. If it is high, this is perhaps due to the high concentration of salts common in coastal areas. Don’t you think that those salts made the negative correlation rather than the pH?

*ZHU:* The soil with pH higher than 8 investigated in the incubation of paddy soils taken from the Tai Lake Region was poorly drained calcareous soil, characterized by a lower percentage mineralization of its N. This may be one of the reasons for the negative correlation appearing between the percentage mineralization of soil N and soil pH.

PALANIAPPAN: I have observed the following during identical incubation experiments: while incubating clayey soil in conical flasks, if acid-washed sand is added and mixed well, then N-mineralization appears to occur at an optimum rate. In the absence of sand, the rate is suppressed.

In your paper you have pointed out that temperature and soil texture significantly influence the rate of N-mineralization. I have found that moisture content also has a serious effect on the process. A near-dry state and a waterlogged condition tend to decrease the process as well. Have you recognized this?

*ZHU:* The results shown in the paper were obtained in the experiments under submerged conditions.

MARTINEZ: In our laboratory incubation experiments, we noticed that sterilization of the soil increased the rate of mineralization of N. Have you noticed this phenomenon in your study? What do you think is the immediate effect of sterilization of the soil that enhanced the mineralization rate of N? Does sterilization affect the structure of the soil?

*ZHU:* Sterilization of soil kills the soil microorganisms and makes them more liable to decomposition. Investigation of the relationship of soil structure to N-mineralization must be carried out with undisturbed fresh soil samples or in the field in situ. Hence, if the investigation of the sterilization effect is done with dried and ground soil, the effect of soil structure on N-mineralization may not be observed. In my laboratory, sterilization has not yet been investigated.

# USE OF ISOTOPES IN STUDYING THE DYNAMICS OF ORGANIC MATTER IN SOILS

Hans-Wilhelm Scharpenseel and
Heinz-Ulrich Neue

For studies of soil organic matter dynamics the radioisotope $^{14}C$ is the most useful tracer. It is used in uniformly $^{14}C$-labeled organic matter for studies of the initial decomposition phase in the $^{14}C$ dating of soil organic matter under steady state turnover conditions.

Uniformly labeled organic matter (green manure, straw, farmyard manure, slurry, or even glucose) decomposes in patterns following an e-function, with half-lives of 2-10 years, leaving 14-25% of the C input after 8 years. According to Jenkinson, half-lives of organic fractions vary between 0.15 and 1,980 years.

The initial phase of fast decomposition by first order rate kinetics is discontinuous, since recent soils (paleosols, anyway) possess apparent mean residence time (AMRT) values of several thousand years for C in the deeper parts of the epipedon.

Evaluation of many hundred radiocarbon dates of profiles of Mollisols, Vertisols, Spodosols, Alfisols, and Inceptisols indicates a significant age vs depth relationship as well as AMRT values that could never occur if the rapid mineralization of uniformly $^{14}C$-labeled organic matter were continuous. Decomposition studies with uniformly $^{14}C$-labeled organic matter have produced information essential for humus management. $^{14}C$ dating of soil organic matter reveals the soil's minimum age and its potential for stabilization and preservation of organic matter.

All stable or radioactive isotopes of noncationic constituent elements could conceivably be used as labels for the study of soil organic matter decomposition, especially $^{3}H$, $^{11}C$, $^{13}C$, $^{14}C$, $^{15}N$, $^{34}S$, $^{35}S$, $^{32}P$, and $^{33}P$.

The first labeled decomposition studies used $^{13}C$ as the tag (Broadbent and Norman 1946, Broadbent 1947, Broadbent and Bartholomew 1948), revealing a priming effect of >100% (even 4-11 times) never observed at this magnitude for $^{14}C$-labeled organic matter. When using $^{13}C$, the variable $\Delta^{13}C$, ± 0% for limestone

---

Ordinariat fur Bodenkunde der Universität Hamburg von Melle Park 10, D-2000 Hamburg 13, FRG, and International Rice Research Institute, Los Baños, Laguna, Philippines.

and –10 to –25%, specific for Calvin, CAM, or Hatch-Slack plant species, must be recognized (Lerman 1972). Natural $^{13}C$ in calcareous soils with D$^{13}$C equal to ± 0 does not interfere with D$^{13}$C of the organic C in soils rich in free carbonates (Scharpenseel 1974). A soil profile of a Haplaqualf scanned for natural $^{13}C$ was interpreted by Schleser et al (1981) regarding reaction kinetics of $^{13}C$ isotope fractionations due to metabolism or mobility of the organic substances. Further $^{13}C/^{12}C$ studies on soil organic matter fractions (Nissenbaum and Schallinger 1974) as well as on salt marsh humus (Haines 1976a, b) show the great potential of the D$^{13}$C method for studies of humus dynamics. Organic matter decomposition can undoubtedly also be studied by observing changes in D$^{13}$C in soil humus in plots traditionally planted to C-3 plants but replanted with C-4 crops, e.g., corn (presently under study in author's laboratory).

Turnover of tritium-labeled grey and brown humic acids has been studied (Scharpenseel 1960a,b). However, purification of the $^{3}H$-labeled humic acids proved to be extraordinarily laborious. Also, tritium labeling is liable to produce artifacts by tritium addition to double bonds instead of H substitution. Furthermore, plants incorporate $^{3}H$ by the atmospheric as well as the soil moisture path (König 1980).

If the soil under investigation maintains a constant C:N, $^{14}C$ and $^{15}N$ should reflect identical decomposition rates. Although it is more difficult to control all $^{15}N$-labeled decay products than to monitor for $^{14}CO_2$, $^{14}CH_4$, and a few simple organic acids, comparing both decay systems or applying double labeling provides an excellent internal control. Double labeling with $^{14}C$ and $^{15}N$ and simultaneous testing of the C and N dynamics were achieved by Haider and Farooq-e-Azam (1982) as a result of decomposing labeled compounds like glucose, polysaccharides, wheat straw, lignin, ring ferulic acid, and protein in a Hapludoll soil. In 24 weeks an average of 70% of the compounds decomposed and 60-80% of the remainder appeared in the hydrolysate. The ratios of $^{14}C$ to $^{15}N$ were also tested in the amino acids and the nonidentifiable N fraction. Double labeling by Broadbent and Nakashima (1974) with $^{13}C$ and $^{15}N$ and that by Dalal (1979) with $^{14}C$ and $^{32}P$ showed compliance between the isotopes, with greater losses of isotope from labeled plant tops than from roots and not much additional loss in the presence of plants.

According to McGill and Cole (1981), a C-bonded S tag should closely follow the N distribution pattern, often correlated with C oxidation as the energy source in biological mineralization. For $^{15}N$ turnover, see *Nitrogen and rice* (IRRI 1979). Most of numerous $^{15}N$ studies of former years were geared to produce N balances. Jansson (1955, 1958) investigated the N cycle in Swedish soils. Broadbent (1968) studied N turnover in soil organic matter. Krishnappa and Shinde (1978) applied uniformly $^{15}N$-labeled rice straw in flooded fields. The recovery rate of $^{15}N$ in the course of two subsequent rice crops, indicative of the decomposition rate, varied from 7 to 21% without fertilizer application; the rate doubled with fertilizer application.

$^{11}C$ has too short a half-life for the minimum period of decay monitoring. $^{14}C$ is the choice isotope. Its suitability is confirmed by studies (Meyer-Spasche and Scharpenseel 1980) showing that transfer factors of $^{14}C$ across the trophic plains — soil - plant - milk - human hair — are equal to unity. $^{14}C$ studies will be dealt with presently.

## FACTORS IN DECOMPOSITION

Organic matter added to a biologically active soil passes an initial phase of a few months or years of rapid decomposition. There is a subsequent steady state phase of contained decomposition, ending possibly in a third phase of immunity to further decomposition. Theng (1972) explained the decisive role of clay minerals, whose importance for the stability and resistance to microbial decomposition of humus had been postulated by pioneers of soil chemistry like Demolon and Barbier (1929) and Mattson (1932). Using $^{14}C$-labeled humic acids, Theng and Scharpenseel (l975) and Tan and McCreery (1975) demonstrated that humic acids with 80 A coil diameters cannot be intercalated by clay minerals such as primary organic decay products; amino acids or proteins can be up to 50% of the clay mass (Weiss 1969). Adsorption at the external surface and protection by interdomain spaces (Aylmore and Quirk 1960, Giles et al 1974) prevail.

The distinction between “biologically active” C — that involved in biological turnover — and “biologically inert,” protected C — that not participating in the turnover — is emphasized by Gerasimov (1971, 1974) as well as by Gerasimov and Chichagova (1971). The latter fraction is chemically and physically protected; when subjected to radiocarbon dating it produces the “absolute age” of the soil. The former fraction reflects the duration of the biological C cycle characteristic of the respective soil group; its radiocarbon date is the “relative age.” In Gerasimov’s view the “absolute age” of a soil’s protected, biologically inert C fraction would be equal to the “maximum age” obtainable according to radiocarbon dating minus the “relative age.”

This view of several organic matter fractions with different grades of exposure to biological degradation tacitly implies that biotic forces are all-important for soil organic matter decomposition. Wurzer (1981), reviewing the justification of taking $CO_2$ evolution as a measure of organic matter decomposition and “soil respiration,” inferred that, according to Hofmann and Hoffmann (1962):

- respiration is tied to $O_2$ consumption, not $CO_2$ evolution;
- decomposition often proceeds by hydrolysis, without the involvement of $O_2$ or $CO_2$;
- $CO_2$ can also be liberated by intermolecular rearrangement without respiration being involved (e.g., in the case of fermentation); and
- $CO_2$ measurement in a layer near the surface misses the considerable quantities of $CO_2$ dissolved in percolating solutions.

Besides, $^{14}CO_2$ evolution from uniformly $^{14}C$-labeled organic matter or from $^{14}C$ humic and fulvic acid produced from such labeled organic matter is not restricted to biological degradation. Scharpenseel and Beckmann (1964a) and Beckmann and Scharpenseel (1964) demonstrated that inactive as well as $^{14}C$-labeled soil organic matter mixed with soil and various cations released $CO_2$ even under fully sterilized conditions. This has been confirmed in various unpublished studies of the senior author of this paper by the use of $^{14}C$-labeled humic acid and fulvic acid preparations (e.g., Table 1). In a large set of tests with several soils and cations, the $CO_2$ released under biotic, abiotic, and photochemically activated (UV-irradiated) conditions was confirmed by Wurzer (1981), and even in calcinated sand by

**Table 1. Decomposition of $^{14}$C-labeled fulvic acid in soil.**

| Treatment[a] | Total rate of decomposition (uc × $10^{-3}$) | Decomposition mg C | Decomposition % compared with biotic | Decomposition of added $^{14}$C as fulvic acid (%) |
|---|---|---|---|---|
| Biotic | 27.01 | 0.60 | 100 | 0.161 |
| Sterile (Hg-preparation) | 5.08 | 0.11 | 18.8 | 0.030 |
| Biotic + UV irradiation | 16.15 | 0.36 | 59.8 | 0.096 |
| Sterile (Hg-preparation) + UV-irradiation | 12.47 | 0.28 | 46.2 | 0.074 |

[a] Each treatment had 3 trials; measurements were made over a 1-week period.

Scharpenseel et al (1982). Experiments were based on uniformly labeled organic matter (wheat straw) as well as on a conventional method (Isermeyer 1952) of $CO_2$ collection.

The influence of metal ions on respiration in biologically active soils is mostly negative. Chang and Broadbent (1981) even calculated threshold and 50% inhibition concentrations for the more important heavy metals (Pb, Cr, Cd, Cu, Zn, and Mn); Singhania and Sauerbeck (1980) observed that Zn as $ZnSO_4$ decreased the overall decomposition in excess of 2,000 ppm concentrations only.

Sterilization of soil and biomass with $CHC1_3$, $CHBr_3$, gamma radiation, and autoclaving as part of Jenkinson's (1966a) decomposition studies (see also Powlson and Jenkinson 1976) with uniformly $^{14}$C-labeled ryegrass revealed heavy decomposition of a more zymogenic nature, with a 1.5-year half-life in the case of the labeled part. Paul and van Veen (1978), pointing to the findings of Tusneen and Patrick (1971), Payne (1970), Ladd and Paul (1973), and van Veen (1977), drew attention to the high requirement of C for biosynthesis, which must be considered when assessing decomposition rates. Cheshire et al (1974) observed this for sugars.

Influencing $^{14}CO_2$ release by planting barley in treated soil was followed by Sparling et al (1982). Reduction of $^{14}CO_2$ evolution due to barley plants was caused not only by competition for moisture supply; by addition of yeast or glucose a small priming effect with incremental $^{14}CO_2$ release could be triggered. The effect is more complex than can be explained by simple nutrient and moisture balance.

An entirely different and original explanation of soil organic matter decomposition is offered by Laura (1975a,b; 1976), who claims the main causative agent is not biological but protolytic activity in the soil. Proton sources are added to the soil mainly by ammonium and organic materials. Sulfates, nitrates, and most of the hydrated cations usually promote organic matter mineralization whereas salts of transition elements depress it. As far as conventional measurements of respiration are concerned, de Jong et al (1979) showed that results of the "carbon dioxide profile method" usually exceed those of the "dynamic chamber method" with continuous $CO_2$ analysis of the air; micrometeorological "above-canopy" measurements are intermediate.

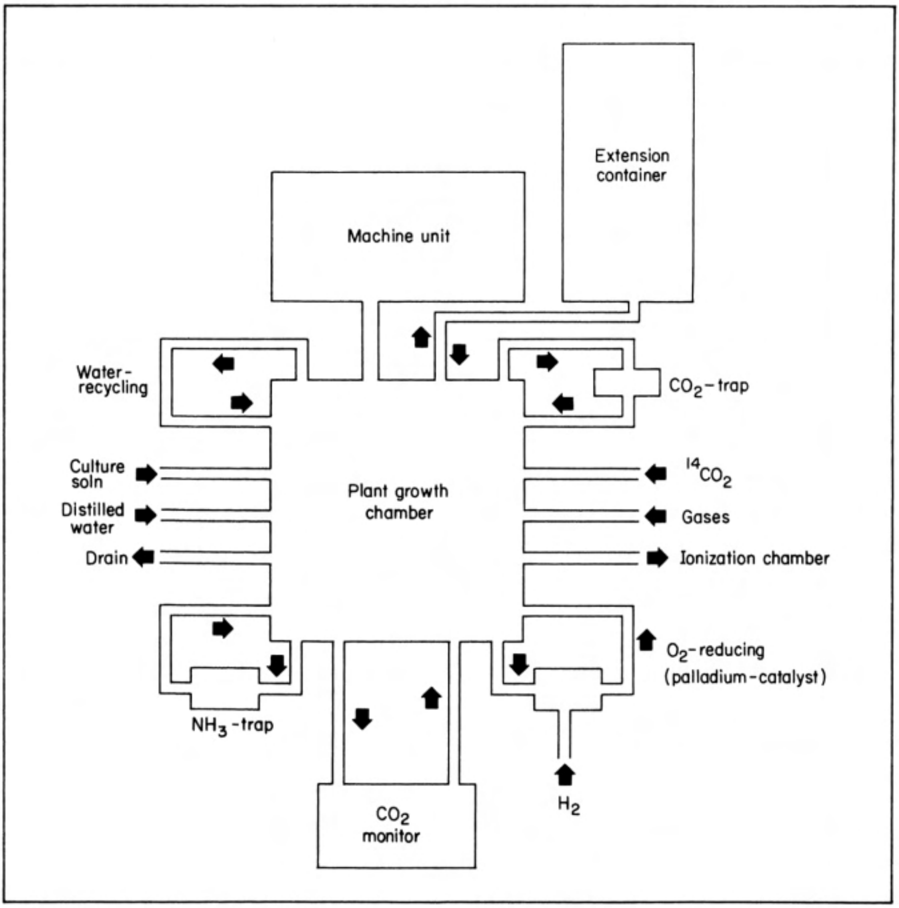
## DECOMPOSITION MEASUREMENTS BASED ON $^{14}$C

$^{14}$C is a weak ß-emitter with a 5,730-year half-life, therefore not requiring decay corrections after year-long observation periods. It is the choice nuclide for tracing first or higher order reactions of organic matter turnover in the soil. There are different facets of $^{14}C$ application:

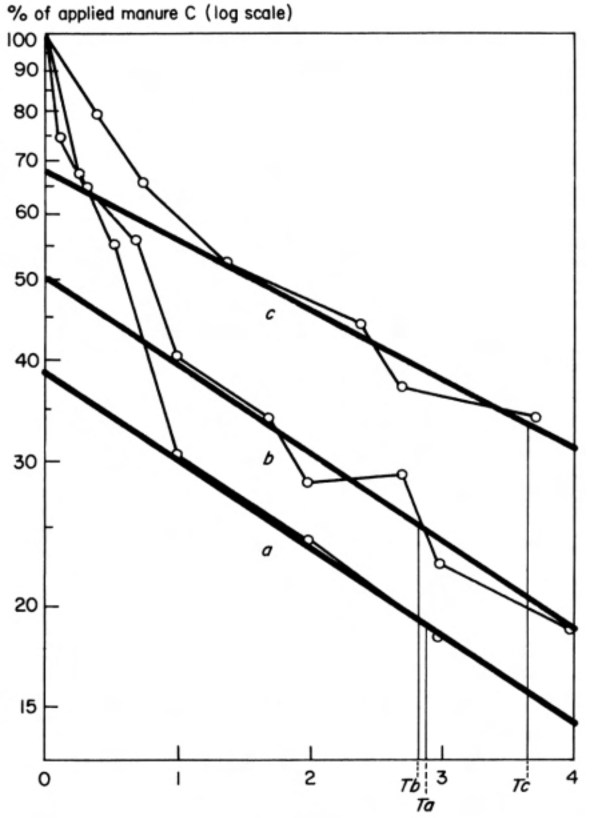
- monitoring turnover and decomposition products of uniformly $^{14}C$-labeled organic matter introduced into the soil,
- studying processes involving $^{14}C$-labeled humic or fulvic acids,
- studying reactions of specific $^{14}C$-labeled organic compounds with the soil colloid system, and
- identifying the organic remainder after arrival at steady state conditions by measurement of the natural $^{14}C$ concentration and radiocarbon dating.

### Production and application of uniformly labeled organic matter

Uniform labeling requires exposure of plants to $^{14}CO_2$ over the whole life span. Otherwise only primary products of the assimilation process such as carbohydrates, amino acids, and carbonic acids will be heavily labeled; polymers like proteins and polysaccharides will remain low in specific activity; and compounds of the crude



**1.** The plant growth chamber.



**2.** Semilogarithmic diagram of the decomposition of $^{14}$C-labeled manures in soil (Oberländer 1973). *a,* green manure; *b,* straw; *c,* farmyard manure; *Ta, Tb, Tc,* decomposition half-lives.

fiber fraction such as lignin, cutin, and suberin, which are important for the humification process, show only very slight labeling. Thus, nonuniformly labeled organic matter used in decomposition studies leads to erroneous results (Jenkinson 1966b, Sauerbeck 1966). Commercial growth chambers for production of uniformly $^{14}$C-labeled plant material are available[1] (Neue et al 1982; see Fig. 1.) But most of the decisive work executed during the 1960s and 1970s was carried out with the help of sophisticated, self-constructed systems (Sauerbeck 1960; Jenkinson 1960, Zeller et al 1966; Oberländer and Roth 1968a; Oberländer 1970,1973; Scharpenseel 1961, 1966; Commissariat de l'Energie Atomique 1977). Several papers by some of the most active authors in the field of organic matter turnover try to give coverage to the major contributions (Jenkinson 1971, Sauerbeck and Johnen 1974, Oberländer 1973, Paul and Van Veen 1978, Flaig 1982). A short list of major findings would include five subject areas, discussed below.

*Decomposition in the field, rates, and fractions.* The decomposition of uniformly $^{14}$C-labeled organic substances, especially under field conditions, has been tested by a few authors who possessed sufficient supplies for large-scale turnover experiments (Jenkinson 1965, 1968, 1971; Führ and Sauerbeck 1968; Oberländer and Roth

---

[1] Weiss Technik, D6301 Reiskirchen 3 (Lindenstruth) Greizer Strasse 41-49.

1968b). Jenkinson (1966a), Oberländer and Roth (1974,1975), and Zeller et al (1968) emphasized the unique role of labeled substrates for organic matter decomposition studies, especially in field experiments. Jenkinson (1964) recognized that the initial phase of decomposition is retarded in acid soils compared to neutral ones. Apparently, fresh and rotted manure are decaying on a similar time scale (Oberländer 1973, Sauerbeck 1968); however, straw decomposes faster in the first year than manure, which has already lost 20-30% of its C during the rotting procedure. Fresh green plant material, farm manure, and slurry plus straw behave similarly (Fig. 2), and a similar rate of C remains even from glucose (Persson 1967). Oberländer and Roth (1980), studying 8- to 14-year-old residues of all these labeled materials in Mollisols with various cultivation methods, found the residues shown in Table 2. After 8 years of fallow, the residues that remained from the different materials were in the proportions of manure : straw : green manure = 100 : 68 : 62.

Under tropical conditions in Nigeria, Jenkinson and Ayanaba (1977) observed a decomposition process that was four times faster. With straw or manure of equal C:N, Oberlander (1973) observed about 42% of manure C in soils after 1 year of decomposition and no difference whether the N added to the straw was in organic or mineral bondage. Martin et al (1982) monitored $^{14}C$-$CO_2$, -$CH_4$, and -organic acid release in submerged rice soils after the addition of a uniformly $^{14}C$-labeled substrate of rice plants. Surprisingly, the $CH_4$ concentration was very high, and more $^{14}C$ was recovered in the soil solution from deeper than surface layers.

Jenkinson (1965) found that 33% of organic matter remained after 1 year, and 19% after 4 years; even then the loss of labeled C was 4 times as high as that of unlabeled C. Oberlander (1973), Jenkinson (1965), Sauerbeck (1968), Sauerbeck and Fuhr (1971), Jenkinson (1971), and Oberlander and Roth (1980) found about 30% of straw or green manure left in the soil after 1 year, 25% after 2 years, and 18% after 5 years, irrespective of climatic conditions within Europe. Jenkinson and Rayner (1977) created a 5-compartment model in the case of 1 t fresh plant C/year per ha as input. They coined names for the fractions and estimated the contents after 10,000 years at steady state, and they predicted for that time a radiocarbon age of 1,240 years (Table 3). According to Oberlander and Roth (1980), equal amounts of C residues would require, for example, 10 t farmyard manure/ha, 3.7 t straw/ha, and 27 t green manure/ha. Green manure apparently has a higher humus building value than commonly assumed.

A long-term annual application of 5 t/ha of $^{14}C$-labeled straw raised the straw-

**Table 2. Percentage of residues of $^{14}C$-labeled organic plant materials after various cultivation methods (Oberlander and Roth 1980).**

| Source | Residues of $^{14}C$-labeled organic plants (%) | | | |
|---|---|---|---|---|
| | Cropping | | Bare soil | |
| | 1 yr | 8 yr | 1 yr | 8 yr |
| Farmyard manure | 62 | 25 | 65 | 23 |
| Slurry and straw | 64 | 23 | 40 | 15 |
| Straw | 42 | 16 | | |
| Green manure | 33 | 14 | | |

**Table 3. Half-lives and pod sizes of different soil fractions (Jenkinson and Rayner 1971).**

| Fraction | Half-life (yr) | Pool size |
|---|---|---|
| DPM (decomposable plant material) | 0.156 | 0.01 + |
| RPM (resistant plant material) | 2.31 | 0.47 + |
| BIO (soil biomass) | 1.69 | 0.28 + |
| POM (physically stabilized organic matter) | 49.5 | 11.3 + |
| COM (chemically stabilized organic matter) | 1980 | 12.2 + |

induced C in the soil after 4 years to about 120% of the C in the first straw dose (Fig. 3).

A formula for straw decomposition is badly needed for calculation of the frequency of required straw manuring for humus conservation. In general Pal and Broadbent (1975) rejected the idea that first-order-rate kinetics were applicable to describe organic matter decomposition, but Jenkinson and Rayner (1977), Russel (1964), Stanford and Smith (1972), Hunt (1977), Gilmour et al (1977), and Sinha et al (1977) confirmed its validity. The decomposition rate can be expressed by

$$V_{dec} = \frac{-dA}{dt} = KA$$

or

$$A = A_o \cdot e^{-Kt}$$

*Effect of quantity of organic matter and field conditions.* At the onset of isotope studies on decomposition, Broadbent and Bartholomew (1948) presented the observation that small amounts of added organic matter decompose more rapidly than large quantities. This idea was only partly accepted at first (Hallam and Bartholomew 1953, Sauerbeck 1966). Confirmation seemed to depend on whether the amount of $^{14}$C remaining in the soil was measured instead of the evolving gaseous products, and if C addition were not to exceed 2% (Sorensen 1963, Jenkinson 1965, Sauerbeck 1968, Oberlander and Roth 1968b). Pinck and Allison (1951) inferred that in fact the amount of $^{14}$C released was nearly independent if the quantity of carbon added did not exceed 1.5% of the dry weight of the soil and if the decomposition was monitored for 3-6 months. Jenkinson (1971, 1977a) and Oberlander and Roth (1980) learned that when sufficient quantities of $^{14}$C-labeled organic matter permitted field trials, the rate of addition scarcely influenced the rate of decomposition. However, Jenkinson (1977b) observed, that $^{14}$C-labeled organic matter was retained more effectively in highly organic soils than in soils of low organic matter content.

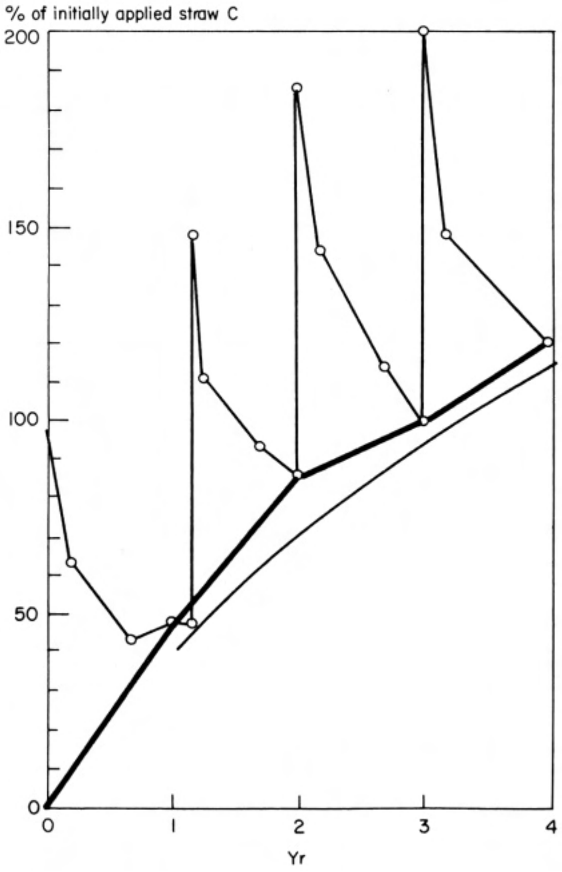
Flaig (1982) concluded that decomposition is faster under fallow conditions than in grassland; that the effects of crop cultivation, soil pH, and organic matter content are moderate; but that the impact of the clay content is considerable. With regard to stimulation or organic decomposition by N application, Sauerbeck (1968) and Oberlander and Roth (1980) agreed on observing an acceleration in N-deprived soils and on seeing no effect in N-rich soils. Sauerbeck found this acceleration evident during the first few weeks after N application. In Oberlander and Roth’s case the stimulation resulted from a heavy N application (600 kg/ ha).

Jenkinson (1966a, 1968), who was using soil previously sterilized by autoclaving or fumigation, found strong decomposition. The labeled portion of organic matter suggested more zymogenic decomposition in a decay regime of 1.5 years (the half-life period). The unlabeled part followed the decay constant of autochthonous C over 3 years of observation. The lowest concentration of the label was found in 6 N HC1 unhydrolyzables, which also had the widest C:N. The alkali soluble part was slightly higher in specific activity. Jenkinson and Powlson (1976) found 50% (*K* value 0.5) for the evolution of $CO_2$ after chloroform treatment, whereas Anderson and Domsch (1978) reported only 41% (*K* value 0.41).

*Incorporation of labeled compounds into fractions.* All fractions due to soil organic matter decomposition show wider diversity of label concentration than the conventional fractions of fulvic acids, humic acids, and humins (Jenkinson 1971, Mutakar and Wagner 1967, Sorensen 1963). Jenkinson (1968) found, that the specific activities differed by a factor of 16.

In all observed cases, soils supplied with whole plant material or decay products had, after prolcnged decomposition, higher specific activities in the 6 N HC1-hydrolyzed fraction or in the fulvic acids, humic acids, and humins than in the

**3.** Decomposition of annually applied $^{14}C$-labeled straw and accumulation of the slowly decomposed labeled residues (Oberlander 1973).



insoluble residue (Sorensen 1963, in the case of whole plants; Wagner 1968, Mayaudon and Simonart 1958a, Mutakar and Wagner 1967, in the case of glucose; Simonart and Mayaudon 1961, in the case of plant protein). On the other hand, for lignin a lower label concentration was found in the hydrolyzable part than in the residue (Mayaudon and Simonart 1959b, Sorensen 1963). However, all the fractions of soil organic matter also carry the tag derived from labeled input materials (Chekalov and Illyuviyeva 1962, Oberlander and Roth 1968a, Persson 1968, Sauerbeckand Führ 1968), if they are plant protein (Simonart and Mayaudon 1961), labeled microorganisms (Mayaudon and Simonart 1963), or redistributed activity by the isolation procedures of humic acid and fulvic acid (Sauerbeck and Fuhr 1968, Oberländer and Roth 1968). Labeled glucose in the soil also has a pathway component toward labeled amino acids (Mayaudon and Simonart 1963, Sorensen 1963). Wagner and Mutakar (1968) found 20% of the label in the amino acid fraction after 6 months. Glucose $^{14}C$ transfer into other monosaccharides was verified by Kiefer and Mortensen (1963) and Cheshire et al (1969).

Jenkinson (1968) observed that the more severe the acid hydrolysis, the greater was the dissolved fraction, but the lower its specific $^{14}C$-activity. Intensive studies on the nature of the fractions of labeled substances after decomposition were conducted by Simonart and Mayaudon (1962) and Mayaudon and Batistic ( 1970). Oberlander (1980) studied fractions arising from the decomposition of $^{14}C$-labeled green manure. Here, the specific gravity of the humin fraction was unexpectedly high, indicating cellulose decomposition rather than the slow buildup of clay humic matter complexes (see Oberlander and Roth 1980). After 1 month, humic acids were also accumulating considerable amounts of the $^{14}C$ label. Oberlander and Roth (1980) used “humification indices” — $C_h/C_f$ versus time. The index is about 0.5 for Inceptisols, and near 1.0 for Mollisols. Also the $K$ values (rate constants) vary considerably and require correction for microbial synthesis. $K$ values for wheat straw decreased from an initial 0.03/day to 0.003/day (Paul and van Veen 1978).

Jenkinson and Rayner (1977) and Gilmour et a1 (1977) explained this decrease as a result of the different components of soil organic matter — lipids, cellulose, lignin — having individual decomposition rates and $K$ values.

Jenkinson and Ayanaba (1977) recognized that, despite four times more rapid decomposition in tropical Nigeria, ryegrass and maize decomposition patterns resembled those in England, with 20% residue after 1 year and 14% after 2 years. Paul and Van Veen (1978) and Shields and Paul (1973) arrived at half-life values of 75-125 days based on $CO_2$ output.

*Fresh substrate and effects of priming action.* Mere disruption of soils causes an increase in C and N mineralization (Hiura et a1 1976, Rovira and Greacen 1975, Craswell and Waring 1972, Waring and Bremner 1964, Edwards and Bremner 1967).

The stimulation of decomposition by the addition of manure was described by Löhnis (1926). Broadbent and Norman (1946) made first measurements by applying organic matter, isotopically labeled with $^{13}C$, for simultaneous measurement of the partitioning effect between the evolving unlabeled $CO_2$ from the soil and the labeled, substrate derived $CO_2$. The authors observed a strong enhancement of soil organic matter decay upon the addition of young organic substances, a positive priming effect.

Jenkinson (1966) drew attention to the importance of applying truly uniformly labeled organic matter to avoid apparent priming effects due to experimental error. Using unlabeled organic matter, Jansson (1960) could not confirm a priming effect. Moureaux (1967) pointedly expressed that conventional measurements, properly conducted, were extremely laborious. The majority of critical experimentors, using $^{14}C$-labeled organic matter, and some reviewers (Bingeman et al 1953, Stotzky and Mortensen 1958; Hayes and Mortensen 1963; Sorensen 1963; Smith 1966; Sauerbeck 1963, 1966, 1968) found quite low or no priming effects at all. No one confirmed the large priming effects of the pioneer work by Broadbent and Norman (1946) and Broadbent and Bartholomew (1948).

*Stabilization, conservation, and accumulation of plant carbon.* Young, uniformly labeled plant matter mineralizes, even 4 years after application to the soil, several times faster than the resident soil organic matter (Jenkinson 1965). Even after a further number of years, the young plant matter remains intermediate between fresh plant residues and old, autochthonous soil organic matter, and some of it is probably unchanged lignin (Persson 1968). Repeated addition of labeled substrate to the soil reactivates the leftover biomass (Mayaudon and Simonart 1963). Restabilization by sorption on soil colloids was proved for proteins by Simonart and Mayaudon (1961). The same authors (1966) found 6.3-6.5 times as much $^{14}C$ and also N in the hydrolyzable fraction than in the residue fraction, whereas the unlabeled C was represented in a ratio of 1.1 only. They concluded that the labeled C behaved more similarly to the N than to the unlabeled, autochthonous C. The continued heavy $^{14}CO_2$ release after irradiation and fumigation of the soil was explained by Jenkinson (1968, 1971) as due to decay of heavily labeled microbes killed by the sterilization procedures.

Jenkinson (1968), Sauerbeck and Führ (1968), and Jansson and Persson (1968) regarded the separation of humified and nonhumified constituents as an inherently difficult methodological problem, since coextraction of high moleculars like lignin with humic acid extraction is unavoidable.

Gross decomposition was found to proceed faster after fallow under root crops, at least in the course of the first 2 years, than under grain crops; later on, the difference leveled off. Jenkinson (1964), Sauerbeck and Führ (1971), and Oberlander (1973) could not confirm any such difference.

Considerations of the organic matter balance are not totally in agreement. Welte (1963) claims that a crop rotation with 60% grain crops and 1.8 t/ ha annual supply of residues can maintain the humus content of a soil with <2.5% humus and <2% annual rate of mineralization. However, increasing monoculture of wheat with accompanying higher mineralization cannot maintain organic matter conservation even with higher input of residues due to increased yields (Oberlander 1973). Sauerbeck and Führ (1971) calculated the maximum C enrichment in soils supplied with 2 t straw/year to be 6.5 t C/ha after >25 years. The turnover time of slowly decomposable humified straw at annual replenishment is about 6-7 years. In case of 2% yearly mineralization, the annual supply of 2 t would not suffice to maintain the C level in the soil. Jenkinson (1966) deviated from Sauerbeck and Fuhr by assessing the turnover time at 15-45 years.

Most pertinent results point to a low increase of humified C in soils, even from farmyard manure. Also, a yearly input of 5 t dry matter/ha would produce, according to Oberlander and Roth (1972), only a maximum accumulation of 3-6 t humified carbon versus 36.7 t/ha of native soil C.

In conventional calculations of the rate constant *r* from C and N analysis for consistent annual supply versus mineralization, it appears that all organic matter fractions have the same input-decomposition pattern; but this is highly questionable. Each fraction should have its own rate constant (Schmalfuss 1957, Welte 1963, Warren 1956). Henin et al (1959) took this into account by using a model with several equations and by identifying split rate constants.

Oberlander (1973) chose the well-known kinetic interpretation, following the decay equation with semilog plots of decomposition curves for green, straw, and farmyard manure (Fig. 2):

$$X = X_o\, e -\gamma t; \quad \frac{dX}{dt} = -\gamma X$$

Obviously, there is a considerable gap between experimental turnover periods using uniformly $^{14}$C-labeled organic matter and residence time periods of autochthonous C in soils when assessed by radiocarbon dating — amounting to hundreds or several thousands of years. Some authors therefore distinguish between two independent organic matter pools, one composed of less stable humic matter with rapid turnover, and a core of old, inert, protected material (Gerasimov 1971, 1974; Kleinhempel et al 1971; Sauerbeck and Fuhr 1971; Scharpenseel 1971b). A link between the maximum maintainable organic matter pool and the clay mineral content of the soil, responsible for resistance against biological and chemical decomposition mechanisms, seems obvious.

### $^{14}$C-labeled humic or fulvic acids

$^{14}$C-labeled humic compounds have been produced from uniformly labeled organic matter (Scharpenseel 1966, Führ and Sauerbeck 1966) and employed for studies of humic acid decomposition in soils (Scharpenseel and Beckmann 1964a,b) under the influence of various factors such as metals or different sources of lime. The uptake of humic substances by roots (Führ and Sauerbeck 1964, 1965, 1966, 1967) and the humification of $^{14}$C-labeled proteins by the soil (Simonart and Mayaudon 1961) have also been explored. Martin (1977) studied the chemical nature of the $^{14}$C-labeled organic matter released from growing wheat roots in the soil, while Haider and Martin (1968) concentrated their efforts on problems of the formation of labeled humic acids by microorganisms. Scharpenseel (1962) subjected $^{14}$C-labeled humic acid to decomposition by proteolytic enzymes and proved the existence of proteins in humic substances. With $^{3}$H-labeled humic acids using the Wilzbach gas exposure method (Scharpenseel 1960a), interconvertibility of humic acid fractions was demonstrated.

### Specific $^{14}$C-labeled organic compounds

Numerous studies, whose detailed results would exceed the scope of this paper, have been carried out with individual labeled compounds such as sugars, proteins, amino acids, polysaccharides, lignins, phenolic compounds, organic acids, pigments, and microbial products to test either their specific precursors or their transformation reactions in the humification process. Some of the major contributions are listed in Table 4.

**Natural radiocarbon measurements**

Natural radiocarbon measurement in soil permits calculation of its minimum age — the apparent mean residence time (AMRT) of soil C — based on an increasing age gradient with depth of soil layer (Scharpenseel et al 1968a,b,c, Scharpenseel and Pietis 1969; Scharpenseel 1971a,b; 1972a,b; Scharpenseel and Schiffmann 1977a,b). The mere existence of soil C of great age at the deepest fringe of the epipedon, showing an AMRT of 5,000-6,000 years in Holocene soils of about 8,000 years true age (soil formation since Boreal) substantiates that exponential organic matter decomposition, as observed during the first few years of $^{14}C$-labeled organic matter decomposition, is discontinuous (Scharpenseel 1975a). Natural $^{14}C$ concentrations measured infractions of soil organic matter indicate inhomogeneity of the $^{14}C$ level, dependent on the relative age each fraction represents within the C cycle and on the mode of protection against biotic decomposition it has received under the existing soil chemical, physical, and mineralogical regime (Scharpenseel et al 1968d; Scharpenseel 1972c, 1975a,b, 1976; Goh et al 1977). Steady state decomposition of soil organic matter is definitely not governed any more by the decay equation $X = X_o e^{-At}$
where

$$T\frac{1}{2}\ (\text{in}\ \lambda = \frac{ln2}{T\frac{1}{2}})$$

amounts to just a few years. Some long living compartments of organic matter were identified by Jenkinson and Rayner (1977), who calculated average $^{14}C$ age, AMRT, and turnover time; eventually two different organic matter pools, as suggested by Sauerbeck and Gonzalez (1977), might have to be considered. Measurement of natural $^{14}C$ in $CO_2$ emanating from the old, deepest zone of the epipedon — which has never been done — is urgently needed. It seems to be the only way of using natural $^{14}C$ to decide to what extent the deeper humus layers, being probably protected by clay organic complexation, exist under continued decomposition. Paul and Van Veen (1978), rejecting the model of Jenkinson and Rayner, suggested instead protection by physical entrapment within soil aggregates as well as by adsorption.

Soil dating based on the undecomposed C pool is the reverse of measuring the decomposition of uniformly $^{14}C$-labeled organic matter in the soil. While for true age measurements only charcoal is acceptable, soil humus dates represent the minimum age of the soil organic matter, considering unavoidable rejuvenations due to leaching of modern C, root growth, and animal transport. The AMRT of the deepest fringe of the epipedon is the measurable minimum age closest to the true age. The validity of this interpretation has been elaborately disputed (Geyh 1970; Geyh et al 1971; Campbell et al 1967; Jenkinson 1969; Martel and Paul 1974; Paul et al 1964, O'Brien and Stout 1978; Rafter and Stout 1969; Scharpenseel et al 1968a,c; Scharpenseel 1971a, 1972a, 1977; Scharpenseel and Schiffmann 1977a,b).

In the light of several thousand soil dates produced during the last 15 years, an

Table 4. Transformation studies with $^{14}C$-labeled compounds in soils.

| Glucose, dextran, sugars, amino sugars | Dialyzable proteins, proteins, peptides, amino acids | Dialyzable hemicellulose, starch, cellulose, lignin | Polysaccharides, lipo-polysaccharides |
|---|---|---|---|
| Chahal and Wagner (1965) | Mayaudon and Simonart (1965) | Cheshire, Mundie, and Shepherd (1969) | Keefer and Mortensen (1963) |
| Cheshire, Mundie, and Shepherd (1969) | Simonart and Mayaudon (1961) | Mayaudon and Simonart (1959a) | Mayaudon and Simonart (1965) |
| Mutakar and Wagner (1967) | Simonart and Mayaudon (1959) | Mayaudon and Simonart (1959b) | Martin, Haider, Farmer, and Fustec-Mathon (1974) |
| Simonart and Mayaudon (1958b) | Verma, Martin, and Haider (1975) | Simonart and Mayaudon (1959) | |
| Bondietti, Martin, and Haider (1972) | Mayaudon (1968) | Mayaudon and Simonart (1961) | |
| Guckert, Cure, and Jacquin (1971) | Wagner and Mutakar (1968) | Cheshire, Mundie, and Shephard (1974) | |
| Wagner and Mutakar (1968) | Scharpenseel (1962) | Crawford, Crawford, and Pometto (1977) | |
| Wagner and Tang (1976) | Mayaudon and Simonart (1959a) | Haider and Farooz-e-Azam (1982) | |
| Mayaudon and Simonart (1958a,b) | | | |

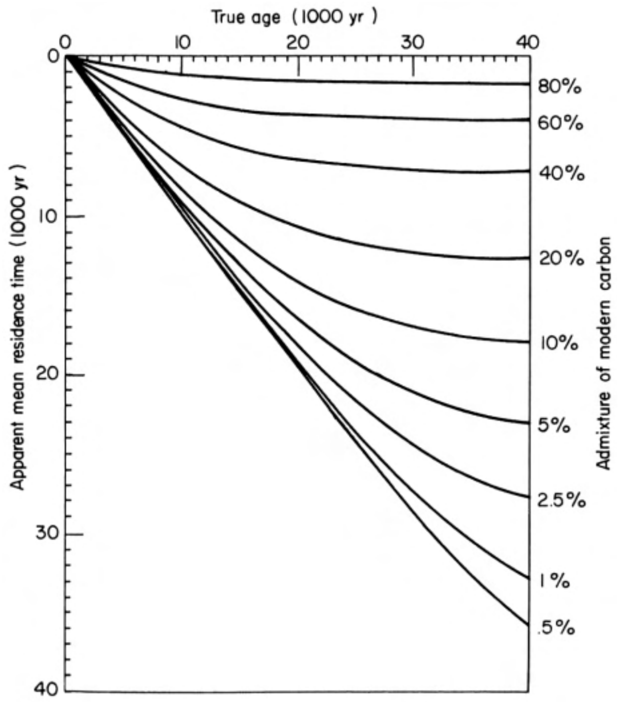
early hypothesis of Jenkinson (1971) that the old $^{14}C$ dates in soil material could reflect only finely distributed charcoal must be dismissed. Figure 4 indicates that, due to exponential radioactive decay, a small percentage of rejuvenating modern C in an old soil can produce a dramatic shift to a younger radiocarbon age, whereas even considerable amounts of old, dead C have a comparatively lower influence on the apparent soil age. A similar graph, covering the first, almost linear part of <2,500 years of age, is in Campbell et al (1967).

Efforts have been made to search for the oldest or even a biologically inert soil organic matter fraction (see Gerasimov and Chichagowa 1971, Gerasimov 1974, this report). The procedure of yielding the relatively oldest fraction, i.e., coming closest to the true age of the soil formation, would become the choice method for routine pretreatment of samples. Contributions concerning this problem are numerous (Campbell et al 1967; Grant-Taylor 1972; Lobo et al 1974; Martel and Paul 1974; Nakhla and Delibrias 1967; Östlund and Engstrand 1963; Paul et al 1964, 1976;

| Phenols, phenolic acids, pyrogallic acid, purpurogallin, catechol-glycine | Organic acids benzoic acid, cinnamic acid, syringic acid, coniferylic, alcohol, vanillin | Foliar pigments | Microbial fractions |
|---|---|---|---|
| Haider, Lim, and Flaig (1962) | Harms, Söchtig, and Haider (1969a) | Simonart and Batistic (1959) | Hurst and Wagner (1969) |
| Söchtig, Harms, and Haider (1968) | Harms, Sochtig, and Haider (1969b) | | Haider and Martin (1979) |
| Kastori, Harms, Söchtig, and Haider (1970) | Haider and Martin (1975) | | |
| Andreux, Golebiowska, Chone, Jacquin, and Metche (1977) | Martin, Neue, and Scharpenseel (1982) | | |
| Harms, Sochtig, and Haider (1971) | | | |
| Haider and Farooze-e-Azam (1982) | | | |

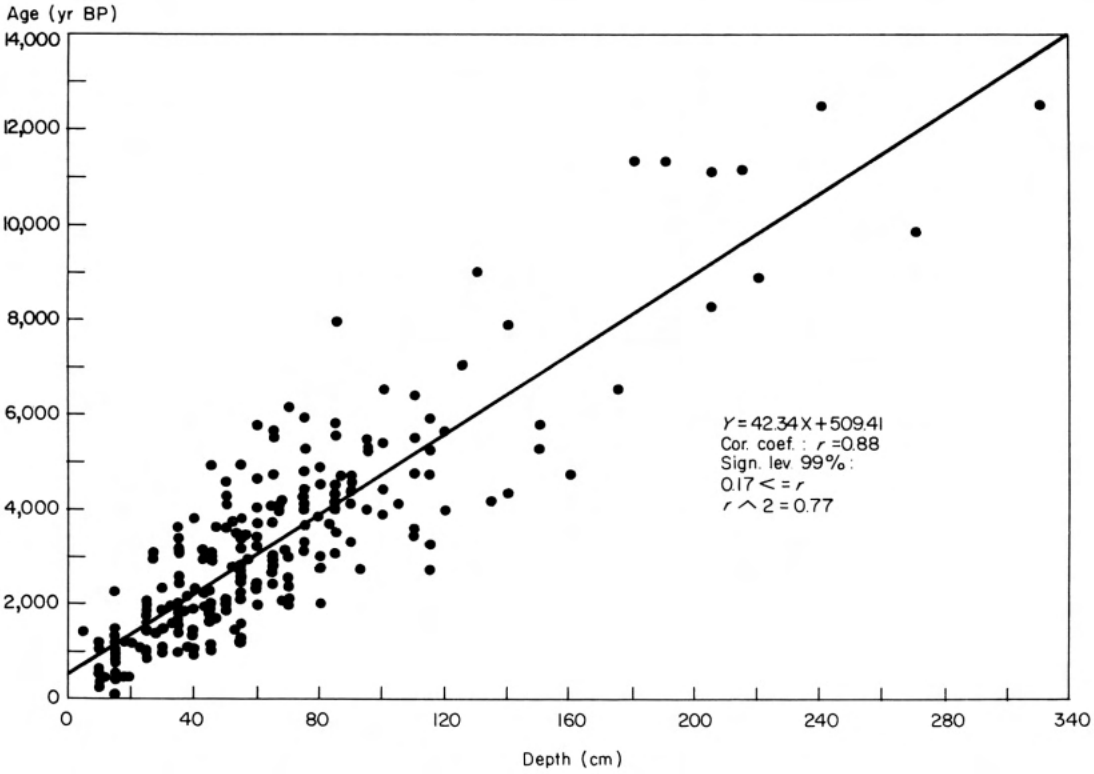
Polach and Costin 1971; Rubilin and Kozyrewa 1974; Goh et al 1977; Goh et al 1979; Scharpenseel et al 1968d; Scharpenseel and Pietig 1969; Scharpenseel 1972c, 1975a,b, 1976). It has turned out that HCI or $HNO_3$ hydrolysis removes much of the younger carbonaceous material (Scharpenseel 1976, Goh et al 1979).

During the first decade of radiocarbon dating, application of the method to complex material such as soil humus was very limited. Broecker et al (1956), de Vries (1958), and Felgenhauer et al (1959) dated fossil soils based on cold alkali extracted humic acid C. De Vries (1958) discussed the potential contaminations due to root growth or recent C infiltration, but, like Münnich (1957), he found the downward migration of organic matter in sediments unexpectedly low. Ruhe et al (1957) related the $^{14}C$ dates of wood and molluscan remains to the age of the embedding soil. Early appraisal of radiocarbon dating and its value for soil organic matter studies came from Scholtes and Kirkham (1957), van Heuvelen (1959), Tamm and Ostlund (1960), and Scharpenseel (1961).

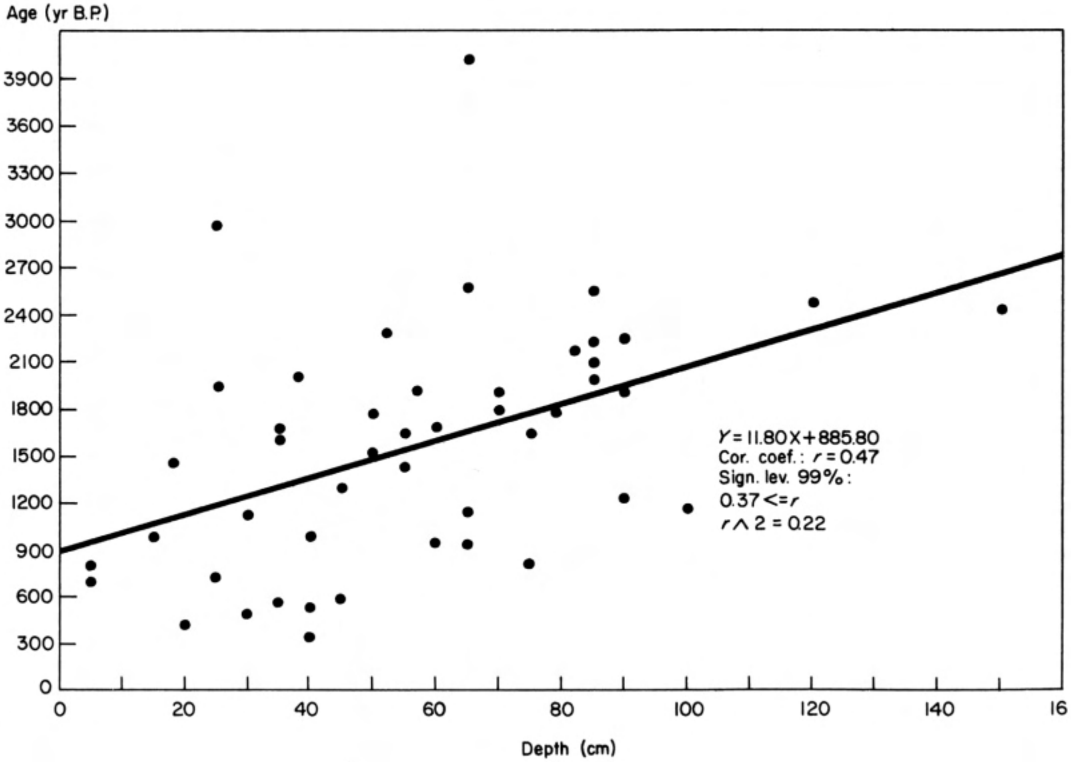


**4.** Rejuvenation and aging of true soil age due to admixture of modern and dead carbon.

Soil type-related approaches of soil dating by the $^{14}C$ method, whether based on extracted humic acid or on total organic C, trace back to Niemeyer (1959), Fastabend and von Raupach (1962), and Mückenhausen et a1 (1968) with regard to the Plaggepts of North Germany; to Zakosek (1962) and Neugebauer and Zakosek (1962) concerning the age of Smonica (Vertisol); and to östlund and Engstrand (1963), Kohl and Quitta (1966, cited in Scharpenseel 1972a), and Nemecek (1971) with regard to the age of Mollisols. östlund and Engstrand (1963) used $^{14}C$ dating techniques in Lapland, Perrin et a1 (1964) in East Anglia, Lüders (1964) in Lower Saxony, and Godwin and Willis (1964) in Scotland with regard to Spodosols. Subsequently, thorough studies on the Spodosols of the Vosges were carried out in France by Durand and Guillet (1966), Guillet (1968, 1972a,b,c), Guillet and Robin (1972), Hassko et a1 (1969, 1974), and Righi and Guillet ( 1976). Scanning the natural $^{14}C$ concentration in a soil profile reveals the minimum age of the soil and reflects the activity of organic matter decomposition. Soil organic matter chronology in whole profiles has been favored throughout dating work on fossil as well as recent soils (Beckmann and Hubble 1974, with Krasnozems; Blackburn et a1 1979, with Vertisols in Australia; Conry and Mitchell 1971, with Irish Plaggepts; Guillet 1972a,b, with Spodosols in France; Herrera and Tamers 1971, with soil catenas in Venezuela; Mückenhausen et a1 1968, with Plaggepts of north Germany; Nemecek 1971, with Mollisols of the CSSR; Rubilin and Kozyrewa 1974, with Mollisols in the



**5.** C residence time vs depth in Mollisols. B. P. = before present.



**6.** C residence time vs depth in Spodosols. B. P. = before present.

USSR; Ruhe et al 1971, with paleosols in loess deposits of the USA; Yaalon and Scharpenseel 1972, with Vertisols and Alfisols in Israel; Rosell et al 1973, with Vertisol in Argentina; Scharpenseel 1977, with various soils of calcareous parent material; and Scharpenseel et al 1980, with diverse paleosols of Tunisia).

In an attempt to elucidate the natural radiocarbon profile, i.e., age vs depth interrelationship of organic matter of different soil orders, all samples of recent soils, dated in the author's laboratory, which were clearly definable according to origin, soil description, and classification, were compiled and subjected to regression (Fig. 5-9). Figure 5 shows a highly significant ($r$ = 0.88) age vs depth relationship for European Mollisols with old C up to 18,000 years in Russian Mollisols as the AMRT. The steep regresssion line shows high age vs depth, indicating good capacity for organic matter conservation.

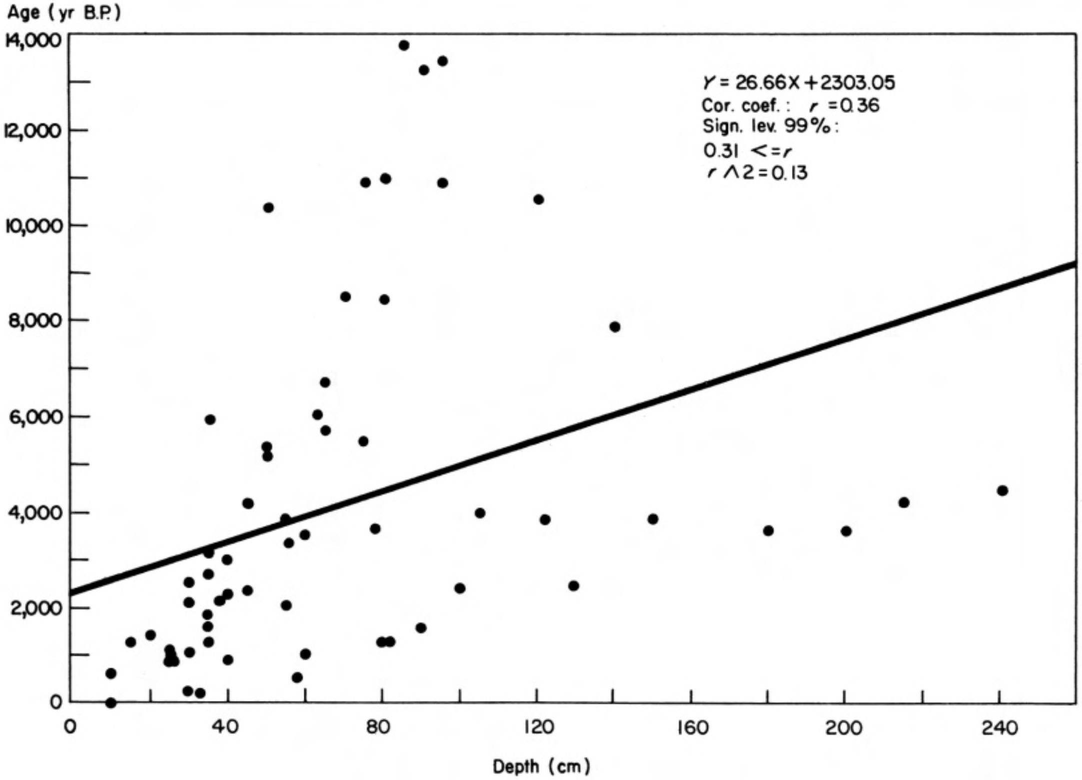
In case of Spodosols (Fig. 6) the depth function of age is less clearly documented. But significance is confirmed with $r$ = 0.47. Older C species are rare despite the acid milieu and low biological activity. Spodosols are strongly rejuvenated by young C from the litter zone, and they are simply rather young soil formations. The flat regression line indicates low capacity for organic matter conservation.

Inceptisols (Fig. 7) have a pronouncedly older region from loamy soils and a younger region derived from sandy soils. Alfisols (Fig. 8) show more coherence, having a high $r$-factor of 0.73 and reaching AMRT values of 15,000, confirming what was postulated earlier in this paper that organic matter seems protected in the argillic horizon.

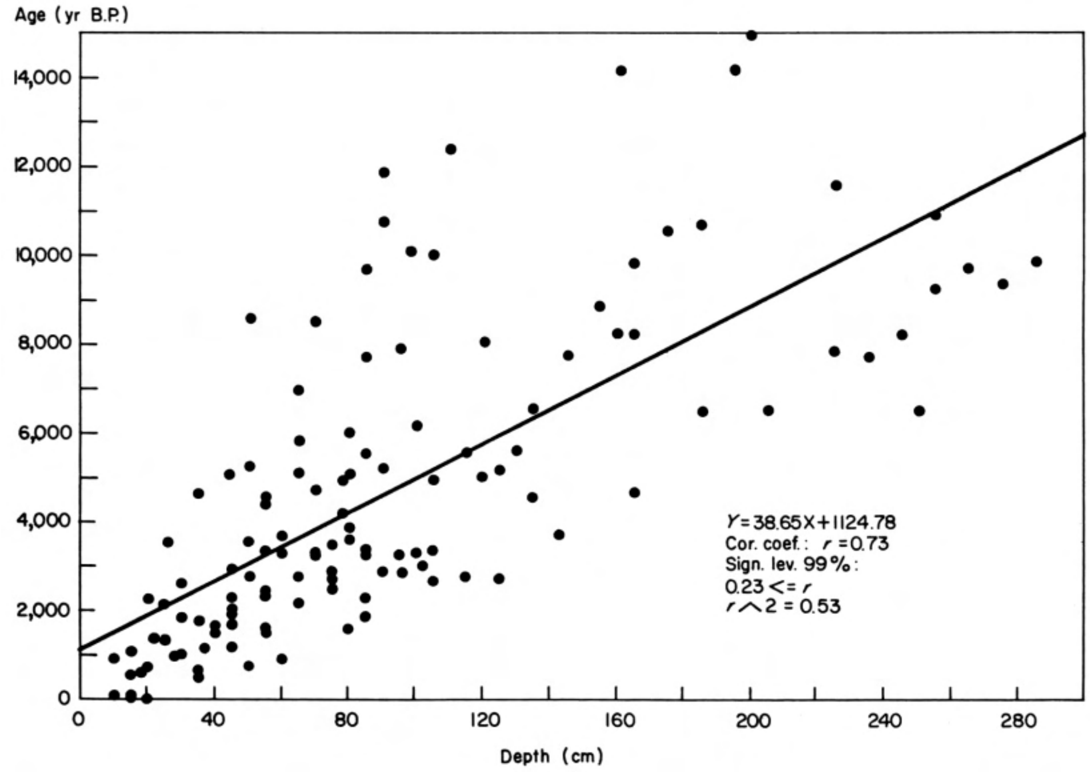
The Vertisols (Fig. 9) are derived from locations all over the world. There is some regional specificity. The lowest age vs depth wing represents mainly the Sudan Vertisols; the high age vs depth wing is mostly from Mediterranean Vertisols. Generally, the majority of Vertisols are relatively young. The oldest C species have AMRT values of about 22,000 years, although their regional origin is outside the influence of glaciation. The slope of the regression line expresses good organic matter conservation.

Thus, combining the rapid decomposition of uniformly $^{14}$C-labeled modern organic matter in the soil with the undisputably high radiocarbon age of organic matter in the lower parts of an epipedon or argillic horizon appears incompatible. Probably, the truth for the whole process of decomposition lies between those two boundary mechanisms. An obvious phenomenon is the increasing resistance of organic matter to biotic and other types of decay with growing age and depth of localization (Scharpenseel and Schiffmann 1977b). Detailed elucidation of the determinants will require more research into possible protection mechanisms and modes of organic decomposition in thin layers from the surface of the epipedon to the bedrock.

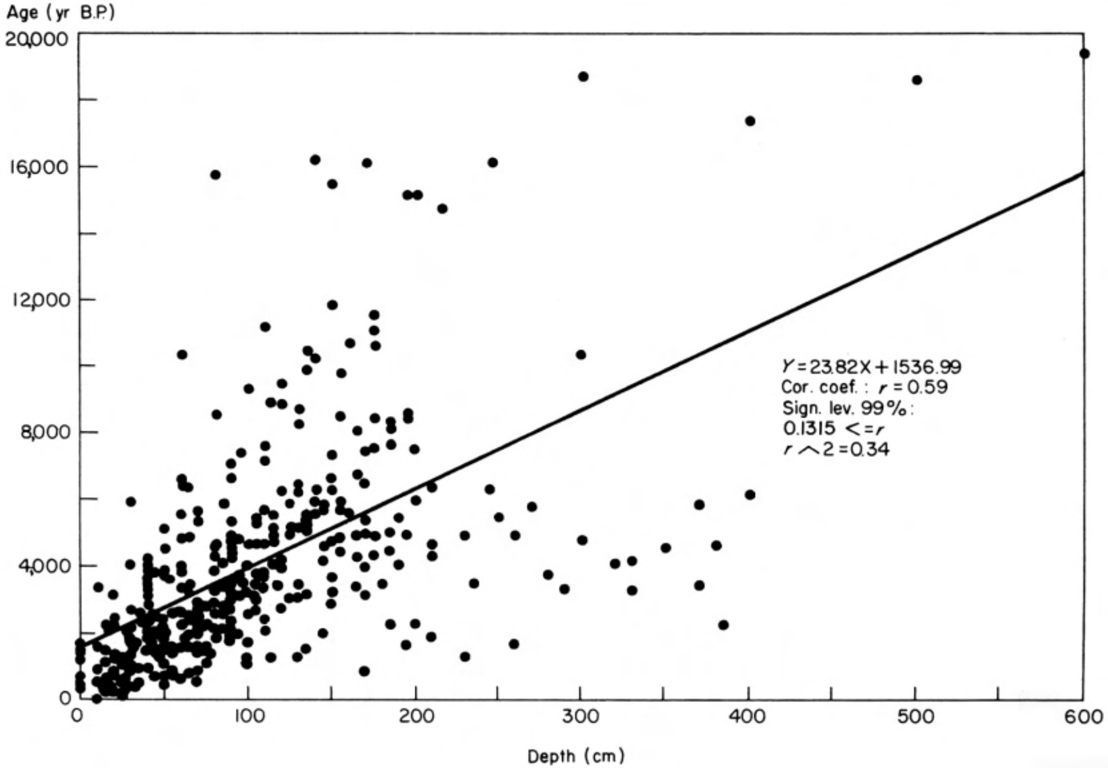
Nakhla and Delibrias (1967), Lobo et al (1974), and Meyer-Spasche and Scharpenseel (l980) applied an unusual approach to monitor $^{14}$C-labeled organic matter decomposition by using the bomb $^{14}$C curve, attributing annually specific $^{14}$C activities to all organic matter grown since 1956, the beginning of thermonuclear testing.



**7.** C residence time vs depth in Inceptisols. B. P. = before present.



**8.** C residence time vs depth in Alfisols. B. P. = before present.



**9.** C residence time vs depth in Vertisols. B. P. = before present.

## MODELS FOR INTERPRETATION OF $^{14}$C-DATING

Measurements of the natural $^{14}$C concentrations in soil samples, i.e., of the specific activity of natural $^{14}$C, or of the deviation in % of the D$^{13}$C value from Craig's PDB Belemnite-carbonate standard (1953), simply indicate properties of the natural soil. Their interpretations regarding soil age (Libby 1952) or organic matter turnover are attempts with disputable justification (Geyh 1971).

The first pertinent model was presented by Perrin et al (1964) with regard to soil (Spodosol) age, based on the specific $^{14}$C activity $X$. From their equation $X = \int I_o \alpha e^{-\lambda t}$ the authors concluded that the age $t$ cannot be evaluated, since the magnitude of eluviation rate a and its variation with time are unknown. Also, the equation does not account for the mineralization of organic matter.

For the five-compartment model of Jenkinson and Rayner (1977), being projected by radiocarbon dating for the time after 10,000 years of continued input of 1 t C/ha per year, apparent radiocarbon age was calculated at 1,240 years, which appears rather young (Fig. 4).

Jenny's coefficient of decomposition

$$K = \frac{A}{Fe + A}$$

($Fe$ = humus level in equilibrium state; $A$ = annual leaf and twig droppings) was applied by Steinhardt (1979) to calculate $K$ for mountainous forest soils in Venezuela.

Lobo (1972) and Flexor (1972) developed a model combining C content and the $^{14}$C:$_{12}$C of atmospheric $CO_2$ since the beginning of thermonuclear testing, i.e., bomb C levels, with the parameter time. Residence time and migration speed of different organic matter fractions were calculated; also, conclusions were drawn regarding $CO_2$ volatilization from various levels of profile depth (Lobo et al 1974) in connection with two ferrallitic soils from Brazil. One input source from the immediate upper level and a second source from the litter were discerned as yearly organic matter input into individual soil horizons or layer.

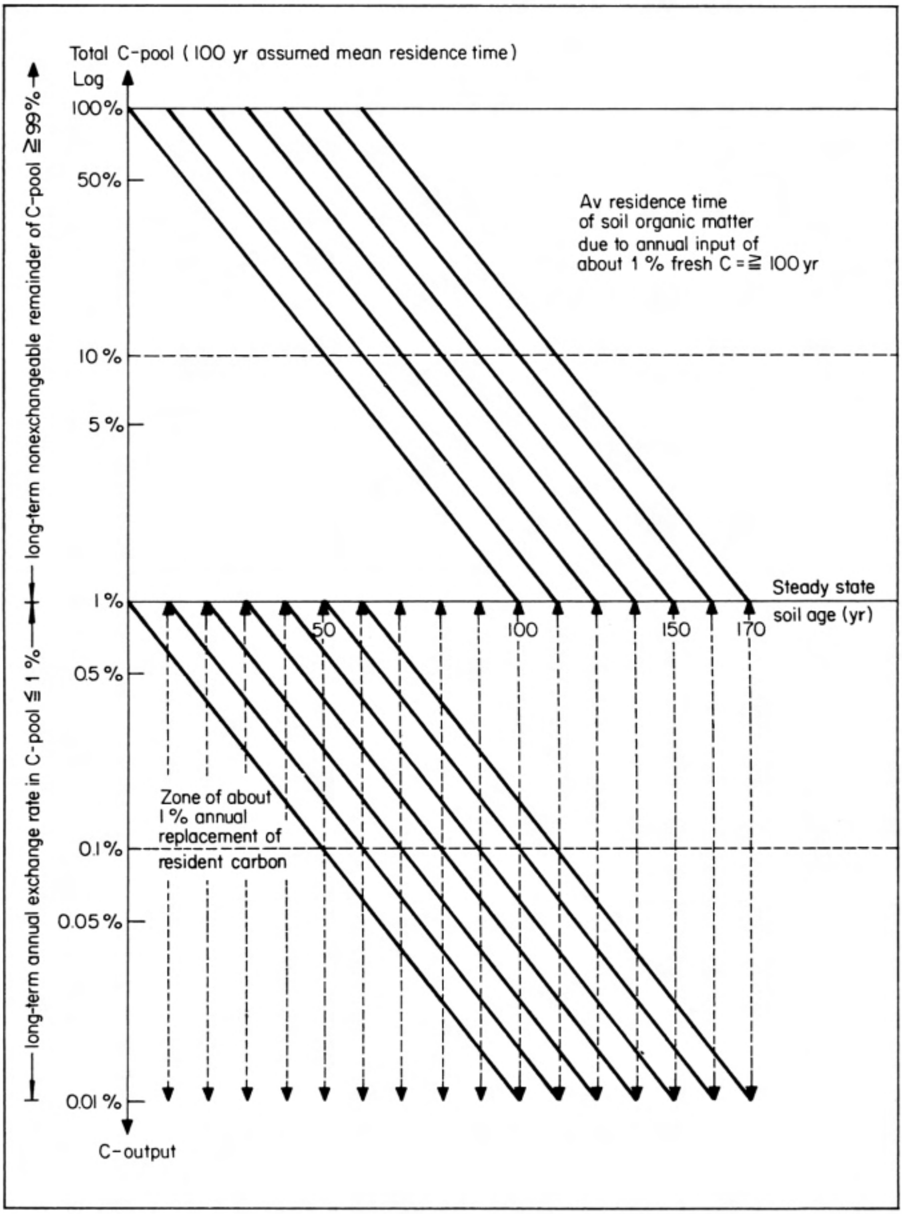
Schiffmann and Scharpenseel (1974) divided soil C dynamics into three facets: C input, C transport, and C turnover. Each facet represents a multitude of individual processes whose control would be required for establishment of a C activity model. Simplification is unavoidable. It seems feasible to divide the soil into elementary cells, each exerting C dynamics, whereby lateral C transport is ignored for the sake of simplicity. All the C flows in all units can be measured only if specific activities of recent plant C and of all flows, and all C contents within flows, remain constant. One single layer has but one input flow of C = F and one output (loss) flow of C = $rX$. Under steady state conditions $F = rX$.

The specific activity of $^{14}$C, $I_s(t)$ after a longer time period t gets the expression

$$I_s(t) = \frac{r}{r + \lambda} I_o$$

Since $I_o$ and $\lambda$ are known as constants and $I_s(t)$ is measured, the decomposition constant $r$ can be calculated and the input flow $F$ becomes

$$F = \frac{I_s \cdot \lambda}{I_o - I_s} \cdot X$$



**10.** Carbon replacement and steady state age of soil.

($X$ = the constant amount of C in the respective layer). $I_o$ and $I_s$ are experimental $^{14}C$ concentrations of standard and soil samples derived from the individual thin-layer compartments.

A two-layer system requires balanced equations for specific activities and total C contents and calculation of the decomposition constant for both layers together as well as for each individual layer. From these equations all required flows can be calculated. Conditions in an $n$-layer system can be solved by repeated application of the solution of the two-layer system.

Dörr and Münnich (1979) developed a model describing $CO_2$ transport from the soil to the atmosphere. Since gas transport in the soil is by diffusion rather than by mass flow, $^{13}C$ in soil $CO_2$ is higher because of isotope fractionation in the course of molecular diffusion (by 4% lower diffusion constant of $^{13}C$) than in the $CO_2$ leaving the soil. A slight eddy diffusion due to small oscillations of atmospheric pressure and results of tortuosity can affect the $CO_2$ captured by Lundegardh cups and NaOH-filled absorption bottles with a Mariotte bottle as an air pump. $CO_2$ flux density is at maximum near the soil surface and gradually approaches zero at greater depth.

## AN INTEGRATED SYSTEM

Three facts have to be accepted and incorporated into any decomposition model:

- Young, uniformly $^{14}C$-labeled organic matter decomposes rapidly in the initial phase of remineralization.
- The remaining undecomposed part, spared from biotic or abiotic decomposition, possesses high radiocarbon age.
- Because of the size of the soil organic matter pool, which amounts to about 100 times the annual photosynthetic product, about 1% of the annual new organic matter input as well as output due to loss and mineralization would maintain a steady state with an average C residence time of 100 years. If most of the 1% annual input is quickly remineralized, a steady state would require less than 1% output of the resident pool. As a consequence, the average or apparent mean residence time (AMRT) can be correspondingly higher.

While the rapid decomposition phase gives information about the immediate fate of fresh, decomposing organic matter in the soil, as well as about humus balances and required humus management for the near future, natural radiocarbon measurements reflect the AMRT of the protected, enduring organic matter and reveal the potential of the soil for organic matter preservation.

Figure 10 indicates the interaction between the approximate annual influx of 1% fresh organic matter (relative to the total organic matter pool of the pedosphere) and compensating humus mineralization. The factor for percentage turnover rate undoubtedly varies for different soil orders, depths, and agroecological zones.

## REFERENCES CITED

Anderson, J. P. E., and K. H. Domsch. 1978. Mineralization of bacteria and fungi in chloroform fumigated soils. Pages 61-102 *in* E. A. Paul and J. A. van Veen. Translation of ISSS, 3, symposia papers.

Andreux, F., D. Golebiowska, T. Chone, F. Jacquin, and M. Metche. 1977. Caractérisation et transformations en milieu mull d'un modele humique issu de l'autoxydation du systeme catechol-glycine et marque selectivement au carbone-14. Pages 43-57 *in* Soil organic matter studies. Proceedings on symposium, FAO/IAEA, Sept. 1976, Braunschweig, Germany, 11.

Aylmore, L. A. G., and J. P. Quirk. 1960. Domain or turbostratic structure of clays. Nature 187:1046-1048.

Beckmann, H., and H. W. Scharpenseel. 1964. Kohlensaureentbindung in sterilisierten Böden. Z. Pflanzenernähr. Düng. Bodenkde. 105:102-112.

Beckmann, G. G., and G. D. Hubble. 1974. The significance of radio-carbon measurements of humus from krasnazems (ferralsols), in subtropical Australia. Pages 366-371 *in* Transactions 10th international congress on soil science. 6(II): Moscow.

Bingeman, C. W., J. E. Varner, and W. P. Martin. 1953. The effect of the addition of organic materials on the decomposition of an organic soil. Soil Sci. Soc. Am., Proc. 17:34-38.

Blackburn, G., J. R. Sleeman, and H. W. Scharpenseel. 1979. Radiocarbon measurements and soil micromorphology as guides to the formation of Gilgai at Kaniva, Victoria. Aust. J. Soil Res. 17:1-15.

Bondietti, E., J. P. Martin, and K. Haider. 1972. Stabilization of amino sugar units in humic type polymers. Soil Sci. Soc. Am., Proc. 36:597-602.

Broadbent, F. E., and A. G. Norman. 1946. Some factors affecting the availability of the organic nitrogen in soil. Soil Sci. Soc. Am., Proc. 11:264-267.

Broadbent, F. E. 1947. Nitrogen release and carbon loss from soil organic matter during decomposition of added plant materials. Soil Sci. Soc. Am., Proc. 12:246-249.

Broadbent, F. E. 1968. Turnover of nitrogen in soil organic matter. Pontif. Acad. Sci. Scripta Varia. 32:61.

Broadbent, F. E., and W. V. Bartholomew. 1948. The effect of quantity of plant material added to soil on its rate of decomposition. Soil Sci. Soc. Am., Proc. 13:271-274.

Broadbent, F. E., and T. Nakashima. 1974. Mineralization of carbon and nitrogen in soil amended with carbon-13 and nitrogen-I5 labeled plant material. Soil Sci. Soc. Am., Proc. 38:313-315.

Broecker, W. S., J. L. Kulp, and C. S. Tucek. 1956. Lamont natural radiocarbon measurements. III. Sci. 124:154-165.

Campbell, C. A., E. A. Paul, D. A. Rennie, and K. J. McCallum. 1967. Factors affecting the accuracy of the carbon-dating method in soil humus studies. Soil Sci. 104:81-85.

Chahal, K. S., and G. H. Wagner. 1965. Decomposition of organic matter in Sanborn field soils amended with $^{14}$C glucose. Soil Sci. 100:96-103.

Chang, F. H., and F. E. Broadbent. 1981. Influence of trace metals on carbon dioxide evolution from a Yolo soil. Soil Sci. 132:416-421.

Chekalov, K. I., and V. P. Illyuviyeva. 1962. Use of the isotope $^{14}$C for studying processes of decomposition of organic matter in soil. Pochvovedenie 5:40-50.

Cheshire, M. V., C. M. Mundie, and H. Shepherd. 1969. Transformation of $^{14}$C glucose and starch in soil. Soil Biol. Biochem. 1:117-130.

Cheshire, M. V., C. M. Mundie, and H. Shepherd. 1974. Transformation of sugars, when rye hemicellulose labeled with $^{14}$C decomposes in soil. J. Soil Sci. 25:90-98.

Commissariat de l'Energie Atomique, Departement de Biologie, Service de Radio Agronomie, Cadarache, France. 1977. Pamphlet explaining growth chamber and products.

Conry, M. J., and G. F. Mitchell. 1971. The age of Irish plaggen soils. Pages 129-138 *in* Paleopedology: origin, nature and dating of Paleosols, Jerusalem.

Craswell, E. T., and S. A. Waring. 1972. Effect of grinding on the decomposition of soil organic matter. II. Oxygen uptake and nitrogen mineralization in virgin and cultivated cracking clay soils. Soil Biol. Biochem. 4:435-442.

Crawford, D. L., R. L. Crawford, and A. L. Pometto III. 1977. Preparation of specifically labeled 14C-(lignin)- and 14C-(cellulose)- lignocelluloses and their decomposition by the microflora of soil. Appl. Environ. Microbiol. 33: 1247-1251.

Dalal, R. C. 1979. Mineralization of carbon and phosphorus from carbon-14 and phosphorus-32 labeled plant material added to soil. Soil Sci. Soc. Am. J. 43:913-916.

de Jong, E., R. E. Redmann, and E. A. Ripley. 1979. A comparison of methods to measure soil respiration. Soil Sci. 127:300-306.

Demolon, A., and G. Barbier. 1929. Conditions de formation et constitution du complexe argilo-humique des sols. C. R. Acad. Sci., Paris, 188:654-656.

de Vries, H. 1958. Radiocarbon dates for upper Eem and Würm interstadial samples. Eiszeitalter G. 9:10-17.

Dörr, H., and K. O. Münich. 1979. Carbon-14 and carbon-13 in soil $CO_2$. Proc. 10th Int. Radiocarbon Conference, Bern and Heidelberg. Paper 715.

Durand, G. L., and B. Guillet. 1966. Radiogéologie, Datation de la tourbière du Beillard par la méthode du $^{14}C$. C. R. Acad. Sci., Paris, 262:28-31.

Edwards, A. P., and J. M. Bremner. 1967. Microaggregates in soils. J. Soil Sci. 18:64-73.

Fastabend, H., and F. van Raupach. 1962. Ergebnisse der $^{14}C$-Untersuchung an einigen Plaggenböden des Emslandes. Geol. Jb. 79:863.

Felgenhauer, F., J. Fink, and H. de Vries. 1959. Studien zur absoluten und relativen Chronologie der fossilen Böden in Österreich. Archaeol. Austriaca 25:35-73.

Flaig, W. 1982. Dynamics of organic matter decomposition in soils. Pages 115-124 *in* Transactions 12th international congress of soil science, Delhi. Symposia papers I.

Flexor, J. M. 1972. Medida da radioactividade especifica C 14/ C 12 applicacao ao estudio do comportamento dinamico do caebono no solo. Tese Instituto Fisica da Universitat de Sao Paulo.

Führ, F., and D. Sauerbeck. 1964. Über die Aufnahme und Translokation 14C-markierter organischer Rotteprodukte bei Raphanus sativus. Z. Pflanzenernähr., Düng., Bodenk. 105:136.

Führ, F., and D. Sauerbeck. 1965. Die räumliche und chemische Verteillung durch die Wurzel aufgenommener organischer Rotteprodukte bei Daucus carota. Z. Landw. Forsch. 19, Sdh. 153-163.

Führ, F., and D. Sauerbeck. 1966. The uptake of straw decomposition products by plant roots. Pages 73-83 *in* The use of isotopes in soil organic matter studies. Report of the FAO/IAEA technical meeting, Pergamon Press, Oxford.

Führ, F., and D. Sauerbeck. 1967. The uptake of colloidal organic substances by plant roots as shown by experiments with 14C-labeled humus compounds. Pages 317-328 *in* Isotopes in plant nutrition and physiology. International Atomic Energy Agency, Vienna.

Führ, F., and D. Sauerbeck. 1968. Decomposition of wheat straw in the field as influenced by cropping and rotation. Pages 241-250 *in* Isotopes and radiation in soil organic matter studies. Vienna.

Gerasimov, J. P. 1971. Nature and originality of Paleosols. Pages 15-29 *in* D. H. Yaalon, ed. Paleopedology: origin, nature, and dating of paleosols. Israel University Press.

Gerasimov, J. P. 1974. The age of recent soils. Geoderma 12: 17-25.

Gerasimov, J. P., and O. A. Chichagova. 1971. Some problems in the radiocarbon dating of soil. Soviet Soil Sci. 3-11.

Geyh, M. A. 1970. Möglichkeiten und Grenzen der Radiokohlenstoff-Altersbestimmung von Böden-Methodische Probleme .Mitt. Dtsch. Bodenkndl. Ges. 10:239-241.

Geyh, M. A., J. H. Benzler, and G. Röschmann. 1971. Problems of dating Pleistocene and holocene soils by radiometric methods. Pages 63-75 *in* Paleopedology: origin, nature, and dating of Paleosols, Jerusalem.

Giles, C. H., D. Smith, and A. Huitson. 1974. A general treatment and classification of the solute adsorption isotherm. I. Theor. J. Colloid Interface Sci. 47:755-765.

Gilmour, C. M., F. E. Broadbent, and S. M. Beck. 1977. Recycling of carbon and nitrogen through land disposal of various wastes. Pages 173-194 *in* Soils for management of organic water and waste waters. Proceedings of a symposium, Published by ASA, CSSA, SSSA, Madison, Wisconsin.

Godwin, H., and E. H. Willis. 1964. Cambridge University natural radiocarbon measurements. VI. Radiocarbon 6:116-137.

Goh, K. M., J. D. Stout, and T. A. Rafter. 1977. Radiocarbon enrichment of soil organic matter fractions in New Zealand soils. Soil Sci. 123:385-391.

Goh, K. M., B. O'Brien, and J. A. Stout. 1979. Special communication on soil pretreatment by high concentrations of nitric acid for radiocarbon dating. 11th International Radiocarbon Conference. Heidelberg.

Grant-Taylor, T. L. 1972. The extraction and use of plant lipids as a material for radiocarbon dating. Pages 439-448 *in* Proceedings of the 8th international conference on radiocarbon dating. Wellington, New Zealand.

Guckert, A., B. Cure, and F. Jacquin. 1971. Comparative evolution of the polysaccharides of the humin after incubation of $^{14}C$-glucose and $^{14}C$-straw. Transactions International Symposium Humus et Planta V. Prague 155-160.

Guillet, B. 1968. Essay de détermination de l'age de deux podzols vosgiens par la palynologie. C Ecol. Planta, Gauthiers-villars, III:101-119.

Guillet, B. 1972a. Relation entre l'histoire de la végétation et la podzolisation dans les Vosges. Thèse Univ. Nancy.

Guillet, B. 1972b. Datation des sols par le $^{14}C$ natural. II. Application a la determination et à la signification des âges d'horizons $B_h$ et $B_s$ de podzols vosgiens. Bull. E.N.S.A.I.A. Nancy, XIV/1, 123-131.

Guillet, B. 1972c. Datation des sols par le $^{14}C$ naturel. I — La méthode de datation en scintillation liquide. Bull. E.N.S.A.I. A., XIV/1, 117-122.

Guillet, B., and A. M. Robin. 1972. Interpretation de datations par le $^{14}C$ d'horizons $B_h$ de deux podzols humo-ferrugineux, l'un formé sous callune, l'autre sous chênaie-hêtraie. C. R. Acad. Sc. Paris, 274:2859-2862.

Haider, K., S. Lim, and W. Flaig. 1962. Untersuchungen über die Einwirkung von Mikroorganismen auf $^{14}C$-markierte phenolische Verbindungen. Landw. Forschung 15:1-9.

Haider, K., and J. P. Martin. 1968. The role of microorganisms in the formation of humic acids. Pages 188-195 *in* Isotopes and radiation in soil organic matter studies. International Atomic Energy Agency, Vienna.

Haider, K., and J. P. Martin. 1975. Decomposition of specifically carbon-14 labelled benzoic and cinnamic acid derivatives in soil. Soil Sci. Soc. Am. Proc. 39:657-662.

Haider, K., and J. P. Martin. 1979. Abbau und Umwandlungen von Pflanzenrückständen durch die Mikroflora des Bodens. Z. Pflanzenernähr. Bodenk. 142:456-475.

Haider, K., and Farooq-e-Azam. 1982. Umsetzung $^{14}C$-markierter Pflanzeninhaltstoffe im Boden in Gegenwart von $^{15}NH_4^+$. Z. Pflanzenernähr. Bodenk. (in press)

Haines, E. B. 1976a. Relation between the stable carbon isotope composition of fiddler crabs, plants and soils in a salt marsh. Limnol. Oceanogr. 21:880-883.

Haines, E. B. 1976b. Stable carbon isotope ratios in the biota, soils and tidal water of a Georgia salt marsh. Est. Coastal Mar. Sci. 4:609-616.

Hallam, M. J., and W. V. Bartholomew. 1953. Influence of rate of plant residue addition in accelerating the decomposition of soil organic matter. Soil Sci. Soc. Am. Proc. I7:365.

Harms, H., H. Söchtig, and K. Haider. 1969a. Untersuchungen zur Aufnahme und Umwandlung $^{14}$C-markierter Phenole durch die Pflanze. I. Aufnahme von $^{14}$C-carboxyl-markierter p-Hydroxybenzoe-, Vanillin- und Syringasäure durch die Wurzeln von Weizenkeimpflanzen und Verteilung der Aktivität über die Pflanze. Plant Soil 31 (1):129-142.

Harms, H., H. Sochtig, and K. Haider. 1969b. Untersuchungen zur Aufnahme und Umwandlung $^{14}$C-markierter Phenole durch die Pflanze. II. Die Umwandlung von p-Hydroxybenzoesäure, Vanillinsäure sowie Syringasäure nach der Aufnahme durch die Wurzel von Weizenkeimpflanzen. Plant Soil 31 (2):257-272.

Harms, H., H. Sochtig, and K. Haider. 1971. Aufnahme and Umwandlung von in unterschiedlichen Stellungen $^{14}$C-markierten Phenolcarbonsäuren in Weizenkeimpflan-Zen. Z. Pflanzenphysiol. 64:437-445.

Hassko, B., B. Guillet, and R. Coppens. 1969. Nancy natural radiocarbon measurements II. Radiocarbon 11:463-468.

Hassko, B., B. Guillet, R. Jaegy, and R. Coppens. 1974. Nancy natural radiocarbon measurements III. Radiocarbon 16:118-130.

Hayes, M. H. B., and J. L. Mortensen. 1963. Role of biological oxidation and organic matter solubilization in the subsidence of Rifle peat. Soil Sci. Soc. Am., Proc. 27:666-668.

Henin, S., G. Monnier, and L. Turc. 1959. Un aspect de la dynamique des matières organiques du sol. C. R. Acad. Sci. Paris 248:138.

Herrera, R., and M. A. Tamers. 1971. Radiocarbon dating of tropical soil associations in Venezuela. Pages 109-115 *in* Paleopedology: origin, nature, and dating of Paleopsols, Jerusalem.

Hiura, K., T. Hattori, and C. Furusaka. 1976. Bacteriological studies on the mineralization of organic nitrogen in paddy soil. I. Effect of mechanical disruption of soils on ammonification and bacterial number. Soil Sci. Plant Nutr. 22:459-465.

Hofmann, E., and G. Hoffmann. 1962. Über Herkunft und Weg des Kohlendioxids im Boden. Z. Pflanzenernähr. Bodenk. 97:97.

Hunt, H. W. 1977. A simulation model for decomposition in grasslands. Ecology 58:469-484.

Hurst, H. M., and G. H. Wagner. 1969. Decomposition of $^{14}$C-labeled cell wall and cytoplasmic fractions from hyaline and melanic fungi. Soil Sci. Soc. Am., Proc. 33:707-711.

IRRI (International Rice Research Institute). 1979. Nitrogen and rice. Los Baños, Philippines. 499 p.

Isermeyer, H. 1952. Eine einfache Methode zur Bestimmung der Bodenatmung und der Karbonate im Boden. Z. Pflanzenernähr. Düng. Bodenk. 56:26.

Jansson, S. L. 1955. Orientierende Studien über den Stickstoffkreislauf im Boden mit Hilfe von $^{15}$N als Leitisotop. Z. Pflanzenernähr. Dung. Bodenk. 69:190-198.

Jansson, S. L. 1958. Tracer studies on nitrogen transformations in soil with special attention to mineralization-immobilization relationships. Lantbrukshögsk. Annaler 24:101-361.

Jannson, S. L. 1960. On the establishment and use of tagged microbial tissue in soil organic matter research. Trans. Seventh Int. Congr. Soil Sci. II:635-642.

Jannson, S. L., and J. Persson. 1968. Co-ordination of humus chemistry and soil organic matter biology by isotopic techniques. Pages 111-122 *in* Isotopes and radiation in soil organic matter studies. International Atomic Energy Agency, Vienna.

Jenkinson, D. S. 1960. The production of ryegrass, labeled with carbon-14. Plant Soil 13:279-290.

Jenkinson, D. S. 1964. Decomposition of labeled plant material in soil. Pages 199-207 *in* Experimental pedology. Butterworth, London.

Jenkinson, D. S. 1965. Studies on the decomposition of plant material. I. Losses of carbon from $^{14}$C-labeled ryegrass incubated with soil in the field. J. Soil Sci. 16:104-115.

Jenkinson, D. S. 1966a. The turnover of organic matter in soil. Pages 187-197 *in* The use of isotope in soil organic matter studies. Rep. FAO/IAEA Techn. Meet. Pergamon, Oxford.

Jenkinson, D. S. 1966b. The priming action. Rep. FAO/IAEA Techn. Meet. Pages 199 *in* The use of isotopes in soil organic matter studies. Pergamon, Oxford.

Jenkinson, D. S. 1968. Studies on the decomposition of plant material in soil. 3. J. Soil Sci. 19:25-39.

Jenkinson, D. S. 1969. Radiocarbon dating of soil organic matter. Page 73 *in* Rep. Rothamsted Experimental Station for 1968.

Jenkinson, D. S. 1971. Studies on the decomposition of $^{14}$C-labeled organic matter in soil. Soil Sci. 111:64.

Jenkinson, D. S. 1977a. Studies on the decomposition of plant material in soil. IV. The effect of rate of addition. J. Soil Sci. 28:417-423.

Jenkinson, D. S. 1977b. Studies on the decomposition of plant material in soil. V. The effect of plant cover and soil type on the loss of carbon from C-14 labeled ryegrass, decomposing under field conditions. J. Soil Sci. 28:424-434.

Jenkinson, D. S., and D. S. Powlson. 1976. The effects of biocidal treatments on metabolism in soil. I. Fumigation with chloroform. Soil Biol. Biochem. 8:167-177.

Jenkinson, D. S., and A. Ayanaba. 1977. Decomposition of carbon-14 labeled plant material under tropical conditions. Soil Sci. Soc. Am. J. 41:912-915.

Jenkinson, D. S., and J. H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. 123:298-305.

Kastori, R., H. Harms, H. Sochtig, and K. Haider. 1970. Untersuchungen zur Aufnahme und Umwandlung $^{14}$C-markierter Phenole durch die Pflange. III. Die Aufnahme, der Transport und die Umwandlung von 14C-markiertem Thymohydrochinon durch Weizenkeimpflanzen. Plant Soil 33:597-611.

Kiefer, R. F., and J. L. Mortensen. 1963. Biosynthesis of soil polysaccharides: 1. Soil Sci. Soc. Am., Proc. 27:156-160.

Kleinhempel, D., H. E. Freytag, and K. Steinbrenner. 1971. Grundlagen und Aspekte der Steuerung des Umsatzes organischer Stoffe im Boden. Arch. Bodenfruchtbarkeit 15:155.

Konig, L. A. 1980. Transfer von Tritium in Pflanzen. Report to Kernforschungszentrum Karlsruhe, FRG.

Krishnappa, A. M., and J. E. Shinde. 1978. The turnover of $^{15}$N-labeled straw and FYM in a rice- rice rotation. FAO/IAEA Int. Sympos. Use of Isotopes and Radiation in Research on Soil-Plant Relationships, Colombo. IAEA - SM - 235/32.

Ladd, J. N., and E. A. Paul. 1973. Changes in enzymic activity and distribution of acid-soluble amino acid-nitrogen in soil during nitrogen immobilization and mineralization. Soil Biol. Biochem. 5:825-840.

Laura, R. D. 1975a. The role of protolytic action of water in the chemical decomposition of organic matter in the soil. Pedologie 25, 157-170.

Laura, R. D. 1975b. On the stimulating effect of drying a soil and the retarding effect of drying a plant material. Plant Soil 44:463-465.

Laura, R. D. 1976. On decomposition and “primed decomposition” of organic materials in soils. Can. J. Soil Sci. 379-382.

Lerman, J. C. 1972. Carbon 14 dating: Origin and correction of isotope fractionation errors in terrestrial living matter. Pages 612-624 *in* Proceedings of the 8th International conference on radiocarbon dating, Wellington, New Zealand.

Libby, W. F. 1952. Radiocarbon dating. University of Chicago Press, Chicago.

Lobo, P. F. S. 1972. Utilization du $^{14}$C atmospherique comme traceur de la matiere organique des sols. Univ. Fédérale, Salvador, Bahia.

Lobo, P. F. S., J. M. Flexor, J. L. Rapaire, and G. Sieffermann. 1974. Essai de détermination du temps de résidence des fractions humiques de deux sols ferrallitiques par l'utilisation du radiocarbone naturel et thermonucléaire. Cah. O.R.S.T.O.M., Sér. Pedol. 12/1:115-123.

Lohnis, F. 1926. Nitrogen availability of green manure. Soil Sci. 22:253-290.

Luders, R. 1964. Stark entwickelte Podsole unter Eichen-Birkenwald bei Voltlage im westlichen Niedersachsen und die Frage nach ihrem Alter. Z. Pflanzenernähr. Düng. Bodenk. 107:215-222.

Martel, Y. A., and E. A. Paul. 1974. The use of radiocarbon dating of organic matter in the study of soil genesis. Soil Sci. Soc. Am., Proc. 38:501-506.

Martin, J. K. 1977. The chemical nature of the carbon-14 labeled organic matter released into soil from growing wheat roots. Effects of soil micro-organisms. *In* Soil Organic Matter Studies, Proc. Symp. FAO/IAEA Braunschweig, FRG 1:197-203.

Martin, J. P., K. Haider, W. J. Farmer, and E. Fustec-Mathore. 1974. Decomposition and distribution of residual activity of some $^{14}$C-microbial polysaccharides and cells, glucose, cellulose and wheat straw in soil. Soil Biol. Biochem. 6:221-230.

Martin, U., H. U. Neue, and H. W. Scharpenseel. 1982. Interim report to IRRI on 14C-labeled organic matter of rice plants, decomposing in submerged soil. Release of $CO_2$, $CH_4$ and organic acids.

Mattson, S. 1932. The laws of soil colloidal behavior. VII. Proteins and proteinated complexes. Soil Sci. 23:41-72.

Mayaudon, J. 1968. Stabilization biologique des proteines-$^{14}$C dans les sol. Pages 177-188 *in* Isotopes and radiation in soil organic matter studies. Technical meeting FAO/IAEA, Vienna.

Mayaudon, J., and P. Simonart. 1958a. Etude de la décomposition de la matiere organique dans le soil au moyen de carbon radioactif. II. Plant Soil 9:381-384.

Mayaudon, J., and P. Simonart. 1958b. Etude de la decomposition de la matiere organique dans le sol au moyen de carbone radioactif. I. Decomposition du glucose radioactif dans le sol. A. Repartition de la radioactivité dans fractions humique du sol. Plant Soil 9:376-380.

Mayaudon, J., and P. Simonart. 1959a. Etude de la décomposition de la matiere organique dans le sol au moyen de carbone radioactif. III. Decomposition des substances solubles dialysables des proteins et des hemicelluloses. Plant Soil 11:170-175.

Mayaudon, J., and P. Simonart. 1959b. Etude de la decomposition de la matière organique dans le sol au moyen de carbone radioactif. V. Decomposition de cellulose et de lignine. Plant Soil 11:181-192.

Mayaudon, J., and P. Simonart. 1961. Decomposition of cellulose-14C and lignin-14C in the soil. Ecology of Soil Fungi.

Mayaudon, J., and P. Simonart. 1963. Humification des microorganismes marqués par $^{14}$C dans le sol. Ann. Inst. Pasteur, Pans, 105:257-266.

Mayaudon, J., and P. Simonart. 1965. Métabolisme de la glycine $^{14}$C dans le sol. Suppl. Ann. Inst. Pasteur, Paris, 109:224-234.

Mayaudon, J., and L. Batistic. 1970. Dégradation biologique de la lignine $^{14}$C dans le sol. Ann. Inst. Pasteur, Paris, 118:191.

McGill, W. B., and C. V. Cole. 1981. Comparative aspects of cycling of organic C, N, S, and P through soil organic matter. Geoderma 26:267-286.

Meyer-Spasche, H., and H. W. Scharpenseel. 1980. Die Grundbelastung von Böden mit $^{14}$C und dessen Transfer zum Menschen. Z. Pflanzenernähr., Bodenk. 143:537-545.

Moureaux, C. 1967. Une mèthode simple d'étude de l'effet excitateur. Biol. Sol N.S., 8:14.

Mückerhausen, E., H. W. Scharpenseel, and F. Pietig. 1968. Zum Alter des Plaggenesch. Eiszeitalter u. Gegenwart 19: 190-196.

Münnich, K. O. 1957. Erfahrungen mit der $^{14}$C-Datierung verschiedener Arten von Sedimenten. Verh. 4. int. Tagung. Quartärbotaniker, Geobot. Inst. Rubel, Zürich, Heft 34, 109-117, Huber-Verlog Bern/Stuttgart.

Mutakar, V. K., and G. H. Wagner. 1967. Humification of carbon-14 labeled glucose in soils of Sanborn field. Soil Sci. Soc. Am., Proc. 31:66-70.

Nakhla, S. M., and G. Delibrias. 1967. Utilisation du C-14 d'origine thermonucléaire pour l'étude de la dynamique du carbone dans le sol. Radioactive dating and methods of low level counting. Proc. Symp. IAEA; Monaco 169.

Nemecek, J. 1971. On the problem of radiocarbon dating of holocene chernozems. Humus et Planta V, Prague 377-378.

Neue, H. U., H. W. Scharpenseel, and U. Martin. 1982. Ammoniak — bgabe durch Blätter von Reispflanzen. Z. Pflanzenernähr. Bodenk. (in press)

Neugebauer, V., and H. Zakosek. 1962. Die Smonica. Abh. Hess. Landesamtes-amt Bodenforsch. Wiesbaden 37.

Niemeyer, G. 1959. $^{14}$C Datierungen der Kulturlandschaftsgeschichte Nordwestdeutschlands. Abh. Braunsch. Wiss. Ges. 11:87.

Nissenbaum, A., and K. M. Schallinger. 1974. The distribution of the stable ($^{13}$C/$^{12}$C) in fractions of soil organic matter. Geoderma 11:137-145.

Oberländer, H. E. 1970. Leitisotope im System Boden-Dünger-Pflanze. Pages 161-163 *in* 100 Jahre Landwirtschaftlich-chemische Bundesversuchsanstalt Wien.

Oberländer, H. E. 1973. The fate of organic manures in soil as traced by means of radiocarbon. Pontif. Acad. Sci. Scripta Varia. 38:1001-1062.

Oberländer, H. E., and K. Roth. 1968a. Der Betrieb einer Wachstumskammer zur Markierung von Pflanzen mit $^{14}$C. Atompraxis 14:288.

Oberländer, H. E., and K. Roth. 1968b. Transformation of $^{14}$C-labeled plant material in soils under field conditions. Pages 351-361 *in* Isotopes and radiation in soil organic matter studies. Technical meeting FAO/IAEA, Vienna.

Oberländer, H. E., and K. Roth. 1972. Die Umwandlung von $^{14}$C markiertem Gründünger im Boden. Landwirtsch. Forsch. 25:295.

Oberländer, H. E., and K. Roth. 1974. Ein Kleinfeldversuch über den Abbau und die Humifizierung von $^{14}$C-markietem Stroh und Stallmist. Bodenk. 25:111.

Oberländer, H. E., and K. Roth. 1975. Die Umwandlung eines $^{14}$C-markierten Düngers aus Gülle und Stroh im Boden. Bodenk. 26:139.

Oberländer, H. E., and K. Roth. 1980. Der Umsatz $^{14}$C-markierter Wirtschaftsdünger im Boden. Landwirtsch. Forschung 33:179-188.

O'Brien, B. J., and J. D. Stout. 1978. Movement and turnover of soil organic matter as indicated by carbon isotope measurements. Soil Biol. Biochem. 10:309-317.

Östlund, H. G., and L. G. Engstrand. 1963. Stockholm natural radiocarbon measurements V. Radiocarbon 5:203-227.

Pal, D., and F. E. Broadbent. 1975. Kinetics of rice straw decomposition in soils. J. Environ. Qual. 4:256-260.

Paul, E. A., C. A. Campbell, D. A. Rennie, and K. J. McCallum. 1964. Investigation of the dynamics of soil humus utilizing carbon dating techniques. Pages 201-208 *in* Transactions 8th international congress on soil science, Bucharest, III.

Paul, E. A., and W. B. McGill. 1976. Turnover of microbial biomass, plant residues and soil humic constituents under field conditions. Page 149 *in* IAEA-FAO symposium on soil organic matter studies 1.

Paul, E. A., and J. A. Van Veen. 1978. The use of tracers to determine the dynamic nature of organic matter. Pages 61-102 *in* Transactions of ISSS congress, Edmonton, Vol. 3, Symposia papers.

Payne, W. J. 1970. Energy yields and growth of heterotrophs. Ann. Rev. Microbial. 24:17-52.

Perrin, R. M. S., E. H. Willis, and C. A. H. Hodge. 1964. Dating of humus podzols by residual radiocarbon activity. Nature: 202/4928, 165-166.

Persson, J. 1967. A biological-chemical study of soil organic matter fractionations. Trans. Meet. Comms. II and IV Int. Soc. Soil Sci. 1966:59-64.

Persson, J. 1968. Biological testing of chemical humus analysis. Lantbrukshoegst Högsk. Ann. 34:81-217.

Pinck, L. A., and F. E. Allison. 1951. Maintenance of soil organic matter 3. Soil Sci. 71:67-75.

Polach, H. A., and A. B. Costin. 1971. Validity of soil organic matter radiocarbon dating: Buried soils in snowy mountains, southeastern Australia as example. Pages 89-96 *in* Paleopedology: origin, nature, and dating of Paleosols, Jerusalem.

Powlson, D. S., and D. S. Jenkinson. 1976. The effects of biocidal treatments on metabolism in soil. II. Gamma irradiation, autoclaving, air-drying and fumigation. Soil Biol. Biochem. 8:179-188.

Rafter, T. A., and J. D.. Stout. 1969. Radiocarbon measurements as an index of the rate of turnover of organic matter in forest and grassland ecosystems in New Zealand. I.N.S.R-65, Institute of Nuclear Sciences, New Zealand.

Righi, D., and B. Guillet. 1976. Datation par le $^{14}$C naturel de la matière organique d’horizons spodiques de podzols des Landes du Medoc, France. IAEA-FAO Symposium Soil Organic Matter Studies, 1976, Braunschweig, IAEA-SM-211/70.

Rosell, R. A., H. W. Scharpenseel, and N. Hein. 1973. Edad de la materia organica de suelo vertisol de la Provincia de Entre Rios, Argentina. Ciencia e Investigacion, T. 29, Enero-Febrero, 30-32.

Rovira, A. D., and E. L. Greacen. 1975. The effect of aggregate disruption on the activity of microorganisms in the soils. Aust. J. Agric. Res. 8:659-673.

Rubilin, E. W., and M. G. Kozyrewa. 1974. The age of Russian chernozem. Sov. Soil Sci. 6:383-392. Also *in* Transl. Pochvovedeniye 7:16-26.

Ruhe, R. V., M. Rubin, and W. H. Scholtes. 1957. Determination of soil age. Am. J. Sci. 25:255-671.

Ruhe, R. V., G. A. Miller, and W. J. Vreeken. 1971. Paleosols, loess sedimentation and soil stratigraphy. Pages 41-60 *in* Paleopedology: origin, nature, and dating of Paleosols, Jerusalem.

Russel, J. S. 1964. Mathematical expression of seasonal changes in soil organic matter. Nature 204:161-162.

Sauerbeck, D. 1960. Zur Markierung von Pflanzen mit $^{14}$C. Atompraxis 6:221-225.

Sauerbeck, D. 1963. A critical evaluation of incubation experiments on the priming effect of green manure. Pages 209 *in* Report FAO/IAEA Technology Meeting on use isotopes soil organic matter studies. Brunswick.

Sauerbeck, D. 1966. Über den Abbau $^{14}$C-markierter organischer Substanzen in Böden und ihren Einfluß auf den Humushaushalt. Habil.-Schrift, Univ. Bonn.

Sauerbeck, D. 1968. Comparison of plant material and animal manure in relation to their decomposition in soil. Page 219 *in* The proceedings IAEA/FAO symposium on use isotopes radiation in soil organic matter studies. Vienna 3.

Sauerbeck, D., and F. Führ. 1968. Alkali extraction and fractionation of labeled plant material before and decomposition. *In* Proceedings IAEA/FAO symposium on use isotopes radiation *In* soil organic matter studies. Vienna 3.

Sauerbeck, D., and F. Führ. 1971. Decomposition and humification of $^{14}$C-labeled plant residues in the field. Trans. Int. Symp. “Humus et Planta V,” Praha 173.

Sauerbeck, D., and B. Johnen. 1974. Radiometrische Untersuchungen zur Humusbilanz. Landwirtsch. Forsch. Sonderh. 30/11:137.

Sauerbeck, D., and M. A. Gonzalez. 1977. Diels decomposition of carbon-14 labeled plant residues in various soils of the Federal Republic of Germany and Costa Rica. Pages 159-170 *in* Soil organic matter studies. Proceedings of symposium FAO/IAEA, 1976 Braunschweig, Germany, 1.

Sauerbeck, D., and B. G. Johnen. 1977. Root formation and decomposition during plant growth. Pages 141-148 *in* Soil organic matter studies. Proceedings of symposium FAO/ IAEA, 1976, Braunschweig, Germany, 1.

Scharpenseel; H. W. 1960a. Herstellung und Reinigung von tritiummarkierten Grau- und Braun-huminsäure-Präparaten sowie von Tritium-Purpurogallin. Z. Pflanzenernähr. Bodenkde. 91:131-146.

Scharpenseel, H. W. 1960b. Untersuchungen mit radioaktiv markierten Huminsäuren und Vorstufen. 2. Teil. Z. Pflanzenernähr. Bodenkde. 91:193-202.

Scharpenseel, H. W. 1961. Zur Herstellung von allseitig C-14 markiertem Pflanzen- und Huminsäure-Materia1. Landwirtsch. Forsch. 14:42-48.

Scharpenseel, H. W. 1962. Studies with $^{14}$C- and $^{3}$H-labeled humic acids as to the mode of linkage of their amino acid fractions and with $^{35}SO_4^-$- $^{35}$S-methionine and $^{35}$S-cystine regarding the sulfur turnover in humic acid and soil. Pages 115-133 *in* Radioisotopes in soil-plant nutrition studies, IAEA, Proc. Vienna.

Scharpenseel, H. W. 1966. Labelling of soil organic matter. Pages 351-364 *in* The use of isotopes in soil organic matter studies. Report of the FAO/IAEA Technical Meeting. Pergamon, Oxford.

Scharpenseel, H. W. 1971a. Radiocarbon dating of soils — problems, troubles, hopes. Pages 97-98 *in* D. H. Yaalon, ed. Paleopedology: origin, nature, and dating of Paleosols, Jerusalem.

Scharpenseel, H. W. 1971b. Special methods of chromatographic and radiometric analysis. Soil Biochem. 2:96-128.

Scharpenseel, H. W. 1972a. Messung der natürlichen C-14 Konzentration in der organischen Substanz von rezenten Böden. Eine Zwischenbilanz. Z. Pflanzenernähr. Bondenkde. 133:241-263.

Scharpenseel, H. W. 1972b. Natural radiocarbon measurements on humic substances in the light of carbon cycle estimates. Pages 281-292 *in* Proceedings of international meeting on humic substances, Nieuwersluis, Netherlands.

Scharpenseel, H. W. 1972c. Natural radiocarbon measurement of soil and organic matter fractions and on soil profiles of different pedogenesis. Pages 382-392 *in* Proceedings of 8th international conference radiocarbon dating, New Zealand.

Scharpenseel, H. W. 1974. Zur Berechtigung der Interpretation natürlicher Radiokohlenstoffmessungen an organischem Kohlenstoff $CaCO_3$-reicher Böden. Mitt. Dt. Bodenkdl. Ges. 18:198-201.

Scharpenseel, H. W. 1975a. Relativalter und Sukzession von Fraktionen der organischen Boden-substanz. Mitt. Dtsch. Bodenkundl. Ges. 22:453-466.

Scharpenseel, H. W. 1975b. Relative age and age sequence of fractions of soil organic matter. ESNA, Applic. Nucl. Methods in Biol. and Agric., Newsl., Dec. 1975: 10-17.

Scharpenseel, H. W. 1976. Soil fraction dating. Pages 277-283 *in* Proceedings of 9th international confenrence on radiocarbon dating, Los Angeles/ La Jolla.

Scharpenseel. H. W. 1977. The search for biologically inert and lithogenic carbon in recent soil organic matter. Pages 193-200 *in* Proceedings of IAEA conference, soil organic matter studies, II.

Scharpenseel, H. W., and H. Beckmann. 1964a. Untersuchungen zur Kohlendioxid-Entbindung des Bodens II. Teil. Spezielle Studien unter Verwendung radioaktiver Tracer. Z. Pflanzenernähr., Dung. Bondekde. 104:110-119.

Scharpenseel, H. W., and H. Beckmann. 1964b. Studien über Kalkwirkungen und beobachtete Sonderwirkungen des Hüttenkalkes unter Verwendong von $^{14}$C-Hominsäure und $^{55}$Fe sowie $^{45}$C-Hüttenkalk. Arbeitsgem. Hüttenkalk, Düsseldorf, Germany.

Scharpenseel, H. W., M. A. Tamers, and F. Pietig. 1968a. Altersbestimmung von Böden durch die Radiokohlenstoffdatierungsmethode. II. Z. Pflanzenernähr. Bodenkde. 119:34-44.

Scharpenseel, H. W., M. A. Tamers, and F. Pietig, 1968b. Altersbestimmung von Böden durch die Radiokohlenstoffdatierungsmethode. II. Z. Pflanzenernähr, Bodenkde. 119:44-52.

Scharpenseel, H. W., M. A. Tamers, and F. Pietig. 1968c. Altersbestimmung von Biden durch die Radiokohknstoffdatierungsmethode. 9th Int. Congr. Soil Sci. Trans. III:577-589.

Scharpenseel, H. W., C. Ronzani, and F. Pietig. 1968d. Comparative age determination on different humic matter fractions. Pages 67-73 *in* Isotopes and radiation in soil organic matter studies. Proceedings of IAEA technical meeting, Vienna.

Scharpenseel, H. W., and F. Pietig. 1969. Einfache Boden- und Wasserdatierung durch Messung der $^{14}$C-oder Tritiumkonzentration. Geoderma 2:273-289.

Scharpenseel, H. W., and H. Schiffmann. 1977a. Radiocarbon dating of soils, a review. Z. Pflanzen-ernähr. Bodenkde 140:159-174.

Scharpenseel, H. W., and H. Schiffmann. 1977b. Soil radiocarbon analysis and soil dating. Geophys. Surveys 3:143-156.

Scharpenseel, H. W., H. Zakosek, H. U. Neue, and H. Schiffmann. 1980. Search for pedogenic phases during the younger pleistocene and halocene (Soltanien and Rharbien) of Tunisia. Radiocarbon 22:879-884.

Scharpenseel, H. W., H. U. Neue, and M. Wurzer. 1982. $^{14}$C-organic matter decomposition in loess-Hapludalf and calcinated quartzsand. (in preparation for publication)

Schiffmann, H., and H. W. Scharpenseel. 1974. Stand der Studie zur Kohlenstoffdynamik und Kohlenstoff-Verweilzeit in der Pedosphäre. Intermediate report to Federal Ministry of Science and Research. West Germany, BMFT, SN-0015.

Schleser, G. H., R. Pohling, and B. Meyer. 1981. $^{13}$C record in an undisturbed forest soil. Z. Naturforsch. 34a:119–120.

Schmalfuss, K. 1957. Der Feldversuch “Ewiger Roggenbau” in Halle. Phorphorsäure 17:133.

Scholtes, W. H., and D. Kirkham. 1957. The use of radiocarbon for dating soil strata. Pedologia 7:316-323.

Shields, J. A., and E. A. Paul. 1973. Decomposition of $^{14}$C-labelled plant material under field conditions. Can. J. Soil Sci. 53:297-306.

Simonart, P., and J. Mayaudon. 1958. Etude de la dècomposition de la matière organique dans le sol au moyen de carbon radioactif. II. Decomposition du glucose radioactif dans le sol. B. Repartition de la radioactivité dans l’a-humus. Plant Soil 9:381-384.

Simonart, P., and L. Batistic. 1959. Etude de la dècomposition de la matière organique dans le sol au moyen de carbone radioactif. IV. Décomposition des pigments foliares. Plant Soil 11:176-180.

Simonart, P., and J. Mayaudon. 1959. Etude de la décomposition de la matiére organique dans le sol au moyen de carbone radioactif. III. Décomposition des substances solubles des proteines et hemicelluloses. Plant Soil 11:170-175.

Simonart, P., and J. Mayaudon. 1961. Humification des protéines-$^{14}$C dans le sol. Pages 91-103 *in* International symposium Pedologie, Gent, Belgium.

Simonart, P., and J. Mayaudon. 1962. Décomposition de matiere organique $^{14}$C dans le sol. Cr. Rech. Inst. Encour. Rech. Sci. Ind. Agric. 28:107-112.

Simonart, P., and J. Mayaudon. 1966. Etude des transformations de la matiere organique du sol au moyen du carbon-14. Pages 245-257 *in* The use of isotopes in soil organic matter studies. Rep. FAO/IAEA Tech. Meet. Braunschweig-Völkenrode 1963.

Singhania, R. A., and D. Sauerbeck. 1980. Influence of zinc on aerobic and anaerobic decomposition of organic matter. Z. Pflanzenernähr., Bodenkde. 143:385-390.

Sinha, M. K., D. P. Sinha, and H. Sinha. 1977. Organic matter transformations in soils. V. Kinetics of carbon and nitrogen mineralization in soils amended with different organic materials. Plant Soil 46:579-590.

Smith, J. H. 1966. Some interrelationships between decomposition of various plant residues and loss of soil organic matter as measured by carbon-14 labelling. Pages 223-233 *in* The use of isotopes in soil organic matter studies. Report of FAO/IAEA technical meeting Braunschweig-Völkenrode 1963.

Sochtig, H., H. Harms, and K. Haider. 1968. Uptake and transformation of $^{14}$C-labeled phenolic acids by wheat seedlings. Pages 531-540 *in* Isotopes and radiation in soil organic matter studies. International Atomic Energy Agency, Vienna.

Sörensen, H. 1963. Studies on the decomposition of carbon-14 labeled barley straw in soil. Soil Sci. 95:45-51.

Sparling, G. P., M. V. Cheshire, and G. M. Mundie. 1982. Effect of barley plants on the decomposition of $^{14}$C-labelled soil organic matter. J. Soil Sci. 33:89-100.

Stanford, G., and S. J. Smith. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am., Proc. 36:465-472.

Steinhardt, U. 1979. Jährliche Abbauraten im venezolanischen Wolkenwald. Göttinger Bodenkundliche Berichte 56:1-185.

Storzky, G., and J. L. Mortensen. 1958. Effect of addition, level and maturity of rye tissue on the decomposition of a muck soil. Soil Sci. Soc. Am., Proc. 22:521-524.

Tamm, C. O., and H. G. Östlund. 1960. Radiocarbon dating of soil humus. Nature 185:706-707.

Tan, K. H., and R. A. McCreery. 1975. Humic acid complex formation and intermicellar adsorption by bentonite. Proc. Int. Clay Conf. Mexico City. Appl. Publ. LTD., Wilmette, Illinois, USA. 629-643.

Theng, B. K. G. 1972. Formation, properties and practical applications of clay-organic complexes. J. Roy. Soc. N. Z. 2:437-457.

Theng, B. K. G., and H. W. Scharpenseel. 1975. Clay organic complexes between montmorillonite and C-14 labeled humic acid. Pages 643-651 *in* Proceedings of international clay conference., Mexico City, Appl. Publ. LTD, Wilmette, Illinois, USA.

Tusneen, M. E., and W. H. Patrick. 1971. Nitrogen transformations in waterlogged soils. Bull. Louisiana Agric. Exp. Stn. 657:75 p.

van Heuvelen, B. 1959. Radiocarbon dating of humus from a humus podzol profile underlying peat. Boor and Spade 10:27-28.

van Veen, J. A. 1977. The behavior of nitrogen in soil. A computer simulation model. Ph D thesis, V. U. Amsterdam.

Verma, L., J. P. Martin, and K. Haider. 1975. Decomposition ofcarbon-14 labelled proteins, peptides and amino acids; free and complexed with humic polymers. Soil Sci. Soc. Am., Proc. 39:279-284.

Wagner, G. H. 1968. Significance of microbial tissues of soil organic matter. Pages 197-205 *in*

Isotopes and radiation in soil organic matter studies. Technical meeting, FAO/IAEA, Vienna.

Wagner, G. H., and V. V. Mutakar. 1968. Amino components of soil organic matter formed during humification of $C^{14}$-glucose. Soil Sci. Soc. Am. Proc. 32:683-686.

Wagner, G. H., and D. E. Tang. 1976. Soil polysaccharides synthesized during decomposition of glucose and dextran and determined by $^{14}C$ labeling. Soil Sci. 121:222-226.

Waring, S. A., and J. M. Bremner. 1964. Effect of soil mesh size on the estimation of mineralizable nitrogen in soils. Nature 202:1141.

Warren, R. G. 1956. N-P-K residues from fertilizers and farmyard manure, in long term experiments at Rothamsted, Proc. Fertil. Soc. 37, 1.

Weiss, A. 1969. Organic derivatives of clay minerals, zeolites and related minerals. Page 773 *in* Eglington and Murphy, ed., Organic geochemistry. Springer.

Welte, E. 1963. Der Ab-, Auf- und Umbau der Humusstoffe im Boden und seine Bedeutung für die Bodenfruchtbarkeit. Bodenkultur 14A: 97.

Wurzer, M. 1981. Einflyuß von Metallen / Schwermetallen auf den Abbau der organischen Bodensubstanz. Diploma-thesis, Hamburg University. 160 p.

Yaalon, D. H., and H. W. Scharpenseel. 1972. Radiocarbon dating of soil organic matter in Israel soils. Is. J. Agric. Res. 22/3:154–155.

Zakosek, H. 1962. Zur Genese und Gliederung der Steppenböden im nördlichen Oberrheintal. Abh. Hess. Landesamtes Bodenforsch., Wiesbaden, 37.

Zeller, A., H. E. Oberländer, and F. Hiemer. 1966. A growth chamber for raising carbon-14 labeled plants. *In* Report FAO/IAEA technical meeting on use of isotopes in soil organic matter studies. Braunschweig-Völkenrode 1963, Oxford 401.

Zeller, A., H. E. Oberländer, and K. Roth. 1968. A field experiment on the influence of cultivation practices on the transformation of $^{14}C$-labeled farmyard manure and $^{14}C$-labeled straw into humic substances. Page 265 *in* Proceedings of IAEA/FAO symposium on isotopes radiation soil organic matter studies, Vienna.

## DISCUSSION

NAGAR: I agree with you that the potential of $^{14}C$ techniques should be further utilized in soil organic matter research. It is claimed that one new chemical fertilizer produces large numbers of roots and thus producing sufficient organic matter by their decomposition. But some scientists are of the opinion that the application of organic matter along with chemical fertilizer is absolutely essential for maintaining soil health. Dr. Lester Brown has published a paper in Science (Nov 1981) which indicates deterioration in the fertility of a considerable portion of American soils because of the continuous use of chemical fertilizer alone. In my opinion, by using $^{14}C$ techniques and computer simulation techniques, we can solve this controversy. What is your opinion?

*SCHARPENSEEL:* AMRT would reveal the degree of rejuvenation of soil organic matter in consequence of root growth and development of the edaphon under possible influence of pure mineral or mineral plus organic manure application.

FLAIG: You have shown that the rate of decomposition of organic materials depends on soil type. Is this dependency caused more or less by physical properties of the soil (e.g., type of sorption complexes, etc.) or by another microbial population, which decomposes, e.g. in one case cellulose faster and in another case lignin?

*SCHARPENSEEL:* There can be little doubt that both physical properties and microbial composition influence the rate of decomposition of soil organic matter. Specific results regarding the prevalence of microbial populations exerting faster cellulose or lignin decomposition in association with certain soil types are likely to exist in the (soil) microbiological literature. However, I don't know of such results based on tracer work. The type of sorption complex is certainly one of the major variables, if we consider the close link between survival or mean lifetime of soil organic matter and its attachment to clay surfaces.

AMIEN: In plotting age against depth in several soil orders, Spodosol gives the lowest coefficient. Don't you think that this is more influenced by the soil texture than by the soil order?

*SCHARPENSEEL:* The soil order stands for a complex of diagnostic soil properties and genetic processes. Scattering or organic matter of different ages in Spodosols is mainly associated with the concentration of water-soluble fulvic acids or the participation of organic matter in chelate transport, which is typical for Spodosols; the ease of transport certainly is favored, as you suggest, by the mostly coarse sand texture of Spodosols.

# GASEOUS PRODUCTS OF THE DECOMPOSITION OF ORGANIC MATTER IN SUBMERGED SOILS

Heinz-Ulrich Neue and Hans-Wilhelm Scharpenseel

Gaseous products in submerged soils are an integral part of the decomposition of organic materials. To understand the entire picture of chemical changes in rice soils and their relation to lasting soil fertility, the decomposition pattern of organic matter and the role of the resultant products — including gaseous ones — must be considered with focus placed on the reduction of inorganic oxides as well as organic substrates related to microbial changes in the soil.

The gaseous products in submerged soils are metabolically formed and interrelated but no simple relationship can be discerned in complex environments. Various environments have different decomposition patterns and therefore also show differences in the formation of gaseous products which apparently result from changes in the type and availability of nutrients and the pH and Eh of the soil. Gaseous products are closely related to the decomposition of organic matter, and some directly influence the availability of nutrients as well as the growth of rice.

The main processes that occur in submerged soils can be regarded as a series of successive oxidation-reduction reactions mostly mediated by different types of bacteria. Flooding alters the character of the microbial flora in soils by causing a shortage of $O_2$. Generally, aerobes are replaced by facultative anaerobes, which in turn are followed by obligate anaerobes.

In aerobic biological oxidation, the liberated energy, free molecular $O_2$, is the ultimate electron acceptor. Facultative anaerobes use nitrate, manganic oxide, ferric oxide, carbonate, and other compounds with high oxidation levels as the electron acceptors. The most striking difference between anaerobic and aerobic decomposition lies in the nature of the end products. In normal, well-drained soils the main end products are $CO_2$, $H_2O$, nitrate, sulfate, and resistant humus; in submerged soils they are $CO_2$, $H_2O$, $H_2$, $CH_4$, $NH_3$, mercaptans, $H_2S$, and partially humified residues (Ponnamperuma 1972). The successive microbial changes are accompanied by a stepwise biochemical and chemical reduction of the soil, a lowering of the redox potential, and a change in pH to near neutral. The pattern of changes and the accompanying formation of gases are related to soil properties, environmental factors, and management.

---

The International Rice Research Institute, Los Baños, Laguna, Philippines; and Ordinariat für Bodenkunde der Universität Hamburg von Melle Park 10, D-2000, Hamburg 13, FRG.

Gaseous products are interrelated with microbial functions and atmospheric gas exchange. They are impartant factors in biochemical and chemical changes in submerged soils, and they directly or indirectly influence the availability of plant nutrients and the growth of rice. Studies on gaseous decomposition products of organic matter in submerged soils — for instance with isotopically labeled material — are of vital importance in view of mineralization and formation of humus.

## GASEOUS PRODUCTS

Though the criteria of the gaseous phase may be generally accepted, there is no agreement about the definition of a gas. Mostly, the term “gas” is used for matter that does not condense under given circumstances (Neumuller 1973). In this paper all substances in submerged soils which do not condense at temperatures below 30° C are defined as gases.

$CH_4$ and $CO_2$ produced during anaerobic decay of organic matter have been investigated in a large variety of environments, including landfills (Games and Hayes 1974), sewage sludges (Nissenbaum et al 1972), mixed bacterial cultures (Rosenfeld and Silverman 1959), lake and marine sediments (Koyama et al 1973), glacial drifts (Wasserburg et al 1963), and paddy soils (Yamane 1958a, Takai 1970). In anaerobic soils or cultures containing soil, the following gases have been identified: $H_2$, $N_2$, CO, $O_2$, $CH_4$, NO, $C_2H_4$, $C_2H_6$, $N_2O$, $H_3P$, $CO_2$, $H_2S$, propylene, propane, propadiene, $NH_3$, $SO_2$, butadiene, butane, and $NO_2$. The physical constants of these gases are listed in Table 1. No acetylenic compounds have apparently been found in anaerobic soil.

**Table 1. Physical constants of gases in anaerobic soils.**

| Gas | Synonym, formula | Melting point (°C) | Boiling point (°C) |
|---|---|---|---|
| Hydrogen | $H_2$ | – 259.1 | – 252.9 |
| Nitrogen | $N_2$ | – 209.9 | – 195.8 |
| Carbon monoxide | CO | – 199 | – 191.5 |
| Oxygen | $O_2$ | – 218.4 | – 182.9 |
| Methane | $CH_4$ | – 182.5 | – 164 |
| Nitrogen oxide | Nitric oxide | – 163.6 | – 151.8 |
| Ethene | Ethylene, $CH_2$-$CH_2$ | – 169.2 | – 103.7 |
| Ethane | $CH_3 - CH_3$ | – 183.3 | – 88.6 |
| Nitrogen oxide | Nitrous oxide | – 90.8 | – 88.5 |
| Hydrogen phosphide | Phosphine, $H_3P$ | – 133.5 | – 87.5 |
| Carbon dioxide | $CO_2$ | – 56.6<br>(5.2 atm) | – 78.5 |
| Hydrogen sulfide | $H_2S$ | – 85.5 | – 60.7 |
| Propene | Propylene, $CH_2$ - CH - $CH_3$ | – 185.3 | – 47.4 |
| Propane | $CH_3 - CH_2 - CH_3$ | – 189.7 | – 42.1 |
| Propadiene | Allene, dimethylene-methane,<br>$CH_2$ - C - $CH_2$ | – 136 | – 34.5 |
| Ammonia | $NH_3$ | – 77.7 | – 33.4 |
| Sulfur dioxide | $SO_2$ | – 72.7 | – 10 |
| Butadiene | $CH_2$ - CH - CH - $CH_2$ | – 108.9 | – 4.4 |
| Butane | $CH_3 - CH_2 - CH_2 - CH_3$ | – 138.4 | – 0.5 |
| Nitrogen peroxide | Nitrogen dioxide, $NO_2$ | – 11.2 | + 21.2 |

The largest portion of the gases usually found in higher amounts in submerged soils consists of $CO_2$, $CH_4$, and $N_2$. Within a few hours of soil submergence, microorganisms consume all the $O_2$ present in the water or trapped in the soil (Evans and Scott 1955, Yamane 1958b, Ponnamperuma 1972). $O_2$ and other atmospheric gases can enter the soil only by molecular diffusion in the interstitial water. This process is thought to be 10,000 times slower than diffusion in gas-filled pores (Ponnamperuma 1972). At the surface of a flooded soil, an oxidized layer, which gets $O_2$ from the floodwater, is developed (Yoshida 1975). However, Patrick and Sturgis (1955) found no $O_2$ 1 cm below the soil water interface of flooded soils. Houng (1981) reported that even with a percolation rate of 2-3 cm/day, the thickness of the oxidizing zone may be 1 cm or less. The $O_2$ available in floodwater, therefore, does not seem to limit the activity of aerobic bacteria in the thin surface soil layer, though it may require a considerable flux of $O_2$ to maintain activity. The concentration of dissolved $O_2$ in floodwater during the day varies from 2 to 18 ppm, and it sometimes reaches air saturation or higher (Yoshida 1975), depending on the metabolic activity of algae and aquatic weeds. Though it may require a considerable flux, the surface layer is suitable for N fixation and oxidizing bacteria.

The root-soil boundary of flooded soils planted to rice may also be an important sphere for $O_2$, which can diffuse from the roots to the surrounding media. Because of the great surface area of plant roots, the root-soil boundary may provide enough $O_2$ to permit aerobic respiration by the rhizosphere bacteria. This $O_2$ should also be the terminal electron acceptor for aerobic, mostly chemolithoautotrophic bacteria, which derive their energy by oxidizing inorganic compounds and using $CO_2$ as their C source. Aside from oxidizing bacteria, N-fixing bacteria should get more emphasis in this field.

$N_2$ is the major gas component in soil immediately after flooding. Its rapid evolvement soon after flooding possibly results from relative accumulation due to aerobic and anaerobic respiration of nitrate, if it is present in soil. $N_2$ seems also to be transported to the rhizosphere by the air-transporting system of the rice plant (Yoshida, T. and Broadbent 1975). It would be suitable for active N fixation as it is reported at the surface of a flooded soil (Rice and Paul 1967, Magdoff and Bouldin 1970). The large amount of $N_2$ via the air-transporting system of the rice plant becomes evident in the results of Harrison and Aiyer (1913), who reported that at later growth stages of rice plants more than 70% of the gaseous phase in flooded soils planted to rice was $N_2$, whereas about only 35% of the gaseous phase in unplanted paddy soils consisted of $N_2$. Also Yoshida et al (1975) found more $N_2$ and less $CH_4$ at later growth stages in wetland soils planted to rice than in unplanted fields.

The volatilization of $NH_3$ in relation to the pH of floodwater and algae growth and the consequent $NH_3$ loss should only be mentioned, as the literature has been reviewed elsewhere (Mikkelsen et al 1978, Freney and Simpson 1982). Interestingly, Neue et al (1982) found that $NH_3$ is also released from above-ground parts of rice. The volatilization starts at maximum tillering and reaches a maximum at the flowering stage.

$CO_2$ and $H_2$ are the typical gases evolved in carbohydrate fermentation, but, like $N_2$, they are not exclusive end products of fermentation. Yamane and Sato (1963) reported the degradation of lower fatty acids and the related gases. In flooded soils they could not find a significant amount of $H_2$ except when glucose had been added (Yamane and Sato 1961b). $H_2$ evolution immediately followed the disappearance of $O_2$ in the first days after flooding. After the release of $H_2$ began a rapid increase of $CO_2$, and finally, with decreasing $CO_2$, an increasing formation of $CH_4$ (Takai et al 1956, Neue 1982). $CH_4$ starts to evolve soon after the lower fatty acids and $H_2$ begin to decrease in flooded soil (Yamane and Sato 1967). The degradation of lower fatty acids is faster in soils planted to rice than in unplanted fields (Neue 1982).

According to Ponnamperuma (1972) 1-3 t $CO_2$ are produced in the plowed layer of 1 ha of soil during the first week of submergence. Carbon dioxide formation in paddy soils can be associated with many reactions, but $CH_4$ is produced only by a small group of obligate anaerobes called Archaebacteria because of their primitive cellular structure (Schlegel 1981). The methanobacteria are considered the final member of the food chain existing in an anaerobic ecology. The first metabolic products of cellulose are succinate, propionate, butyrate, lactate, acetate, $CO_2$, and $H_2$; then acetogenic bacteria metabolize these primary products to the secondary products acetate, formate, $CO_2$, and $H_2$; finally the methanogens produce $CH_4$ from the end products of the primary and secondary metabolites (Schlegel 1981). For rice, $CH_4$ is the typical harmless end product of anaerobic fermentation in flooded soil.

The amount of $CH_4$ released to the atmosphere from anaerobic sites and stomachs of ruminants is considerable. It has been calculated that 1-1.5% of the C is released as $CH_4$ to the atmosphere in the course of mineralization of the biospheric C-pool (Schlegel 1981). On the basis of the annual release of C, calculated at up to $1.85 \times 10^{11}$ t/year (Poldervaart 1955), the amount of C released as $CH_4$ to the atmosphere annually would be $1.85\text{-}27.8 \times 10^9$ t. In the atmosphere it is oxidized by hydroxyl radicals to CO and finally to $CO_2$. A total $CH_4$ biogenic production rate of up to $1.51 \times 10^9$ t/year and $1.9 \times 10^8$ t/year separately for paddy fields is reported by Wedepohl (1978).

Total gas consumption varies considerably at different intervals after flooding, depending on environmental factors, soil properties, management, and plant growth. The wide range of gas volumes shown in Table 2 illustrates these effects. An example of the effect of duration of anaerobic incubation on the formation and composition of gases is shown in Table 3.

## FORMATION AND TRANSFORMATION OF GASEOUS PRODUCTS

Fermentation is the major biochemical function of organic matter degradation, and systematic overviews of the biochemical processes of bacteria have been summarized elsewhere (Doelle 1969, Schlegel 1981). Pyruvate, a terminal metabolite of

**Table 2. Range of gases in submerged soils.**

| Gas | Range (%) |
|---|---|
| Nitrogen | 35 – >90 |
| Methane | 4 – 55 |
| Carbon dioxide | 2 – 10 |
| Hydrogen | 0 – 9 |
| Oxygen | <1 – 6 |

**Table 3. Composition of gases after anaerobic incubation (adapted from Takai et al 1956).**

| Gas | Composition (m1/100 g soil) | | | | |
|---|---|---|---|---|---|
| | 0 day | 1 day | 6 days | 14 days | 20 days |
| $CO_2$ | 50.0 | 52.0 | 99.0 | 125.0 | 91.0 |
| $CH_4$ | 0.0 | 0.0 | 0.0 | 15.0 | 26.0 |
| $N_2$ | 7.5 | 8.0 | 9.9 | 12.4 | 6.5 |
| $H_2$ | 0.0 | 0.0 | 0.5 | 0.7 | 9.9 |
| $O_2$ | 2.2 | 0.0 | 0.0 | 0.0 | 0.0 |

carbohydrate metabolism, is a key compound in the biochemical pathways. Pyruvate is the first product of further processes of degradation, transformation, and neosynthesis.

Because of the high energy release associated with aerobic respiration, the decomposition of organic residues and synthesis of cellular substances proceed rapidly. The bulk of freshly added organic matter disappears as $CO_2$, leaving a residue of more resistant material, chiefly altered lignin (Haider et al 1975).

The outstanding difference between anaerobic and aerobic respiration is in the energy liberated. Oxidizing glucose to $CO_2$ and $H_2O$ liberates about 2,800 kJ/mol of sugar, but converting glucose to lactic acid yields about 88 kJ; to alcohol and $CO_2$ about 75 kJ; or to $CH_4$ and $CO_2$ about 180 kJ. Thus, anaerobic organisms have to decompose far more organic material to release a given amount of energy than aerobic organisms.

Anaerobic respiration is a biological energy yielding redox reaction in which an inorganic compound other than $O_2$ is used as the external electron acceptor. If the electron acceptors are organic substrates (external or internal), the process is called fermentation (Doelle 1969, Schlegel 1981). The oxidation of the key metabolite pyruvate proceeds by three reactions:

$$\begin{aligned}
&\text{pyruvate} + \text{CoA} + \text{NAD} \rightarrow \text{acetyl-CoA} + 2\text{NADH}_2 + \text{CO}_2\\
&\text{pyruvate} + \text{CoA} + 2\text{Fd} \rightarrow \text{acetyl-CoA} + 2\text{FdH} + \text{CO}_2\\
&\text{pyruvate} + \text{CoA} \rightarrow \text{acetyl-CoA} + \text{formate}
\end{aligned}$$

For anaerobic bacteria only the second and third equations are valid (Schlegel 1981). The redox potentials of the reduced form of ferredoxine (Table 4) and formate are so low that, in connection with a special hydrogenase, $H_2$ can be produced:

$$\begin{aligned}
&2\,\text{FdH} \rightarrow 2\text{Fd} + \text{H}_2\\
&\text{formate} \rightarrow \text{H}_2 + \text{CO}_2
\end{aligned}$$

Also, the $H_2$ liberated by the dehydrogenation of glyceraldehyde-3-phosphate as $NADH_2$ can be transferred to organic H acceptors. Many anaerobic bacteria can liberate these reduction equivalents as $H_2$. A special enzyme catalyzes this reaction (Schlegel 1981):

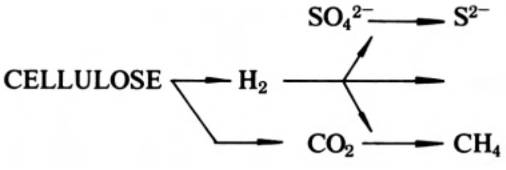
$$\begin{aligned}
&\text{NADH}_2 + 2\text{Fd} \rightarrow \text{NAD} + 2\text{FdH}\\
&2\text{FdH} \rightarrow 2\text{Fd} + \text{H}_2
\end{aligned}$$

**Table 4. Redox potentials of metabolic components (adapted from Schlegel 198**1).

| Component | $E_o$ (V) |
|---|---|
| Fe-S proteins | – 0.2 to –0.6 |
| Hydrogen | – 0.4 |
| Ferredoxine | – 0.4 |
| NAD | – 0.3 |
| Cytochrome $c_3$ | – 0.2 |
| Flavoprotein | – 0.0 |
| Cytochrome b | – 0.0 |
| Cytochrome c | + 0.2 |
| Cytochrome a | + 0.2 |
| Oxygen | + 0.8 |

Molecular hydrogen will be liberated by these reactions only if it is always removed (for $NADH_2$, $E_o$ = –320 mV; for FdH, $E_o$ = –420 mV). In the soil this is done by interspecies H transfer. The more $H_2$ that is removed by interspecies H transfer, the less H acceptor (acetyl-CoA) has to be synthesized; it will be conserved as ATP. Accordingly, less butyrate and more acetate are metabolized (Schlegel 1981).

$CO_2$ and $H_2$ are not the principal end products of carbohydrate fermentation in submerged soils. The main pathway of the liberated $CO_2$ and $H_2$ is the final transformation to $CH_4$ or $H_4S$.

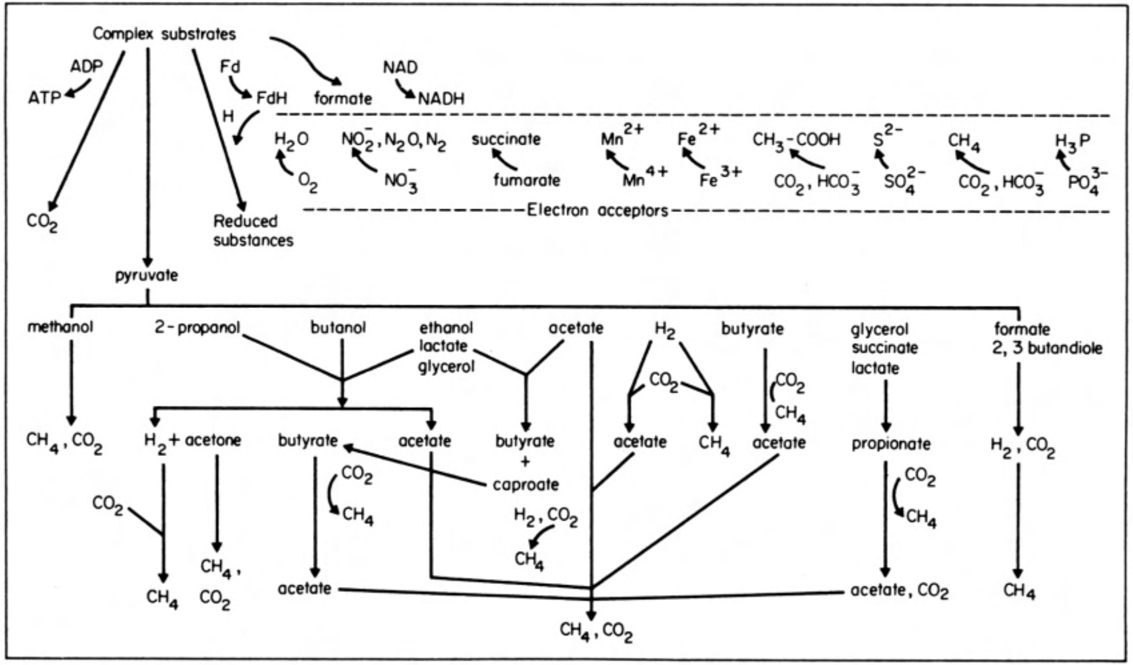


The predominant gaseous end products of anaerobiosis are $CH_4$ and $H_2S$. The sulfate-reducing and methane-producing bacteria are obligate anaerobes. Most methanogens can use $H_2$ as the H donor, while some also use formate, methanol, acetate, or methylamine. Acetate is frequently the main substrate for methanogens (Schlegel 1981). The methanogens are generally restricted to the breakdown of relatively simple organic and inorganic compounds (Barker 1956).

In submerged soils two major biochemical pathways produce methane:

1. reduction of $CO_2$ with $H_2$ or organic molecules as the H donor (Alexander 1961) and
2. decarboxylation of acetic acid (Takai 1970, Yoshida 1975)

Figure 1 illustrates in general the degradation of organic material to $CH_4$ in an anaerobic environment. Methanobacteria are often associated with $H_2$-producing bacteria in a symbiotic relationship. Therefore $H_2$ will seldom be released from submerged soils because methanogens are dependent on $H_2$. Other anaerobic bacteria use $H_2$ as a H donor during ATP synthesis. On the other hand, a high partial pressure of $H_2$ stunts the $H_2$-producing bacteria as mentioned above. Some methanogens can also use CO:



**1.** Generalized scheme of the formation of gaseous products in submerged soils.

$$4CO + 4H_2O \rightarrow 4CO_2 + 4H_2$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Little is known about the biochemical mechanisms and energy yield of the reduction of $CO_2$ to $CH_4$. It has been established that methanogens use special enzymes not found in other bacteria or organisms. In the final step of reduction, mercaptoethansulfonate is one of the intermediates (Schlegel 1981). Methanogens are often associated with bacteria that transform $H_2$ and $CO_2$ to acetic acid:

$$4H_2 + 2CO_2 \rightarrow CH_3\text{-}COOH + 2H_2O$$

The frequently reported decrease in the lower fatty acids — mainly acetic acid — as well as $CO_2$ connected with an increase in $CH_4$ illustrates the main pathway of $CH_4$ formation in submerged soils. Takai (1970) reported that the proportion of $CH_4$ derived from $CO_2$ added to flooded soil amounted to 10–15% in one soil and up to 25% in a soil that contained more organic matter. The larger part was formed by the decarboxylation of acetic acid.

The presence of $CH_4$ has been observed in conjunction with sulfate reduction, so that a syntrophic relationship is claimed between sulfate-reducers and $CH_4$-producers (Martens and Berner 1974,1977; Cappenberg 1975; Barnes and Goldberg 1976; Reeburg 1976; Bryant et al 1977; Oremland and Taylor 1978; Kosiur and Warford 1979; Warford et al 1979). The sulfate-reducers yield acetate and H to the methanogens. Takai and Kamura (1966) reported that in rice fields sulfate is reduced before $CH_4$ is formed. Furthermore, it has been observed that sulfate-reducers are more competitive for common substrates (Winfrey and Zeikus 1977, Bryant et al 1977, Abram and Nedwell 1978). According to Schlegel (1981) there are two groups of obligate anaerobic sulfate-reducing bacteria using lactate, acetate, propionate, butyrate, formate, ethanol, fatty acids, and $H_2$ as H donors. One group oxidizes the H donors incompletely, excreting acetate, because they have an imperfect tricarboxylic acid cycle. The second group is able to oxidize alcohols, acetate, higher fatty acids, or benzoate totally; some can grow chemoautotrophically with $H_2$ and formate, and their assimilation products can be metabolized from acetate and $CO_2$ if $H_2$ functions as the H donor.

Most sulfate-reducing bacteria have the capacity to produce very high amounts of $H_2S$ by reducing sulfate with $H_2$, though their growth rate is extremely low (Schlegel 1981). The general equation for this reaction would be:

$$4CH_3\text{-}CO\text{-}COOH + H_2SO_4 \rightarrow 4CH_3\text{-}COOH + 4CO_2 + H_2S$$

Some of these bacteria can transform pyruvate without sulfate to acetate, $CO_2$, and $H_2$:

$$CH_3\text{-}CO\text{-}COOH + H_2O \rightarrow CH_3\text{-}COOH + CO_2 + H_2$$

Proteins will be degraded anaerobically by peptolytic bacteria to amino acids. Mostly these acids would not be fermented separately. There is often a special interrelation of amino acids as electron donors and acceptors. The gaseous end products of protein fermentation are $NH_3$, $CO_2$, $H_2$, and $H_2S$. The following equations are given as examples for the general reaction:

$$CH_3\text{-}CHNH_2\text{-}COOH + 2H_2O \rightarrow CH_3COOH + NH_3 + CO_2 + 4(H)$$
$$CH_2NH_2\text{-}COOH + 4(H) \rightarrow 2CH_3\text{-}COOH + 2NH_3$$

The formation of $N_2O$ in flooded soil during nitrate reduction is reported by Crasswell and De Datta (1980) to be minimal, but other authors claim that a large fraction of the N lost by denitrification should appear in the atmosphere as $N_2O$ rather than as $N_2$ (Delwiche and Bryan 1976). But there is evidence that soils may represent an important sink for $NO_2$ because soils absorb these gases very rapidly (Bremner 1976).

Although the main transformation of P in anaerobic media is to the orthophosphate ion (Ponnamperuma 1972), $H_3P$ can be formed, as demonstrated by Tsubota (1958,1959). Emerging to the thin oxidized surface layer as well as into the flood water, or diffusing to the root-soil boundary, the gaseous products may be metabolized again. Aerobic and facultative aerobic bacteria, especially phototrophic bacteria, can oxidize S compounds, mainly sulfides to sulfates in flooded soil, but sulfide can also be oxidized chemically in the aerobic zone (Connell and Patrick 1968). $H_2$ is oxidized to water aerobically by $H_2$-oxidizing bacteria. Methane is oxidized to methanol, formaldehyde, formate, and $CO_2$.

Most organic compounds can eventually form gases by anaerobiosis: polysaccharides, hexoses, pentoses, tetroses, polyoses, lower fatty acids, amino acids (but not aromatics), purines, and pyrimidines. These substrates can be oxidized by intramolecular cleavage in exergonic reactions. But there are substrates that cannot be fermented by anaerobiosis: aliphatic and aromatic hydrocarbons, steroids, carotinoids, terpenes, fatty acids with more than $C_5$, and porphyrins; they can only be degraded aerobically. During cleavage these substrates do not yield energy. They can only be oxidized by $O_2$ (Schlegel 1981).

## THE KINETICS OF GASEOUS PRODUCTS IN SUBMERGED SOILS

The kinetics of reduction and the kind and amount of reduction products are determined by the nature and content of organic matter, temperature, pH, kind and concentration of inorganic electron acceptors, and the duration of flooding. Successive microbial changes are accompanied by a stepwise biochemical and chemical reduction of the soil, a lowering of the oxidation-reduction potential, and a change in pH to near neutral. The redox potential of the soil reflects the intensity and mode of the microbially controlled decomposition of organic matter (Ottow 1982). The more intensively the mineralization of energy-rich compounds (H-donors) is proceeding, the faster and greater is the decrease of the redox potential (Fabig 1980). On the other hand, the redox potential of the soil solution is the prerequisite for bacteria to yield energy, as they react mostly with external electron acceptors and enzymes. An external electron acceptor is an advantage for getting energy (ATP synthesis) in the absence of $O_2$; otherwise the process has to be done by intermediate metabolic products.

The redox potential of the soil solution is therefore nearly the same as that inside the cells (Ottow 1982). The redox potential ($Eh_o$) therefore only characterizes a steady state at pH 7, if all compounds are in equilibrium. But often the needed activation energy is too high, even though the pH-Eh levels are below the critical ones (Bohn et al 1969). Bacteria usually decrease the activation energy with specific enzymes (reductases) and a proper intracellular redox potential (Table 4). Because of the complex interrelations of decomposition intensity, gas production, levels of intracellular potential, required activation energy, buffer capacity fur electrons and protons, etc., there is still no exact scheme for the biochemical kinetics. Measurements of the redox potential are only a clue to the dynamic processes occurring in the soil (Table 5).

Enzymes are often located or transported to the outside of the cell membrane. To be active they need an adequate redox potential in the system. For reasons of thermodynamic economy, those reactions consuming less energy are favored (Claypool and Kaplan 1974). Thus, Jakobsen et al (1981) confirmed earlier findings that the reduction of nitrate and the formation of manganous ions, ferrous ions, sulfides, and $CH_4$ were generally in accordance with thermodynamic energy principles. It is also evident that this represents a sequence of electron acceptors as well. However some overlap could occur in the formation of manganous and ferrous ions and of sulfides in the later stages of their reactions (Turner and Patrick 1968). This could be caused by delayed solubilization reactions of Mn and Fe compounds (Ponnamperuma 1965). In experiments by Asami and Takai (1970) the amount of Fe reduced was highly correlated with the amount of $CO_2$ produced for about 2 weeks after flooding. They suggested that $CO_2$ evolves as a result of organic acid degradation by bacteria when $Fe^{+3}$ is used as an electron acceptor. Because the amount of Fe in soils is usually much higher than that of nitrate and Mn, the transformation of Fe should greatly influence not only the pH/Eh of the soil but also the gaseous products.

During sulfate reduction 2-3% of the total $CH_4$ production has been detected (Martens and Berner 1974,1977; Oremland and Taylor 1978; Jakobsen et al 1981). This $CH_4$ is formed several hours before the beginning of the formation of sulfide, and concomitantly with the formation of $Fe^{+2}$. Smith et al (1978) observed that small amounts of both ethylene and $CH_4$ are consistently formed at the onset of the formation of $Fe^{+2}$ and before the major formation of $CH_4$. Jakobsen et al (1981) found no evidence of anaerobic oxidation of $CH_4$ by sulfate-reducers, as mentioned elsewhere (Barnes and Goldberg 1976, Reeburgh 1976, Kosiur and Warford 1979, Warford et al 1979). Both nitrate and sulfate have been considered inhibitors of $CH_4$ production by raising the redox potential (MacGregor and Keeney 1973), whereas phosphate favors $CH_4$ production (Takai et al 1969). Nitrate has been found to

**Table 5. Oxidation-reduction potentials of typical soil systems (potentials in mV, 25°C, pH 7).[a]**

| | | |
|---|---|---|
| $O_2 + 4H^+ + 4e^-$ | $= 2H_2O$ | + 830 |
| $NO_3^- + 2H^+ + 2e^-$ | $= NO_2^- + H_2O$ | + 430 |
| $MnO_2 + 4H^+ + 2e^-$ | $= Mn^{2+} + 2H_2O$ | + 410 |
| $Fe(OH)_3 + 3H^+ + e^-$ | $= Fe^{2+} + 3H_2O$ | – 180 |
| $SO_4^{2-} + 10H^+ + 8e^-$ | $= H_2S + 4H_2O$ | – 220 |
| $CO_2 + 8H^+ + 8e^-$ | $= CH_4 + 2H_2O$ | – 240 |
| $P + 3H^+ + 3e^-$ | $= H_3P$ | – 360 |
| $2H + 2e^-$ | $= H_2$ | – 413 |

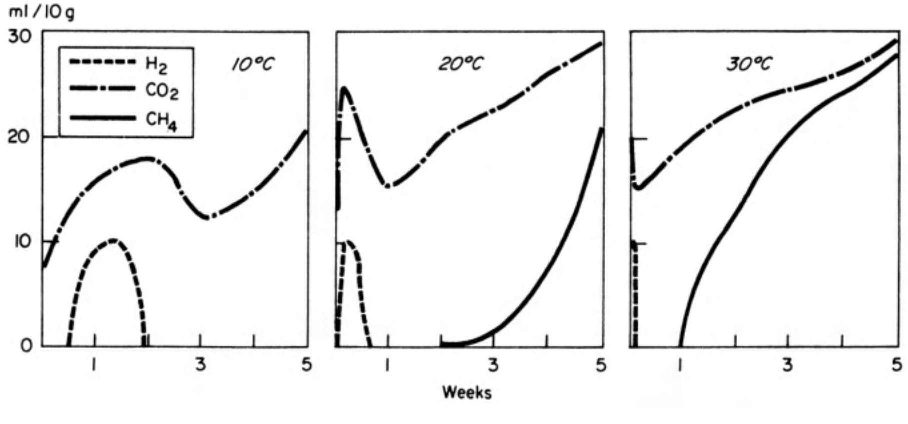
[a]Adapted from Ponnamperuma (1965), Russel (1973).

inhibit $N_2O$ formation (Blackmer and Bremner 1978). The initial effect of nitrate is to delay other anaerobic reactions until all nitrate has been reduced. This is caused by the considerable increase of the redox potential, as well as by the fact that nitrate is reduced only by facultative anaerobes. A direct toxic effect of the reduction products formed by nitrate reduction, inhibiting $CH_4$ formation, has also been reported (Cappenberg 1975, Balderstone and Payne 1976, Winfrey and Zeikus 1977).

A wide range of toxicity of the sulfide ion to $CH_4$ production has been reported; nevertheless, the methanogens are insensitive to most antibiotics as opposed to the eubacteria. Mah et al (1977) concluded from the wide ranges of sulfide toxicity — 0.1 mM $H_2S$ (Cappenberg 1975) to 20 mM total sulfide (Bryant et al 1977) — that the sensitivity of methanogens to sulfide may differ considerably according to species and environment. Sulfide also has an inhibitory effect on the reduction of nitrate (Myers 1972). In a reduced soil, the concentration of $Fe^{+2}$ increases as the pH decreases, rendering the concentration of $H_2S$ independent of pH (Ponnamperuma 1965). Therefore, $H_2S$ development and toxicity should be low to zero in soils with high active Fe and high in soils low in active Fe. Manganese dioxide apparently cannot compete with sulfate as a hydrogen acceptor, but can oxidize $H_2S$ once it forms (Yoshida 1975).

Sulfate reduction proceeds slowly in submerged acid sulfate soils because of the low pH (5–5.5). The optimum pH values for $CH_4$ and sulfide formation range from 6.4 to 7.8 (Jenkins 1963), while some sulfide-oxidizing bacteria can tolerate 1 N $H_2SO_4$ (Schlegel 1981). Liming submerged acid sulfate soils therefore accelerates the reduction considerably (Ponnamperuma 1965).

Temperature has a great influence on the growth of microorganisms and consequently on the decomposition of organic matter and the kinetics of the gaseous products (Fig. 2). With increasing temperature up to 35° C, the decomposition starts earlier and is more vigorous in every case. At higher temperatures, the formation of $CO_2$ and $CH_4$ occurs earlier and is stronger, but that of $H_2$ and organic acids is smaller in amount, although it also occurs earlier (Yamane and Sato 1961a). At



**2.** Effect of temperature on the anaerobic decomposition of organic substrates (adapted from Yamane and Sato 1967).

lower temperatures the periods of accumulation of $H_2$ and organic acids become larger, According to Yamane and Sato (1961a), $H_2$ formation is very vigorous at 10° C and the period of its retention lasts 4 weeks. The amount of $CH_4$ increases with temperature. Most $CH_4$ bacteria function best above 30° C, but some can produce $CH_4$ even at 5°C (Ruttner 1963). Below 20°C, Yamane and Sato (1961a) could seldom observe $CH_4$ formation.

Thus, the period of occurrence and the amount of the gaseous products depend largely on temperature and reductive conditions. All the interactions and interrelations, regarding not only the gaseous products but also the nutrient balance and decomposition pattern, need to be classified to a greater extent.

## INTERRELATIONSHIP BETWEEN GASEOUS PRODUCTS AND RICE GROWTH

The uninterrupted supply of $CO_2$ to the plant is vital from the point of view of agriculture. In this connection, the soil, being the primary source of all $CO_2$, plays a most imporant role (Kononova 1961). Severe $CO_2$ deficits occur at photosynthetic surfaces of a rice crop when active photosynthesis proceeds under high solar radiation (Yoshida et a1 1974). Though atmospheric $CO_2$ is the general source of $CO_2$ in rice crop photosynthesis, direct use of soil $CO_2$ released into the atmosphere is the next most important source (9-12% of net dry matter production). Soil $CO_2$ absorbed by rice roots is almost negligible (Yoshida 1976). Carbon dioxide plays an important role in ionic equilibria in flooded soils. Being chemically active, it forms carbonic acid, bicarbonates, and insoluble carbonates. Its partial pressure determines the pH, Eh, and the solubility of Fe, Mn, and Ca in flooded soils (Ponnamperuma 1976).

$CO_2$ concentrations exceeding 15% are toxic to rice. A high concentration of $CO_2$ in the soil may be an important factor retarding nutrient uptake by rice in flooded muck soils, acid soils, and freshly manured soils (Ponnamperuma 1965). Cho and Ponnamperuma (1971) suggested that excess $CO_2$ was one of the factors retarding the growth of rice on cold acid submerged soils. There is also the question of precipitation of carbonates (Hem 1972).

Sulfide inhibits the respiration and the oxidizing power of rice roots, thus retarding the uptake of nutrients and causing poor growth (Yoshida 1976). $H_2S$ at concentrations as low as 0.1 ppm in culture solution is toxic to rice and may be lethal (Ponnamperuma 1965). Mitsui et al (1951) reported a toxic level at 0.07 ppm. In normal soils the presence of $Fe^{+2}$ keeps the concentration of $H_2S$ so low that it is undetectable. Yamane and Sato (1961b) found no sulfide 4 weeks after flooding in a muck soil in which the Eh remained at 200-300 mV. Reasonably high levels of both sulfide and ferrous iron can occur in the soil solution even at near-neutral pH values if $CO_2$ is produced rapidly (Tanaka et al 1968, Park and Tanaka 1968). The reduction of sulfate in a flooded soil raises the question of the sulfur supply of rice and immobilization of Cu and Zn.

Ethylene formation in flooded soil is presumably caused by facultative anaerobes at $O_2$ concentrations below 1% (Smith and Russell 1969, Smith and Restall 1971). The $C_2H_4$ production depends on the presence of methionine, which is present only in aerobic conditions. Thus, $C_2H_4$ can be produced only for a short period in submerged soils after flooding. In the oxidized thin surface layer, formation may proceed. Ethylene is a critical regulator of microbial activity in the soil, related to organic matter transformation and plant nutrient availabilities (Smith 1976). Ethylene can accumulate in an anaerobic soil at a concentration of 10 ppm (Yoshida 1978), injuring the roots of some plant species. The rice plant, however, has a mechanism to decompose ethylene in the rhizosphere, probably by bacteria (Yoshida and Suzuki 1975). $CH_4$ is the only gaseous hydrocarbon known to accumulate in large amounts in submerged soils after flooding. $CH_4$ inhibits the growth of some dryland crops, but not that of the rice plant.

As gaseous products in submerged soils are closely related to the decomposition of organic matter as well as to nutrient availability and rice growth, there should be more emphasis on establishing experimental techniques for their measurement in long-term field experiments. Until today most experiments have been short-term laboratory studies. Current experiments on the IRRI farm with input of uniformly $^{14}C$-labeled mature rice straw suggest that the decomposition rate of rice straw is faster in submerged soil than in dryland soil in this environment. Other results relating to the formation of $CO_2$ and $CH_4$ show that there might be a priming effect for $CH_4$ production —$CH_4$ might be metabolized more in the food chain originating from soil organic matter than from the added rice straw. These results have to be confirmed and further experiments have to be established on other sites with different environments and management systems.

## REFERENCES CITED

Abram, J. W., and D. B. Nedwell. 1978. Hydrogen as a substrate for methanogenesis and sulphate reduction in anaerobic saltmarsh sediments. Arch. Microbiol. 117:93-97.

Alexander, M. 1961. Introduction to soil microbiology. Wiley, New York.

Asami, T., and Y. Takai. 1970. Behaviour of free iron oxides in paddy soils. (4) Relationship between reduction of free iron oxide and formation of gases in paddy soils [in Japanese, English summary]. J. Sci. Soil Manure Jpn. 41:48-55.

Balderston, W. L., and W. J. Payne. 1976. Inhibition of methanogenesis in salt marsh sediments and whole-cell suspensions of methanogenic bacteria by nitrogen oxides. Appl. Environ. Microbiol. 32:264-269.

Barker, H. A. 1956. Bacterial fermentation. Wiley, New York.

Barnes, R. O., and E. D. Goldber. 1976. Methane production and consumption in anoxic marine sediments. Geology 4:279-300.

Blackmer, A. M., and J. M. Bremner. 1978. Inhibitory effect of nitrate on reduction of $N_2O$ to $N_2$ by soil microorganisms. Soil Biol. Biochem. 10:187-191.

Bohn, H., B. McNeal, and G. O’Connor. 1969. Soil chemistry. Wiley, New York.

Bremner, J. M. 1976. Role of organic matter in volatilization of sulfur and nitrogen from soils. International Symposium Soil Organization Matter Studies, 6-10 Sept. 1976, Braunschweig, FRG, Paper No: IAEA-SM-211/9.

Bryant, M. P., L. L. Campbell, C. A. Reddy, and M. R. Crabill. 1977. Growth of Desulfovibrio in lactate or ethanol media in sulfate in association with $H_2$-utilizing methanogenic bacteria. Appl. Environ. Microbiol. 33:1162-1169.

Cappenberg, T. E. 1975. Relationship between sulfate reducing and methane producing bacteria. Plant Soil 43:125-139.

Cho, D. Y., and F. N. Ponnamperuma. 1971. Influence of soil temperature on the chemical kinetics of flooded soils and the growth of rice. Soil Sci. 112:184-194.

Claypool, G. E., and I. R. Kaplan. 1974. The origin and distribution of methane in marine sediments. Pages 99-139 *in* I. R. Kaplan, ed. Natural gases in marine sediments. Plenum, New York.

Connell, W. E., and W. H. Patrick Jr. 1969. Sulfate reduction in soil: Effects of redox potential and pH. Science 159:86-87.

Craswell, E. T., and S. K. De Datta. 1980. Recent developments in research on nitrogen fertilizers for rice. IRRI Res. Pap. Ser. 49:11.

Delwiche, C. C., and B. A. Bryan. 1976. Denitrification. Ann. Rev. Microbiol. 30:241-262.

Doelle, H. W. 1969. Bacterial metabolism. Academic Press, New York.

Evans, D. D., and A. D. Scott. 1955. A polarographic method measuring dissolved oxygen in saturated soil. Soil Sci. Soc. Am. Proc. 19:12-16.

Fabig, W. 1980. Einfluss des Sauerstoff-Partialdrucks auf die Eignung von einfachen aromatischen Wasserstoff-donatoren (Benzoat, Hydrobenzoat) fur die anaerobe Atmung (Denitrifikation) Diss. Hohenheim. in Hochschulsamml. Naturwiss. Biol. 8.96 p. Hochschulverlag Freiburg.

Freney, J. R., and J. R. Simpson, eds. 1982. Gaseous loss of nitrogen from soil-plant systems. (in press)

Games, L. M., and J. M. Hayes. 1974. Carbon in ground water at the Columbus, Indiana landfill. Pages 81-110 *in* D. B. Waldup and R. V. Ruhe, eds. Solid waste disposal by land burial in southern Indiana. Bloomington, Indiana.

Haider, K., J. P. Martin, and Z. Filip. 1975. Humus biochemistry. Pages 196-244 *in* E. A. Paul and A. D. McLaren, eds. Soil biochemistry. Vol. 4. Marcel Dekker Inc., New York.

Harrison, W. H., and P. A. S. Aiyer. 1913. The gases of swamp rice soil. I. Their composition and relationship to the crop. Mem. Dep. Agric. India Chem. Ser. 5(3):65-104.

Hem, J. D. 1972. Chemistry and occurrence of cadmium and zinc- in surface water and ground-water. Water Resour. 8:661-679.

Houng, K. H. 1981. A theoretical evaluation of the influence of percolation rate on the thickness of the oxidizing zone of paddy soils. Proc. Natl. Sci. Counc. 5(4):274-278.

Jakobsen, P., W. H. Patrick, Jr., B. G. Williams. 1981. Sulfide and methane formation in soils and sediments. Soil Sci. 132(4):279-287.

Jenkins, D. 1963. Sewage treatment. Pages 508-536 *in* C. Rainbow and A. H. Rose, eds. Academic Press, New York.

Kononova, M. M. 1961. Soil organic matter. Its nature, its role in soil formation and in soil fertility. Pergamon Press, Oxford, London, New York, Paris.

Kosiur, D. R., and A. L. Warford. 1979. Methane production and oxidation in Santa Barbara Basin sediments. Estuarine Coastal Mar. Sci. 8:379-385.

Koyama, T., M. Nikaido, T. Tomino, and H. Hayakawa. 1973. Decomposition of organic matter in lake sediments. Pages 512-535 *in* Proceedings of a symposium on hydrogeochemistry and biogeochemistry, Tokyo. Washington, D. C.

MacGregor, A. N., and D. R. Keeney. 1973. Methane formation by lake sediments during in vitro incubation, Water Resourc. Bull. 9:1153-1158.

Magdoff, F. R., and D. R. Bouldin. 1970. Nitrogen fixation in submerged soil-sandy-energy material media and the aerobic-anaerobic interface. Plant Soil 33:49-61.

Mah, R. A., D. M. Ward, L. Baresi, and T. L. Glass. 1977. Biogenesis of methane. Ann. Rev. Microbiol. 31:309-341.

Martens, C. S., and R. A. Berner. 1974. Methane production in the interstitial waters of sulfate-depleted marine sediments. Science 185-1167-1169.

Martens, C. S., and R. A. Berner. 1977. Interstitial water chemistry of anoxic Long Island Sound sediments. I. Dissolved gasses. Limnol. Oceanogr. 22:10-25.

Mikkelsen, D. S., S. K. De Datta, and W. N. Obcemea. 1978. Ammonia volatilization losses from flooded rice soils. Soil Sci. Soc. Am. J. 42:725-730.

Mitsui, S., S. Aso, and K. Kumazawa. 1951. Dynamic studies on the nutrient uptake by crop plants. I. The nutrient uptake of rice roots as influenced by hydrogen sulfide [in Japanese, English summary]. J. Sci. Soil Manure Jpn. 22:46-52.

Myers, R. J. K. 1972. The effect of sulphide on nitrate reduction in soil. Plant Soil 37:431-433.

Neue, H.-U. 1982. Studies on anaerobic decomposition of organic matter in flooded soils. A preliminary report submitted to International Rice Research Institute.

Neue, H.-U., H. W. Scharpenseel, and U. Martin. 1982. Ammoniak-Abgabe durch Blatter von Reispflanzen [in German, English summary]. Z. Pflanzenern. Bodenkunde (in press).

Neumuller, O. A. 1973. Rompps Chemie Lexikon [in German]. Franckh'sche Verlagshandlung, Stuttgart.

Nissenbaum, A., B. J. Presley, and I. R. Kaplan. 1972. Early diagenesis in a reducing fjord, Saanich-Inlet, British Columbia. I. Chemical and isotopic changes in major components of interstitial water. Geochim. Cosmochim. Acta 36:1007-1027.

Oremland, R. S., and B. F. Taylor. 1978. Sulfate reduction and methanogenesis in marine sediments. Geochim. Cosmochim. Acta 42:209-214.

Ottow, J. C. G. 1982. Kurzmitt.: Bedeutung des Redox potentials für die Reduktion von Nitraten und Fe(III) oxiden in Boden [in German]. Z. Pflanzenern. Bodenkd. 145:91-93.

Park, Y. D., and A. Tanaka. 1968. Studies of the rice plant on an “Akiochi” soil in Korea. Soil Sci. Plant Nutr. 14:27-34.

Patrick, W. H., Jr., and M. B. Sturgis. 1955. Concentration and movement of oxygen as related to absorption of ammonium and nitrate nitrogen by rice. Soil Sci. Soc. Am. Proc. 19:59-62.

Poldervaart, A. 1955. The crust of the earth. Geol. Soc. Am. Spec. Pap. 62.

Ponnamperuma, F. N. 1965. Dynamic aspects of flooded soils and the nutrition of the rice plant. Pages 295-328 *in* International Rice Research Institute. The mineral nutrition on the rice plant. John Hopkins Press, Baltimore, Maryland.

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Ponnamperuma, F. N. 1976. Temperature and the chemical kinetics of flooded soil. Pages 249-263 *in* International Rice Research Institute. Climate and rice. Los Baños, Philippines.

Reeburgh, W. S. 1976. Methane consumption in Cariaco Trench waters and sediments. Earth Planet. Sci. Lett. 28:337-344.

Rice, W. A., and E. A. Paul. 1967. The role of anaerobiosis in asymbiotic nitrogen fixation. Can. J. Microbiol. 13:829-836.

Rosenfeld, W. D., and S. R. Silverman. 1959. Carbon isotope fractionation in bacterial production of methane. Sci. 130:1658-1659.

Russell, E. W. 1973. Soil condition and plant growth. 10th ed. Longman, London, New York.

Ruttner, F. 1963. Fundamentals of limnology. 3rd ed. University of Toronto Press, Toronto.

Schlegel, H. G. 1981. Allgemeine Mikrobiologie [in German]. Thieme Verlag, Stuttgart, New York.

Smith, A. M. 1976. Ethylene production by bacteria and reduced microsites in soil and some implications to agriculture. Soil Biol. Bio Chem. 8:293-298.

Smith, K. A., and S. W. F. Restall. 1971. The occurrence of ethylene in anaerobic soil. J. Soil Sci. 22:430-443.

Smith, K. A., and R. S. Russell. 1969. The occurrence of ethylene, and its significance, in anaerobic soil. Nature 222:769-771.

Smith, A. M., P. J. Milham, and W. L. Morrison. 1978: Soil ethylene production specifically triggered by ferrous iron. Pages 327-336 *in* M. W. Loutit and J. A. R. Miles, eds. Microbial ecology. Springer Verlag, New York.

Takai, Y. 1970. The mechanism of methane fermentation in flooded soil. Soil Sci. Plant Nutr. 16:238-244.

Takai, Y., T. Koyama, and T. Kamura. 1956. Microbial metabolism in reduction process of paddy soils. Part I. Soil Plant Food 2(2):63-66.

Takai, Y., and T. Kamura. 1966. The mechanism of reduction in waterlogged paddy soil. Folia Microbiol. 11:304-313.

Takai, Y., Y. Macura, and F. Kunc. 1969. Anaerobic decomposition of glucose continuously added to the soil. Folia Microbiol. 14:327-333.

Tanaka, A., R. P. Mulleriyawa, and T. Yasu. 1968. Possibility of hydrogen sulfide induced iron toxicity of the rice plant. Soil Sci. Plant Nutr. 14:1-6.

Tsubota, G. 1958. On the phosphate-reduction in the paddy field [in Japanese, English summary]. Tochigi Agric. Exp. Stn. Bull. 2:1-13.

Tsubota, G. 1959. Phosphate reduction in the paddy field. Part I. Soil plant food 5(1): 10-15.

Turner, F. T., and W. H. Patrick, Jr. 1968. Chemical changes in waterlogged soils as a result of oxygen depletion. Trans. 9th Int. Congr. Soil Sci. Adelaide 4:53-65.

Wasserburg, G. S., E. Mazor, and R. E. Zartman. 1963. Isotope and chemical composition of some terrestrial natural gases. Pages 219-240 *in* J. Geiss and E. D. Goldberg, eds. Earth science and meteorites. Amsterdam.

Warford, A. L., D. R. Kosiur, and P. R. Dooge. 1979. Methane production in Santa Barbara Basin sediments. Geomicrobiol. 1:117-137.

Wedepohl, K. H., ed. 1978. Handbook of geochemistry. Vol II/1 Elements H(1) to Al(13). Springer Verlag, Berlin, Heidelberg, New York.

Winfrey, M. R., and J. G. Zeikus. 1977. Effect of sulfate on carbon and electron flow during microbial methanogenesis in freshwater sediments. Appl. Environ. Microbiol. 33:275-281.

Yamane, I. 1958a. Manometric micro-analysis of gas mixtures evolved from paddy soil, using van slyke apparatus. Soil Plant Food 4:1-6.

Yamane, I. 1958b. Metabolism in muck paddy soil. II. Determination of gasses evolved from paddy fields and estimation of decomposable organic matter. Soil Plant Food 4:25-31.

Yamane, I., and K. Sato. 1961a. Effect of temperature on the formation of gases and ammonium nitrogen in the waterlogged soils. Rep. Inst. Agric. Res. Tohoku Univ. 12:1-10.

Yamane, I., and K. Sato. 1961b. Metabolism in muck paddy soil. Part 3. Role of soil organic matter in the evolution of free hydrogen sulphide in waterlogged soil. Rep. Inst. Agric. Res. Tohoku Univ. 12(2):73-86.

Yamane, I., and K. Sato. 1963. Decomposition of organic acids and gas formation in flooded soils. Soil Sci. Plant Nutr. 9:32-36.

Yamane, I., and K. Sato. 1967. Effect of temperature on the decomposition of organic substances in flooded soil. Soil Sci. Plant Nutr. 13:94-100.

Yoshida, S., V. Coronel, F. T. Parao, and E. de los Reyes. 1974. Soil carbon dioxide flux and rice photosynthesis. Soil Sci. Plant Nutr. 20:381-386.

Yoshida, S. 1976. Carbon dioxide and yield of rice. Pages 211-219 *in* International Rice Research Institute. Climate and rice. Los Baños, Philippines.

Yoshida, T. 1975. Microbial metabolism of flooded soils. Pages 83-122 *in* E. A. Paul and A. D. McLaren, eds. Soil biochemistry. Vol. 3. New York.

Yoshida, T. 1978. Microbial metabolism in rice soils. Pages 445-463 *in* International Rice Research Institute. Soils and rice. Los Baños. Philippines.

Yoshida, T., and M. Suzuki. 1975. Formation and degradation of ethylene in submerged soils. Soil Sci. Plant Nutr. 121:129-135.

Yoshida, T., and F. E. Broadbent. 1975. Movement of atmospheric nitrogen in rice plants. Soil Sci. 120:288-291.

Yoshida, T., Y. Takai, and D. C. del Rosario. 1975. Molecular nitrogen content in submerged rice field. Plant Soil 42:653-660.

## DISCUSSION

SINGH: What conditions favor volatilization of $NH_3$ from rice leaves?

*NEUE:* Ammonia release is much faster at high temperatures and at realistically low partial pressures of $NH_3$ in the range of 0-5 nbar, as reported by Farguhar et al. Ammonia volatilization might be also related to senescence of leaves by proteolysis, though we found that $NH_3$ volatilization was lower at later growth stages with increasing senescence than at the flowering stage.

SINGH. There are several reports about partial pressures of different gases in submerged high organic matter soils. How much do you think total gas pressures can develop in such conditions and how would they affect soil physically and otherwise if not released to the atmosphere?

*NEUE:* When a soil is flooded, the result is a drastic reduction in both $O_2$ content and in the gaseous exchange capacity. Gases tend to accumulate and build up pressures. I am not aware of total gas pressures, but partial pressures of $CO_2$ determined by the Soil Chemistry Department were up to 0.63 atm. The partial pressure of $CO_2$ holds the key to the quantitative interpretation of Eh, pH, and cation exchange in flooded soils.

FLAIG: Bremner reports that readily decomposable organic matter increases volatilization of N. Did you make the same observation?

*NEUE:* Up to now we have no experimental data in this area. There is no indication in the literature that organic matter promotes volatilization of $NH_3$ rather than decreases it because of the sorption capacity. There could be an enhanced volatilization in respect to urea fertilizer because of the more rapid enzymatic hydrolysis of urea. Volatilization of $N_2$ or $N_2O$ by denitrifying bacteria should be correlated to easily decomposable organic matter. These substrates increase microbial growth and thereby enhance anaerobic conditions, promoting the activity of these bacteria. For $N_2O$ as well as $NO_2$ we have to take into consideration the fact that anaerobic soils are functioning as a sink because those gases are absorbed.

AGBOOLA: In Badeggi, which is a rice research station in Nigeria, the problem of Fe toxicity has been reported under submerged conditions, despite the fact that the soil organic matter is low and shows Fe deficiency under dryland conditions. May I know whether you have any explanation for this based on your experience?

*NEUE:* This is related to the well-known changes of the chemistry of this soil related to submergence and drying, respectively. Submerging the soil will increase the $Fe^{+2}$ content dependent on pH/ Eh changes. If the soil is drying and getting enough oxygen, $Fe^{+2}$ will change to $Fe^{+3}$, which is not available to the plant. Organic matter can serve as an ameliorant for these soils. Through decreasing pH and increasing concentration of $Fe^{+2}$ in the first days after flooding and incorporation, the pH will increase and the $Fe^{+2}$ concentration will be lower for some time. Transplanting some days after incorporation should decrease Fe toxicity. In aerobic conditions chelating mechanisms may improve Fe deficiency.

WAIN: You did not mention the higher fatty acids that occur in organic matter. Do you have evidence of how these are degraded? Presumably this occurs by ß-oxidation.

*NEUE:* According to Schlegel (1981) the following substrates could not be fermented by anaerobiosis because they could not be oxidized by intramolecular cleavage in an exergonic reaction: aliphatic and aromatic hydrocarbons, steroids, carotinoids, terpenes, porphyrines, and fatty acids with more than $C_5$.

FAGI (comment): Application of organic materials or rice straw, based on the papers presented, may inhibit nitrification and denitrification of applied N by three mechanisms: 1) promoting the growth of phototrophic microorganisms (green algae), hence increasing N fixation; 2) providing electron acceptors, so that instead of utilizing H from $NH_4^+$, microorganisms use H from the decomposition products of organic materials; 3) decomposition products of organic materials may be toxic, inhibiting the growth of nitrifying bacteria. Thus, the use of organic materials or rice straw may increase the efficiency of applied N. Therefore, I suggest that the INSFFER team of IRRI include the application of rice straw in addition to urea at the common rates in each country.

LEE: Did you find differences in the ratio of gaseous $CO_2$ to dissolved carbonic acid during rice plant growth and did the ratio influence rice plant growth?

*NEUE:* There are different ratios of $CO_2$ and dissolved carbonic acids and this will influence the biochemistry of the soil. But we have no data in relation to plant growth.

# VOLATILE PRODUCTS AND LOW-MOLECULAR-WEIGHT PHENOLIC PRODUCTS OF THE ANAEROBIC DECOMPOSITION OF ORGANIC MATTER

K. Tsutsuki

The kinetics of volatile products, including volatile fatty acids, alcohols, aldehydes, ketones, volatile S compounds, and low molecular phenolic acids in submerged soils, is reviewed. Incubation of soils at high temperature reduces the accumulation of volatile fatty acids. The formation of alcohols, aldehydes, ketones, and volatile S compounds was minimal. The kinetics of volatile products in submerged soils was greatly affected by the amounts of easily decomposable organic matter and oxidizing substances such as ferric compounds in soils, and by temperature. Concentrations of phenolic acids in paddy soils are considered low enough to cause no injury even when organic materials are incorporated. However, a locally developed adverse environment around the fragment of decomposing plant residue should be taken into consideration in both the formation of volatile fatty acids and that of phenolic acids.

Although organic manures are assuming increasing importance in rice production, there is little information on the decomposition of organic matter in tropical rice soils. In wetland rice soils, organic matter usually undergoes anaerobic decomposition. Organic manures may cause, besides beneficial effects, adverse effects on crops because of their decomposition products, especially during anaerobic decomposition. Anaerobic decomposition includes anaerobic respiration and fermentation. Through fermentation, pyruvic acid, the key metabolite of carbohydrate metabolism, is transformed into an array of substances that include alcohols, diols, glycerol, aldehydes, ketones, volatile and nonvolatile organic acids, $CO_2$, $H_2$, $CH_4$, and $C_2H_2$ (Ponnamperuma 1972). Most of these products have been identified collectively in anaerobic soils. Some of them are toxic to plants and soil biota, depending on their concentrations. Most of these products are volatile or gaseous.

Besides fermentation products, phenolic substances are also considered potentially harmful substances in soils. Phenolic substances are very abundant in soils. Humic acid and fulvic acid can be regarded as high-molecular-weight phenolic acids because of their high contents of carboxylic and phenolic hydroxyl groups (Tsutsuki and Kuwatsuka 1978). Low-molecular-weight phenolic compounds are present in plant residues, cleaved or microbially formed from humic substances or lignin.

---

The International Rice Research Institute. P. O. Box 933, Manila, Philippines.

## VOLATILE FATTY ACIDS

### Kinetics

The formation of volatile fatty acids resulting from the decomposition of organic matter in soil has drawn the attention of researchers for a long time. Takaishi et al (1909) studied the formation of organic acids during the decomposition of organic manure in soils. Their work elucidated the formation of formic acid, acetic acid, butyric acid, and lactic acid during the decomposition processes of oil cake, rice bran, and compost. Acharya (1935a) incubated rice straw with soil and followed the decomposition under anaerobic conditions. He observed that the first phase of the decomposition was the rapid formation of organic acids, followed by the formation of $CH_4$. The decomposition products detected were acetic acid, butyric acid, $CO_2$, $CH_4$, and negligibly small amounts of $H_2$. In his further experiments, Acharya (1935b,c) studied the effects of temperature, pH, and aeration on the course of decomposition. Maximum decomposition of rice straw was observed at 30-35°C at pH 8. Outside this temperature range and above and below pH 8, accumulation of organic acids and retardation of gas formation were observed.

Takijima (1960) detected organic acids in paddy soils in the following order: acetic > butyric > formic > fumaric > propionic > valeric > succinic and lactic. Formation of branched fatty acids such as iso-butyric and iso-valeric acids in paddy soils was detected by Takeda and Furusaka (1975b). Formation of volatile and gaseous products in submerged soils is almost entirely due to facultative and obligate anaerobic bacteria. Pyruvic acid, the final product of glycolysis pathways, is converted to many kinds of organic compounds, depending on the kinds of bacteria and on the environmental conditions during fermentation (Ponnamperuma 1972). Takeda and Furusaka (1970) used anaerobic incubation processes to conduct extensive surveys of bacteria isolated from paddy soil. The number of strict anaerobes was always about 10% of the facultative anaerobes, and the strict anaerobes were mostly clostridia. Among the facultative anaerobes, Enterobacteriaceae predominated during nonsubmerged periods, and *Aeromonas* and coccoid bacteria predominated during flooding (Watanabe and Furusaka 1980).

Acetic acid, which is accumulated in the greatest amount among the organic acids in submerged soil, can be produced by both facultative and obligate anaerobes through many classes of carbohydrate fermentation. It is also a product of proteolytic clostridia (Doelle 1975). Pyruvate is usually transformed via acetyl-CoA and acetylphosphate to acetate. A pathway by which $CO_2$ is converted to acetic acid is also known in some species of clostridia. In the former pathway, one ATP is produced, but no NADH is consumed; in other words, no intermediate is working as an electron donor. Therefore, acetic acid formation is usually accompanied by the formation of other products by which NADH is consumed. Such examples are propionic acid fermentation by *Propionibacterium;* butyric acid fermentation by clostridia; and ethanol, lactate, and succinate formation by mixed acid producers among the Enterobacteriaceae (Doelle 1975). However, acetic acid surpasses other fermentation products in amount in submerged soils. As noted by Neue and Scharpenseel (1983), this may be attributed to the interspecies transfer of $H_2$ liberated from NADH using ferredoxin as an intermediate carrier.

Formic acid is produced concomitantly when acetyl-CoA is produced from pyruvic acid and Coenzyme A by facultative anaerobes belonging to the Enterobacteriaceae, but it is not produced by saccharolytic clostridia (Doelle 1975). Its formation keeps step with acetic acid, but the amount formed is very small (Gotoh and Onikura 1971, Yamane and Sato 1970) probably because formic acid is further decomposed to $H_2$ and $CO_2$, and the $CO_2$ is then used in the synthesis of other products like succinate and $CH_4$ (Doelle 1975).

Butyric acid and priopionic acid are usually produced concomitantly with acetic acid by saccharolytic clostridia and propionibacteria. Strains of ***Propionibacterium*** increased in a submerged soil after prolonged submergence (Watanabe and Furusaka 1980).

The very small amounts of branched fatty acids such as isobutyric and isovaleric acids in paddy soils are considered products of proteolytic clostridia (Takeda and Furusaka 1975a,b).

Volatile fatty acids are intermediate products that are transformed to $CO_2$ by oxidation while the reduction of $Fe^{+3}$ is going on in submerged soils (Kamura et al 1963). After the reduction of $Fe^{+3}$ ceases, the volatile fatty acids are used by methanogenic bacteria as substrates to produce $CH_4$. In methanogenesis in submerged soils, $CH_4$ is formed preferentially from the methyl group of acetic acid, and the formation of $CH_4$ from $CO_2$ is of less importance (Takai 1970).

In soils with a high content of active Fe, only small amounts of volatile fatty acids accumulate, while the contrary is true in soils with a low content of active Fe (Takai et al 1957). Asami and Takai (1963) also found that the formation of volatile fatty acids and $CH_4$ is repressed remarkably when amorphous $Fe(OH)_3$ is added to the soil and then submerged. There was a highly significant positive correlation between the amounts of $Fe^{+2}$ and $CO_2$ formed within the first 2 weeks of submergence. Moreover, when acetic acid was added to a well-reduced soil, a large amount of $CH_4$ was formed, but when acetic acid and amorphous $Fe(OH)_3$ were added together to the reduced soil, a large amount of $CO_2$ was formed instead of $CH_4$. From these results, Asami and Takai assumed the coupling of the oxidation of acetic acid and the reduction of Fe in submerged soils.

An increase in volatile fatty acid formation because of the addition of fresh organic matter has been reported in many papers, including those cited above (Chandrasekaran and Yoshida 1973, Gotoh and Onikura 1971, Lynch 1978, Yamane and Sato 1970, Rao and Mikkelsen 1977).

Temperature greatly affects the kinetics of volatile fatty acids (Yamane and Sato 1967, Cho and Ponnamperuma 1971). Higher temperature accelerates both production and destruction of volatile fatty acids. However, methanogenesis, which accompanies the destruction of acids, is much more accelerated than the production

**Table 1. Characteristics of soil samples.**

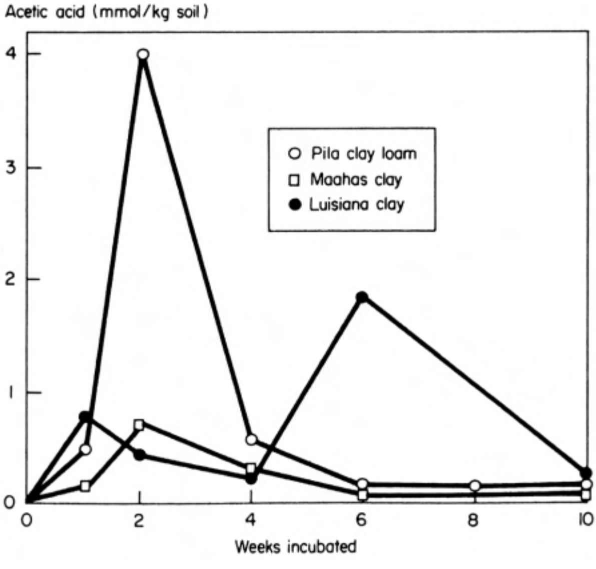
| Soil type | pH | C (%) | Total N (%) | Active Fe (%) |
|---|---|---|---|---|
| Pila clay loam | 7.2 | 2.48 | 0.204 | 0.32 |
| Maahas clay | 6.0 | 1.43 | 0.140 | 1.39 |
| Luisiana clay | 5.4 | 1.56 | 0.117 | 1.89 |

**Table 2. Analyses of organic materials.**

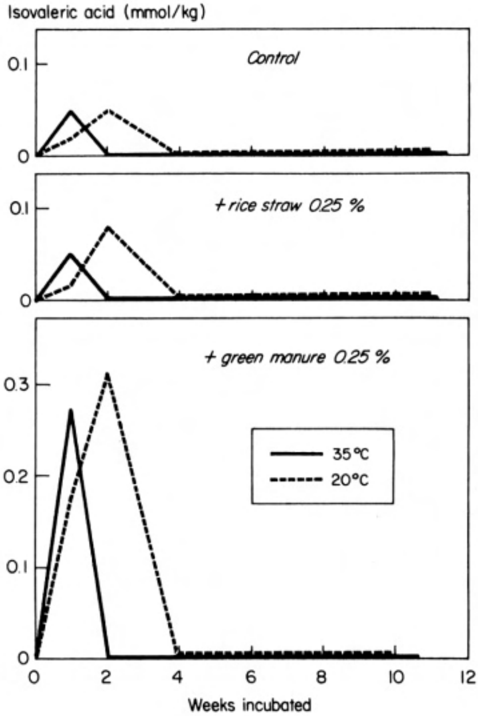
| Material | C (%) | Total N (%) | C:N |
|---|---|---|---|
| Rice straw | 39.6 | 0.56 | 70.5 |
| Rice straw compost | 14.2 | 1.69 | 8.4 |
| Green manure | 45.8 | 3.21 | 14.3 |

of acids at a temperature higher than 25° C (Yamane and Sato 1967). As a result, the accumulation of organic acids is diminished at higher temperatures.

The kinetics of volatile fatty acids was also studied using three soils (Table 1) treated with three kinds of organic materials (Table 2) and incubated anaerobically at 20° and 35° C (Tsutsuki and Ponnamperuma, unpublished). The kinetics of acetic acid in 3 submerged soils treated with rice straw (0.25%) at 20° C is shown in Figure 1. In Pila clay loam, a large amount of acetic acid accumulated within 2 weeks of submergence. A low active Fe content and large amounts of easily decomposable organic matter in the soil were assumed to be the cause of the large accumulation within such a short incubation period. In Maahas clay, organic acid accumulation was low at both temperatures, even when organic matter was added to the soil. A slight accumulation was seen after 2 weeks of submergence. Organic acid accumulation lasted longer in Luisiana clay than in the other soils. When rice straw or green manure was added to this soil at 20° C, acetic acid accumulation showed two peaks — at the first and at the sixth week of incubation. Luisiana clay is a heavy clay and contains a large amount of active Fe. The second peak implies that acetic acid could accumulate after most of the active $Fe^{+3}$ in the soil had been reduced. The acetic acid formed in the first week might have come from strictly anaerobic sites that developed locally in the soil.



**1.** Kinetics of acetic acid in 3 submerged soils treated with rice straw (0.25%) at 20°C.



**2.** Effect of organic matter on kinetics of isovaleric acid in submerged Pila clay loam at 20 and 35°C.

In Figure 2, the accumulations of isovaleric acid in Pila soil treated with rice straw and green manure (both 0.25%) are compared with controls at 20° and 35°C. Isovaleric acid accumulation was prominent when green manure was applied to the soil. Addition of rice straw slightly enhanced the accumulation of isovaleric acid. Pila clay loam produced a significantly larger amount of isovaleric acid than the other soils. The accumulation of isovaleric acid was earlier and lower at 35° C than at 20°C. Isovaleric acid is produced by clostridia utilizing amino acids as electron donors and acceptors (Takeda and Furusaka 1975a). Such a metabolism would become active where the content of other electron acceptors like $Fe^{+3}$ compounds is low and proteinous material is abundant. That is why isovaleric acid was produced in large amounts in Pila clay loam (low active Fe content) treated with green manure, which contains a substantial amount of N. Rice straw did not enhance the formation because of its low N content.

### Volatile fatty acid accumulation in fields

Studies on volatile fatty acid accumulation in arable lands have been closely connected with the evaluation of volatile fatty acids as factors in phytotoxicity. As the phytotoxicity of organic acids is discussed in another session, some field data that might be suggestive in solving this problem are cited below.

Yamane and Sato (1970) found that large amounts of acetic acid (13.5 mmol/ kg soil) and butyric acid (5.5 mmol/ kg soil) were produced when Italian ryegrass

(10.6 t/ha of shoot and 19.3 t/ha of root) was incorporated into rice fields. However, within 2-3 weeks after incorporation, volatile fatty acids almost disappeared.

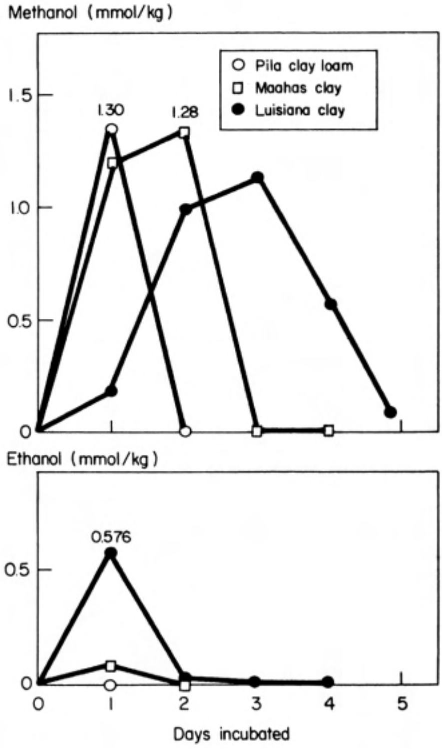
Gotoh and Onikura (1971) conducted a field experiment to examine whether organic acids accumulate to a toxic level in a rice field to which rice straw has been applied. They detected a maximum of 0.31 meq/kg acetic acid (0.91 mM in soil solution) 4 weeks after the incorporation of rice straw (15 t/ha). From the low concentration of volatile fatty acids detected, they concluded that the main factor governing plant growth in the early stages was probably N deficiency, with volatile fatty acids being a minor factor. In warm areas such as Kyushu, where the experiment was conducted, they assumed that volatile fatty acids derived from the decomposing rice straw would probably not cause injury to plants. Though toxicity is considered to be further alleviated in submerged rice soils because of the neutrality of soil pH, Chandrasekaran and Yoshida (1973) suggested that volatile fatty acids can inhibit the growth of rice plants even in a neutral soil because the pH around the rice root is much lower than the pH outside the rhizosphere.

An adverse environment developing in the vicinity of decomposing plant residue was found responsible for the poor establishment of direct-drilled winter oats associated with the presence of unburnt straw in the drill slits (Agricultural Research Council Letcombe Laboratory 1976). The same type of inhibition may occur if rice is direct seeded where applied rice straw or other organic matter has not decomposed well. The distribution of added organic matter in soil is heterogenous, and the concentrations of volatile fatty acids are highest and the pH values lowest at the site of decomposing organic debris itself. It was found that the acetic acid concentration declined exponentially with distance from the straw surface (Agricultural Research Council Letcombe Laboratory 1977).

## ALCOHOL FORMATION

Methanol, ethanol, n-propanol, and n-butanol were detected and quantified in soils treated with leaves of sugarcane and *Crotalaria juncia* by Wang et al (1967a). Isopropanol, iso-butanol, sec-butanol (Adamson et al 1975), and 2,3-butane-diol (Kubota and Furusaka 1981) were detected in soils treated with glucose and incubated anaerobically. Alcohols were found in both submerged and aerobic soils (Wang et al 1967a), but formation and decomposition of alcohols proceeded more slowly in aerobic soils than in submerged soils. Alcohols were not detected in soils that did not receive glucose or other carbonaceous amendments (Adamson et al 1975, Kubota and Furusaka 1981), and they were formed in significant amounts in submerged soils only when 1% green manure (*Glydicidia sepium*) was added; addition of rice straw did not favor the formation of alcohols in submerged soils (Tsutsuki and Ponnamperuma, unpublished).

The kinetics of alcohols in 3 soils at 35° C is shown in Figure 3. The formation of methanol in Pila clay loam, Maahas clay, and Luisiana clay attained a peak 1,2, and 3 days after submergence, respectively. The order in which peak concentrations were formed seems to reflect how easily each soil is reduced. In Pila clay loam, a reduced state developed rapidly because of the high content of easily decomposable organic matter and the low content of active $Fe^{+3}$, while it developed more slowly in Luisiana



**3.** Kinetics of alcohols in 3 submerged soils treated with green manure (1%) at 35° C.

clay because of the high content of active Fe. Formation of ethanol was observed only within 2 days of incubation in all those soils. The amount was largest in Luisiana clay, followed by Maahas clay and Pila clay loam in that order. Ethanol formation in Pila clay loam was insignificant at 35° C.

When the soils were incubated at 20° C, methanol and ethanol were formed more slowly, but accumulated in slightly larger amounts than at 35° C. At 20° C, methanol content attained a peak 2, 4, and 6 days after submergence in Pila clay loam, Maahas clay, and Luisiana clay, respectively. The accumulated amounts of methanol at the peaks were between 1.4 and 1.7 mmol/ kg soil. Ethanol content attained a peak after 1 day in Pila clay loam and Maahas clay, and after 4 days in Luisiana clay. The accumulated amounts were 0.8-1.1 mM, which were also slightly larger than those at 35°C.

Kinds and amounts of alcohols formed in soils vary with type of soil and with the kind of amended organic matter. Ethanol and butanol were formed in large amounts when glucose was added to soils (Adamson et al 1975, Kubota and Furusaka 1981). When leaves of sugarcane, *Crotalaria,* and *Glydicidia* were added to soils, methanol was formed in the largest amount, followed by ethanol. Butanol formation was favored in soils with higher organic C content or in those amended with *Crotalaria* (Wang et al 1967a).

According to Kubota and Furusaka (1981) methanol, ethanol, and butanol were detected only within the first few days of incubation. The same result was obtained by Tsutsuki and Ponnamperuma (unpublished). However, those alcohols were detected even after 4 or 8 weeks of incubation by Wang et al (1967a).

Kubota and Furusaka (1981) detected 2, 3-butane-diol and its percursor acetoin in submerged soils even without glucose, but addition of glucose enhanced and increased the production. They concluded that carbohydrates are metabolized through the 2, 3-butane-diol fermentation pathway as well as through volatile fatty acids under anaerobic soil conditions.

## ALDEHYDES AND KETONES

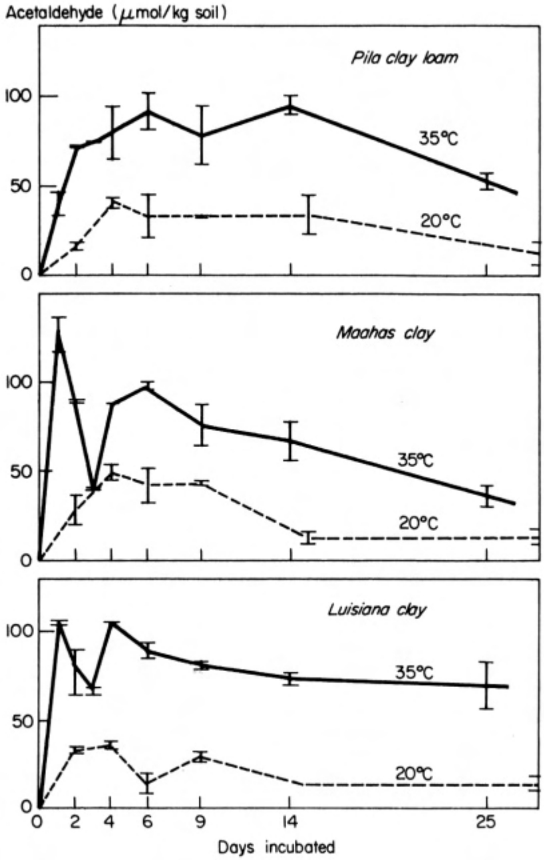
Aldehydes and ketones have been detected in soils under anaerobiosis of glucose (Adamson et al 1975). Acetaldehyde and butyraldehyde were formed in very small amounts representing about 0.01% of the added glucose, while acetone and methylethylketone were formed in larger amounts representing at most 0.4% of the added glucose. In an effort to identify reducing organic substances in the leachate from submerged rice soil, Okazaki et al (1981) detected formaldehyde, acetaldehyde, propionaldehyde, n-butyraldehyde, and n-valeraldehyde at concentrations of 0.03, 0.05, 0.04, 0.01, and 0.01 mmol/kg soil, respectively, from an excessively eluviated wetland rice soil. They considered that these aldehydes play important roles in the dissolution and removal of Fe and Mn from subsurface horizons of excessively eluviated wetland rice soils.

The kinetics of aldehydes was also studied by Tsutsuki and Ponnamperuma (unpublished) in submerged soils amended with green manure (1%) and incubated at 20° C and 35° C (Fig. 4). Formaldehyde, acetaldehyde, and propionaldehyde were detected. The major aldehyde was acetaldehyde, but the amount formed was very low — at most 0.1 mmol at 35° C or 0.05 mmol at 20° C. Because it is an unstable intermediate, the amount of acetaldehyde detected in soil should be regarded as the amount formed within a few days before analysis. The greater amount of acetaldehyde at 35° C than at 20° C may be explained by higher microbial activity at 35°C.

In Maahas clay and Luisiana clay, the formation of acetaldehyde showed two peaks, the first after 1 day and the second after 4-6 days of incubation. After the second peak was attained, acetaldehyde did not disappear rapidly like alcohols, but decreased gradually over 4 weeks. Several percursors are known for acetaldehyde in bacterial metabolism (Doelle 1975). In fermentation, pyruvate, acetyl-CoA, ethanol, and acetate are assumed to be important. Acetaldehyde formed in the first peak might have come from pyruvate, acetyl-CoA, or ethanol derived from the carbohydrates in green manure, and the acetaldehyde formed in the second peak might have come from acetic acid accumulated in the soil. The amounts of formaldehyde and propionaldehyde formed were much lower than the amount of acetaldehyde.

## VOLATILE SULFUR COMPOUNDS

In anaerobic media, the main changes involving S are the reduction of $SO_4^{2-}$ to sulfide and the dissimilation of the amino acids cystine and methionine to $H_2S$,



**4.** Kinetics of acetaldehyde in 3 submerged soils added with green manure (1%).

thiols, ammonia, and fatty acids (Ponnamperuma 1972). Methylmercaptan has been found in submerged soils (Takai and Asami 1962, Asami and Takai 1963, IRRI 1965). Mercaptans showed concentration peaks within 2 weeks of flooding and then declined (IRRI 1965). Higher temperature enhanced the disappearance of methylmercaptan (Asami and Takai 1963). The addition of green manure and stable manure enhanced the formation of methylmercaptan, while the addition of $Fe_2O_3$ interfered with the accumulation of methylmercaptan (Asami and Takai 1963).

Sensitive gas chromatographic techniques using a flame photometric detector enabled the analysis of trace amounts of volatile S gases (Banwart and Bremner 1974). Though the main change of S in anaerobic soils is the reduction of $SO_4^{2-}$ to sulfide, no trace of $H_2S$ was detected over submerged soils treated with $SO_4^{2-}$ or S-containing organic materials (Banwart and Bremner 1976a,b). However, a considerable amount of $H_2S$ was detected from animal manures decomposed without soil (Banwart and Bremner 1975). Not only gaseous $H_2S$ but also water-soluble $H_2S$ is almost chemically undetectable in submerged soils (IRRI 1965). This is due to their removal as insoluble sulfides, chiefly as FeS, and to their instability in the air phase (Ponnamperuma 1972).

According to Banwart and Bremner (1976a), S volatilized from unamended and $SO_4^{2-}$-treated soils, chiefly in the form of $CH_3SCH_3$ (55-100%), associated with small amounts of COS, $CS_2$, $CH_3SH$, and $CH_3SSCH_3$. The amended $So_4^{2-}$ was not transformed to volatile S compounds. More S volatilized under submerged soil conditions than under aerobic conditions. However, the amount of S volatilized from unamended and $SO_4^{2-}$-amended soils was very small (0-84 µg S/kg soil) and did not account for more than 0.05% of the total S in unamended soils.

The release of volatile S compounds from soils treated with S-containing organic materials was also studied by Banwart and Bremner (1976b). Most of the S volatilized from soils treated with sewage sludges was in the form of $CH_3SCH_3$ and $CH_3SSCH_3$, whereas most of the S volatilized from soils treated with animal manures and plant materials was in the form of $CH_3SH$ and $CH_3SCH_3$. Small amounts of COS and $CS_2$ were associated with these compounds. Submerged soil conditions and the addition of S-containing organic materials favored the formation of volatile S compounds. When the application rate of organic matter to the soils was 1%, amounts of S volatilized were 0.27 mg/kg for animal manure-treated soils, 0.38 mg/ kg for sewage sludge-treated soils, and 4.36 mg/kg for plant material-treated soils, on the average.

Minami et al (1981) also analyzed volatile S compounds evolved from rice soils treated with rice straw, compost, and cystine (Table 3). In the soil treated with rice straw, $H_2S$ was detected in the greatest amount among the S-containing products by shaking the flask immediately before analysis. Dimethyl sulfide ($CH_3SCH_3$) was the second most abundant S-containing product; $CH_3SH$, $CH_3SSCH_3$, COS, and $CS_2$ were formed in smaller amounts. The addition of compost did not increase the formation of volatile S compounds from soil as compared with the control.

## PHENOLIC ACIDS

As Takijima (1964) suggested, injury of the rice plant in peat soils or in soils amended with fresh organic matter cannot be explained only by volatile fatty acids; some other toxic substance may participate in the injury.

Aromatic organic acids have much higher toxicity than aliphatic acids. Phenolcarboxylic acids exhibited 50% inhibition of the growth of the roots of rice seedlings at concentrations of 0.6-3 mM (Takijima 1960b). Many researchers found the lowest

**Table 3. Sulfur-containing gases evolved from a submerged soil (*Nyuzen*) treated with organic materials (adapted from Minami et al 1981).**

| Compound | Amt (nmol/kg soil) | | | |
|---|---|---|---|---|
| | Control | Rice straw | Compost | Cystine |
| $H_2S$ | 0 | 1700 | 0 | 4720 |
| COS | 17 | 78 | 23 | 566 |
| $CS_2$ | 7 | 4 | 8 | 71 |
| $CH_3SH$ | 17 | 56 | 0 | 145 |
| $CH_3SCH_3$ | 129 | 483 | 129 | 113 |
| $CH_3SSCH_3$ | 53 | 54 | 0 | 74 |

concentrations of phenolic acids causing injury to various plants to range between 0.1 and 0.01 mM (Takijima 1963).

Walters (1917) may have been the first researcher to recognize phenolic acids as the cause of a soil-borne plant disease. He found 22 ppm of p-hydroxybenzoic acid and 1.7 ppm of benzoic acid in the soil from an orange orchard that was badly affected with the citrus disease commonly known as “die back.” Later, Winter (1955) studied the occurrence of toxic substances in stubbles to elucidate the cause of poor growth of successively grown crops. His co-worker Borner (1955, 1956) detected p-hydroxybenzoic acid, p-coumaric acid, and ferulic acid in the straw and stubble of rye, wheat, and barley. The quantitative determination of phenolic acids in soils was accomplished by Whitehead (1964), who found p-hydroxybenzoic acid, vanillic acid, p-coumaric acid, and ferulic acid in 4 soils, each at a concentration lower than 0.05 mM, Phenolic acids have been assumed to be growth inhibitors for dryland crops (Wang et al 1967b), the phytotoxic substances associated with the decomposition of plant residues in anaerobic soil (Patrick 1971), and the cause of phytotoxic effects of decomposing rice residues in soil (Chou and Lin 1976).

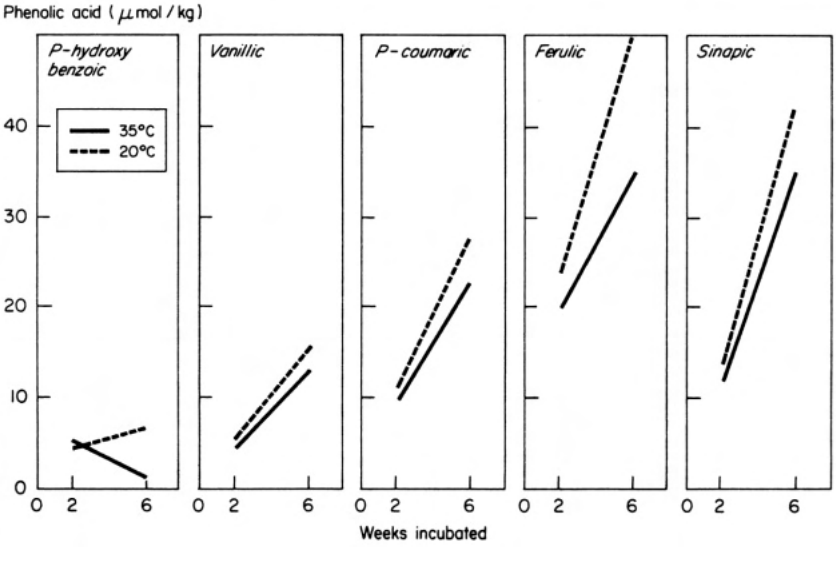
Kuwatsuka and Shindo (1973) determined phenolic acids extractable with a methanol-0.1 *N* NaOH mixture from both fresh rice straw and decomposing rice straw to be p-coumaric, ferulic, p-hydroxybenzoic, and vanillic acids and trace amounts of salicylic, syringic, protocatechunic, ß-resorcylic, caffeic, sinapic, gallic, and gentisic acids. From the results of incubating rice straw at different temperatures under moist and flooded conditions, Shindo and Kuwatsuka (1975a) assumed that phenolic acids, which initially existed in rice straw, were rapidly degraded in the early stages of incubation and subsequently produced again from the lignin component. The pathways from p-coumaric acid to p-hydroxybenzoic acid and from ferulic acid to vanillic acid were deduced from the changes in amounts of these phenolic acids. To alleviate their toxic effects, p-coumaric acid and ferulic acid were also temporarily methylated by soil microbes (Shindo and Kuwatsuka 1975b) and gradually transformed to p-hydroxybenzoic acid and vanillic acid. These latter acids are further transformed via protocatechuic acid to humic substances by polymerization or to aliphatic acids by ring cleavage.

When rice straw was mixed with soil and incubated under moist and flooded conditions, phenolic acids due to rice straw decreased gradually with time. It took nearly 30 days for the amounts of p-coumaric and ferulic acids to decrease to half of their initial levels when the rate of rice straw to soil was 8% (Shindo and Kuwatsuka 1977). After 6-10 weeks of incubation, decreasing curves of p-coumaric and ferulic acids showed shoulders, indicating the formation of these acids in the soil. Phenolic acids decreased more rapidly under moist conditions than under flooded conditions.

Shindo and Kuwatsuka (1978) determined the concentrations of phenolic acids in 9 rice soils in Japan as 10-26 ppm (average 21 ppm); the levels were not affected by rice straw incorporated after the preceding cropping season. It seems that phenolic acids at those levels in rice soils do not affect the growth of either the root on the whole rice plant. Shindo and Kuwatsuka (1976) ascribed the low concentration of phenolic acids in rice soils to leaching. Leaching of phenolic acids in soil profiles is also obvious in the data of Wang et al (1967b).

The kinetics of phenolic acids was investigated by Tsutsuki and Ponnamperuma (unpublished) in 3 submerged soils treated with 0.25% rice straw, rice straw compost, or green manure at 2 temperatures (20° and 35° C). The largest concentrations of phenolic acids ranged between 13.6 µmol/kg soil for p-hydroxybenzoic acid and 74.2 µmol/kg soil for ferulic acid when rice straw was applied. Addition of 0.25% green manure or compost affected the concentration of phenolic acids in soils only a little. Changes in the concentrations of phenolic acids in Luisiana clay after 2 and 6 weeks of submergence at 20° and 35° C are shown in Figure 5. After 2 weeks of anaerobic incubation, the concentration of each phenolic acid was always higher at 20° C. However, the difference due to the incubation temperature was small at this time. The concentration of p-hydroxybenzoic acid increased after 6 weeks of incubation at 20°C, while it decreased with time at 35° C. At 35° C, degradation of p-hydroxybenzoic acid may have been faster than its formation. Concentrations of the other phenolic acids such as vanillic, p-coumaric, ferulic, and sinapic acids increased with increased period of incubation at both temperatures. In Luisiana clay, concentrations of phenolic acids were higher at 20° than at 35° C after 2 and 6 weeks of incubation. However, in Pila clay loam and Maahas clay the concentrations of phenolic acids were higher at 35° after 6 weeks of incubation. Higher temperature might have favored the formation of phenolic acids from rice straw.

The discussions that consider phenolic acids as plant growth inhibitors in soils are usually based upon the concentration of phenolic acids determined by alkaline extraction, and the amounts of water-soluble phenolic acids are very low. The amounts of water-soluble phenolic acids in the soil under permanent pasture at pH 5.8 were equivalent to concentrations in the soil solution ranging from 1.4 µM for p-hydroxybenzoic acid to <10 nM for ferulic acid (Whitehead et al 1981). Amounts up to 2,000 times greater than these were extracted by 2 M NaOH. Kaminsky and Muller (1978) recommend against the use of alkaline soil extraction in the study of



**5.** Kinetics of phenolic acids in submerged Luisiana clay treated with rice straw (0.25%).

allelopathy, because the use of an alkaline extractant results in the chemical modification of the compound under study, and the compounds that are not solubilized by neutral extractants may not be available to plants. However, localized concentrations of phenolic acids close to fragments of decomposing plant material might be sufficiently high to have some effect. Moreover, Rice (1979) considers that some compounds may influence plant growth at concentrations at which they are completely adsorbed by soil particles and are not extractable with water.

## REFERENCES CITED

Acharya, C. N. 1935a. Studies on the anaerobic decomposition of plant materials. I. The anaerobic decomposition of rice straw (*Oryza sativa*). Biochem. J. 29:528-541.

Acharya, C. N. 1935b. Studies on the anaerobic decomposition of plant materials. II. Some factors influencing the anaerobic decomposition of rice straw. Biochem. J. 29:953-960.

Acharya, C. N. 1935c. Studies on the anaerobic decomposition of plant materials. III. Comparison of the course of decomposition under anaerobic, aerobic, and partially aerobic conditions. Biochem. J. 29:1116-1120.

Adamson, J. A., A. J. Francis, J. M. Duxbury, and M. Alexander. 1975. Formation of volatile organic products in soil under anaerobiosis. I. Metabolism of glucose. Soil Biol. Biochem. 7:45-50.

Agricultural Research Council Letcombe Laboratory. 1976. Annual report for 1975. Wantage, UK. pp. 29-31.

Agricultural Research Council Letcombe Laboratory. 1977. Annual report for 1976. Wantage, UK. 107 p.

Asami, T., and Y. Takai. 1963. Formation of methyl mercaptan in paddy soils (II). Soil Sci. Plant Nutr. 9:65-69.

Banwart, W. L., and J. M. Bremner. 1974. Gas chromatographic identification of sulphur gases in soil atmospheres. Soil Biol. Biochem. 6:113-115.

Banwart, W. L., and J. M. Bremner. 1975. Identification of sulfur gases evolved from animal manures. J. Environ. Qual. 4:363-366.

Banwart, W. L., and J. M. Bremner. 1976a. Volatilization of sulfur from unamended and sulfate treated soils. Soil Biol. Biochem. 8:19-22.

Banwart, W. L., and J. M. Bremner. 1976b. Evolution of volatile compounds from soils treated with sulfur containing organic materials. Soil Biol. Biochem. 8:439-443.

Borner, H. 1955. Phenolic compounds from straw and stubble of wheat, barley, and rye [in German]. Naturwissenshaften 42:583-584.

Borner, H. 1956. Paperchromatographic identification of ferulic acid in the water extracts of straw and stubble of wheat, barley, and rye [inGerman]. Naturwissenshaften 43:129-130.

Chandrasekaran, S., and T. Yoshida. 1973. Effect of organic acid transformations in submerged soils on growth of the rice plant. Soil Sci. Plant Nutr. 19:39-45.

Cho, D. Y., and F. N. Ponnamperuma. 1971. Influence of soil temperature on the chemical kinetics of flooded soils and the growth of rice. Soil Sci. 112:184-194.

Chou, C. H., and H. J. Lin. 1976. Autointoxication mechanism of *Oryza sativa.* I. Phytotoxic effects of decomposing rice residues in soils. J. Chem. Ecol. 2:353-367.

Doelle, H. W. 1975. Bacterial metabolism. 2nd ed. Academic Press, New York. 738 p.

Gotoh, S., and Y. Onikura. 1971. Organic acids in flooded soil receiving added rice straw and their effect on the growth of rice. Soil Sci. Plant Nutr. 17:1-8.

International Rice Research Institute. 1965. Annual report for 1964. Los Baños, Philippines. 357 p.

Kaminsky, R., and W. H. Muller. 1978. A recommendation against the use of alkaline soil extractions in the study of allelopathy. Plant Soil 49:641-645.

Kamura, T., Y. Takai, and K. Ishikawa. 1963. Microbial reduction mechanisms of ferric iron in paddy soils (Part I). J. Sci. Soil Manure, Jpn. 32:135-138.

Kubota, M., and C. Furusaka. 1981. Formation of 2,3-butane-diol, acetoin, ethanol, and butanol in paddy soils [in Japanese]. J. Sci. Soil Manure, Jpn. 52:149-154.

Kuwatsuka, S., and H. Shindo. 1973. Behavior of phenolic substances in the decaying process of plants. I. Identification and quantitative determination of phenolic acids in rice straw and its decayed product by gas chromatography. Soil Sci. Plant Nutr. 19:219-227.

Lynch, J. M. 1978. Production and phytotoxicity of acetic acid in anaerobic soils containing plant residues. Soil Biol. Biochem. 10:131-135.

Minami, K., K. Okayama, and S. Fukushi. 1981. Volatile sulfur compounds evolved from paddy soils treated with organic materials [in Japanese]. J. Sci. Soil Manure, Jpn. 52:375-379.

Neue, H. U., and H. W. Scharpenseel. 1983. Gaseous products of the decomposition of organic matter in submerged soils. Pages 315-332 *in* International Rice Research Institute. Organic matter and rice. Los Baños, Laguna, Philippines.

Okazaki, M., H. Wada, and Y. Takai. 1981. Reducing organic substances responsible for removal of Fe (III) and Mn (IV) from subsurface horizon of lowland rice soil. Pages 235-250 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, China.

Patrick, Z. A. 1971. Phytotoxic substances associated with the decomposition in soil of plant residues. Soil Sci. 111:13-18.

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Rao, D. N., and D. S. Mikkelsen. 1977. Effect of rice straw additions on production of organic acids in a flooded soil. Plant Soil 47:303-311.

Rice, E. L. 1979. Allelopathy — an update. Bot. Rev. 45:15-109.

Shindo, H., and S. Kuwatsuka. 1975a. Behavior or phenolic substances in the decaying process of plants. I. Changes of phenolic substances in the decaying process of rice straw under various conditions. Soil Sci. Plant Nutr. 21:215-225.

Shindo, H., and S. Kuwatsuka. 1975b. Behavior of phenolic substances in the decaying process of plants. III. Degradation pathway of phenolic acids. Soil Sci. Plant Nutr. 21:227-238.

Shindo, H., and S. Kuwatsuka. 1976. Behavior of phenolic substances in the decaying process of plants. IV. Adsorption and movement of phenolic acids in soils. Soil Sci. Plant Nutr. 22:23-33.

Shindo, H., and S. Kuwatsuka. 1977. Behavior of phenolic substances in the decaying process of plants. VI. Changes in quality and quantity of phenolic substances in the decaying process of rice straw in a soil. Soil Sci. Plant Nutr. 23:319-332.

Shindo, H., and S. Kuwatsuka. 1978. Behavior of phenolic substances in the decaying process of plants. IX. Distribution of phenolic acids in soils of paddy fields and forests. Soil Sci. Plant Nutr. 24:233-243.

Takai, Y. 1970. The mechanism of methane fermentation in flooded paddy soil. Soil Sci. Plant Nutr. 16:238-244.

Takai, Y., T. Koyama, and T. Kamura. 1957. Microbial metabolism of paddy soils. Part III. Effect of iron and organic matter on the reduction process (I). J. Agric. Chem. Soc. Jpn. 31:211-215.

Takai, Y., and T. Asami. 1962. Formation of methyl mercaptan in paddy soils I. Soil Sci. Plant Nutr, 8: 132-136.

Takaishi, S., K. Tasaki, and M. Imai. 1909. Formation of organic acids during the decomposition of organic manures [part I, in Japanese]. Nougaku-kai-hou 89:3-8.

Takeda, K., and C. Furusaka. 1970. Studies on the bacteria isolated anaerobically from paddy field soil. Rep. Inst. Agric. Res. Tohoku Univ. 21:l-22.

Takeda, K., and C. Furusaka. 1975a. Studies on the bacteria isolated anaerobically from paddy field soil. III, Production of fatty acids and ammonia by *Clostridium* species. Soil Sci. Plant Nutr. 21:119-127.

Takeda, K., and C. Furusaka. 1975b. Studies on the bacteria isolated anaerobically from paddy field soil. IV. Model experiments on the production of branched fatty acids. Soil Sci. Plant Nutr. 21:119-127.

Takijima, Y. 1960. Metabolism of organic acids in soils and their harmful effects on paddy rice growth (part I). Column chromatography of organic acids using home-made silica gel and its application to soil samples [in Japanese]. J. Sci. Soil Manure, Jpn. 31:435-440.

Takijima, Y. 1963. Studies on behavior of the growth inhibiting substances in paddy soils with special reference to the occurrence of root damage in the peaty paddy fields [in Japanese, English summary]. Bull. Nat. Inst. Agric. Sci. Jpn. Ser. B. 13:117-252.

Takijima, Y. 1964. Studies on organic acids in paddy field soils with reference to their inhibitory effects on the growth of rice plants: 2. Soil Sci. Plant Nutr. 10:212-219.

Tsutsuki, K., and S. Kuwatsuka. 1978. Chemical studies on soil humic acids. II. Composition of oxygen containing functional groups of humic acids. Soil Sci. Plant Nutr. 24:547-560.

Walters, E. H. 1917. The isolation of p-hydroxybenzoic acid from soil. Am. Chem. Soc. J. 39:1178-1784.

Wang, T. S. C., T. K. Yang, and T. T. Chuan. 1967a. Soil alcohols, their dynamics and their effect upon plant growth. Soil Sci. 104:40-45.

Wang, T. S. C., T. K. Yang, and T. Chung. 1967b. Soil phenolic acids as plant growth inhibitors. Soil Sci. 103:239-246.

Watanabe, I., and C. Furusaka. 1980. Microbial ecology of flooded rice soils. Pages 125-168 *in* M. Alexander, ed. Advances in microbial ecology, Vol. 4.

Whitehead, D. C. 1964. Identification of p-hydroxybenzoic, vanillic, p-coumaric and ferulic acids in soils. Nature. (London) 202:417-418.

Whitehead, D. C., H. Dibb, and R. D. Hartley. 1981. Extractant pH and the release of phenolic compounds from soils, plant roots and leaf litter. Soil Biol. Biochem. 13:343-348.

Winter, A. G. 1955. Occurrence and significance of antimicrobial and antiphytotic substances in natural soils [in German]. Zeits. Pflanzenernah, Dung, Bodenk. 69:224-233.

Yamane, I., and K. Sato. 1967. Effect of temperature on the decomposition of organic substances in flooded soil. Soil Sci. Plant Nutr. 13:94-100.

Yamane, I., and K. Sato. 1970. Plant and soil in a lowland rice field added with forage residues. Rep. Inst. Agric. Res. Tahoku Univ. 21:79-101.

# NONVOLATILE RESIDUES IN THE ANAEROBIC DECOMPOSITION OF ORGANIC MATTER

Hidenori Wada

Debris of various organisms added to wetland rice fields decomposes and is gradually converted into organic matter. Phototropes, which live in floodwaters and at the soil surface, absorb nutrients. Some of them fix N. The uppermost layer of the Apg horizon is enriched with debris of the phototropes. Debris of phototropes and other organisms, rice stubble, weeds, and manure are plowed into the Apg horizon.

In principle, transformation of the organic debris in the wetland rice field is similar to that in the dryland field. However, since the Apg horizon of the rice field is kept in a reduced condition, some components of the organic debris resist microbial attack and remain in the soil for long periods and some other components become susceptible to microbial attack. Accordingly, the Apg horizon of rice fields contains large amounts of organic debris of varying sizes, chlorophyll-type compounds, and small amounts of organic phosphates. Aggregates are formed on the framework of the plant debris. Properties and decomposition processes of plant debris can be measured after fractionating the debris from the soil. Furthermore, new techniques now help find detailed information about the decomposition processes and/or microbial activities in and around the organic debris.

Debris of various organisms can be incorporated either intentionally or naturally into wetland rice fields. It decomposes and gradually converts into organic matter. These processes and their products in wetland rice fields are somewhat different from those in dryland fields and contribute to building up the characteristics of the wetland rice soil.

## PHOTOTROPES AND SURFACE-PLACEMENT OF RICE STRAW

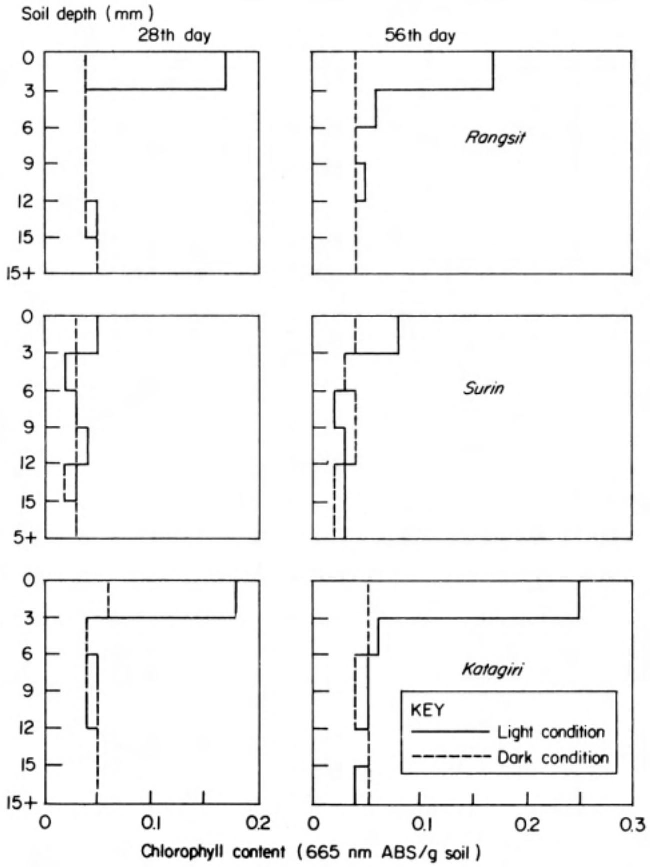
Green algae, diatoms, and floating weeds growing in floodwater and at the soil surface absorb $NH_4^+$, $NO_3^-$, and $H_2PO_4^-$, which otherwise might be lost by denitrification or runoff, or both. After death, their debris is accumulated at the uppermost layer of the Apg horizon, enriching this layer with readily decomposable

---

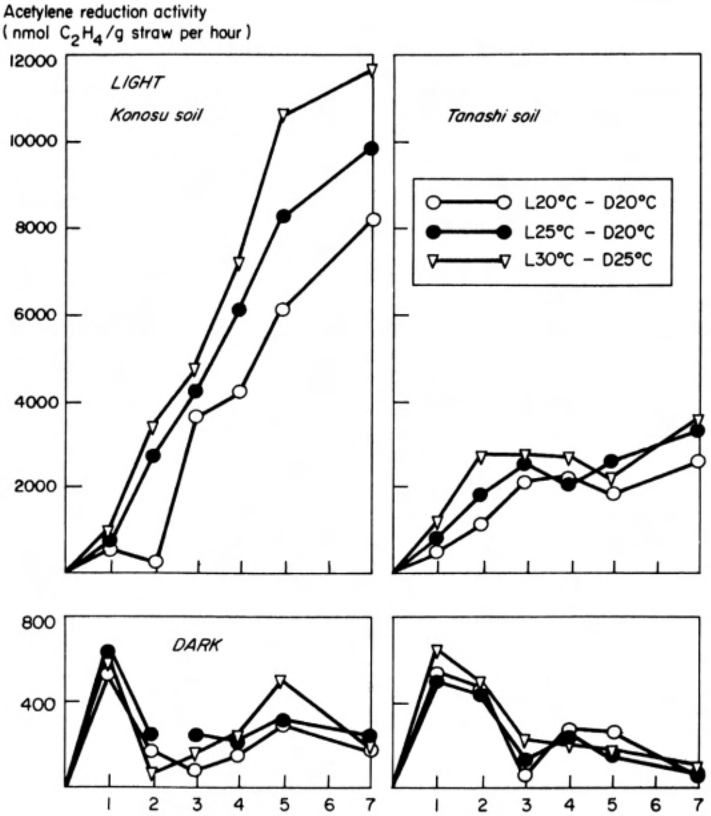
Department of Agricultural Chemistry, Faculty of Agriculture, The University of Tokyo, Yayoi 1–1–1, Bunkyo-ku, Tokyo, Japan.

organic matter rich in N, P, and chlorophyll-type compounds (Chairoj et al 1982, Fig. 1). This rather rapid but small-scale internal cycle of the bioelements is important for maintaining fertility of rice field soils. This may be especially true in tropical regions, where most soils are poor in organic matter and available phosphate and have low absorbing capacity for $NH_4^+$.

The N-fixing activity of phototropes such as blue-green algae and photosynthetic bacteria is usually not high in floodwater or at the surface layer of the Apg horizon. But it was found that growth and N-fixing activity of the phototropes could be enhanced by a new technique (Yoo 1982) involving the placement of rice straw on the surface of the submerged soil. The rice straw furnishes suitable sites for these N-fixing microorganisms and shows very high N-fixing activity during the entire period of submergence in the field as well as in the laboratory. Acetylene reduction activity of the straw, which is fully colonized by the N-fixing microorganisms, is comparable with that of *Rhizobium* in the root nodule of the soybean, that is, about 10,000 nmol/g per hour (Fig. 2).



**1.** Effect of tight incidence on content of chlorophyll-type compounds (Chairoj et al 1982).



**2.** Dependence of $N_2$-fixing activity of surface-placed rice straw on temperature of incubation under submerged condition (Yoo 1982). Konosu soil = alluvial soil, Tanashi soil = volcanic ash soil.

Controlling factors favoring this process are 1) high content of carbohydrates in rice straw, 2) high light intensity, 3) high temperature, 4) abundant supply of phosphate ions, 5) soil pH higher than 5.5, and 6) high population of the phototrophic N-fixing microorganisms. Application of chemical fertilizers and pesticides may not seriously inhibit the growth and N-fixing activity of the phototropes.

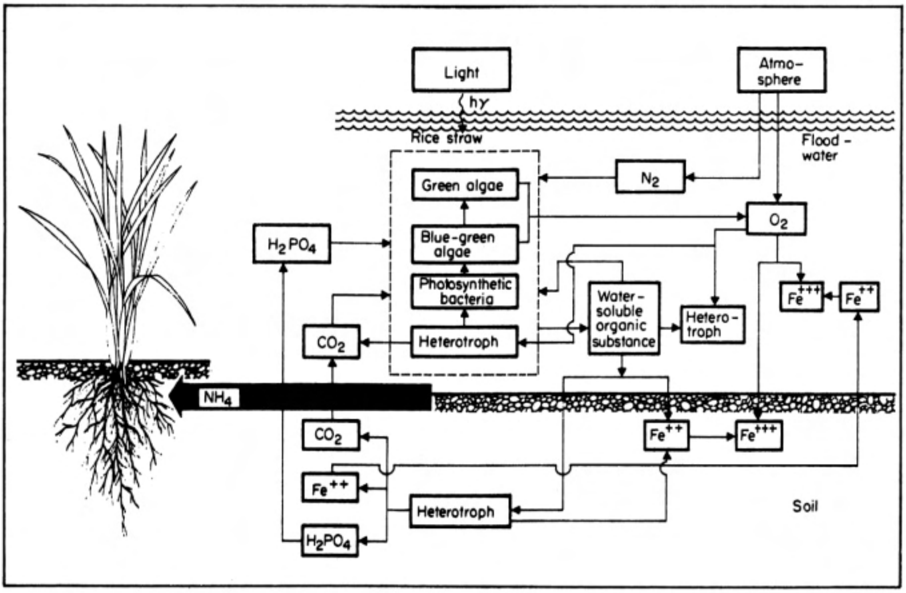
When rice straw is placed on the soil surface, it is vigorously attacked by heterotrophic microorganisms and becomes anaerobic even in oxidative floodwater. Photosynthetic bacteria, which prefer anaerobic conditions, can flourish in the reduced rice straw, utilizing $CO_2$ and organic acids accumulated in the rice straw while receiving sunlight. Several weeks after placement, the rice straw becomes very red because of the luxurious growth of the red-colored photosynthetic bacteria. Debris of these microorganisms may also be decomposed in the rice straw and may keep the rice straw under reduced conditions for a long period, resulting in predominance of the photosynthetic bacteria.

If conditions are favorable, blue-green algae can grow on the rice straw and succeed the photosynthetic bacteria; the latter are suppressed by the $O_2$ that is excreted by the former. Nitrogen-fixing activity of the rice straw is increased further by this alternation of the microorganisms. This succession can be followed easily in the laboratory, but not in the field, presumably because mollusks devour the blue-green algae. The photosynthetic bacteria living in the rice straw may escape the mollusks. Sometimes the blue-green algae are succeeded by green algae and the N-fixing activity of the rice straw declines accordingly.

In addition, the rice straw placed on the soil surface influences the processes that are going on in the submerged soil. Development of an oxidized layer is suppressed by the surface-placed rice straw. Phosphate ions solubilized in the reduced part of the Apg horizon are transferred to the floodwater and are utilized by the microorganisms living in the rice straw. Denitrification may also be inhibited by the surface-placed rice straw. The various effects of the surface placement of rice straw on the "rice-soil-water" system are schematically illustrated in Figure 3.

Since the rice straw is placed on the soil surface, growth of the rice plant is not limited by N starvation or strong reduction of the soil. Such adverse effects on the rice plant are commonly encountered when the rice straw is incorporated in the submerged soil. Actually, growth and yield of the rice plant appear to be increased by the surface placement of rice straw, probably because the supply of N is increased by enhanced N-fixation and supressed denitrification.

Some experimental results suggest that inoculation of rice straw with phototrophic N-fixing microorganisms is helpful for the growth and N-fixing activity of the phototropes on the surface-placed rice straw and the growth and yield of rice plants.



**3.** Effects of surface-placed rice straw on nitrogen economy in the submerged paddy field (Yoo 1982).

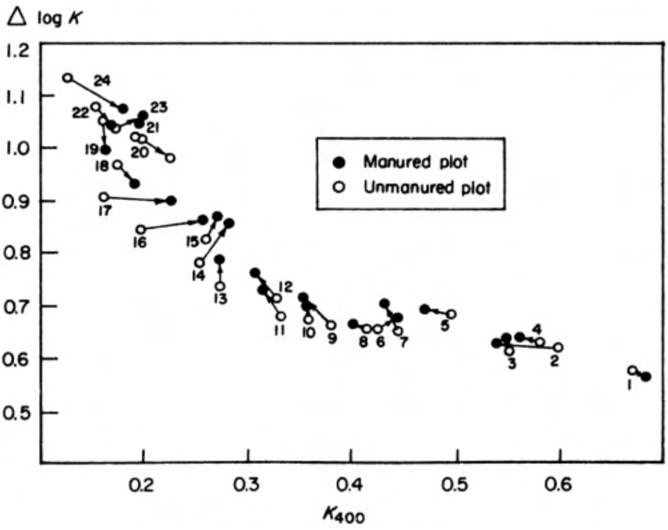
## EFFECTS OF MANURING ON SOIL ORGANIC MATTER

Since ancient times, manuring has been considered one of the most important techniques to increase and maintain soil fertility. Wada (1963) searched for the effects of manuring on soil organic matter by comparing several soil properties between manured plots and unmanured plots at many agricultural experiment stations located throughout Japan. The experiment confirmed that the application of manure increased soil organic matter content and at the same time modified properties of the soil organic matter to varying degrees at different sites. Detailed examination of the data revealed certain regularities in the effects of manuring on organic matter in soil.

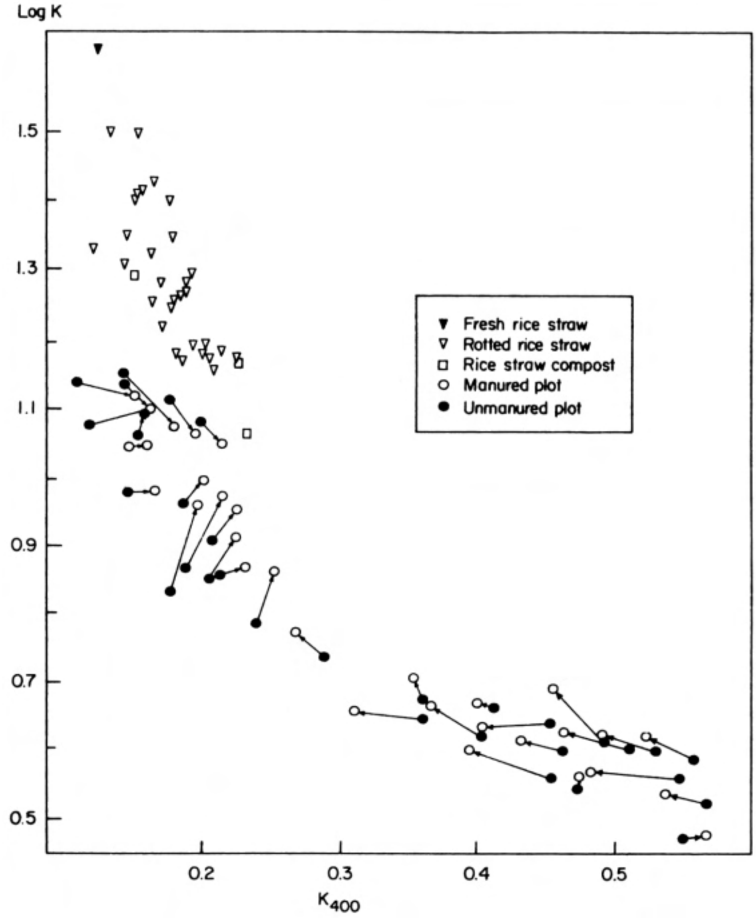
For example, change in the humification degree of NaF-soluble organic matter by manuring is shown in Figure 4; $\Delta$log K and $K_{400}$ are the indices of the humification degree of the organic matter, where $\Delta$log K is the difference between log $K_{400}$ and log $K_{600}$, and $K_{400}$ and $K_{600}$ are the optical densities of the NaF-soluble organic matter at 400 nm and 600 nm, respectively. Change in the humification degree by manuring at each experiment station is represented by a vector from an unmanured plot to a manured plot in Figure 4. Note that almost all the vectors point to a common small region. Similar results were obtained for NaOH-soluble organic matter (Fig. 5).

These regularities supplied a promising clue to solving the complex problem, and a hypothesis was proposed:

- Manuring does not change the amount and the properties of the "native organic matter" of a soil, but adds extra organic matter to it. The main features of this extra organic matter are the same in any soil, and it is similar to the organic



**4.** Change in the humification degree of NaF-soluble organic matter due to manuring at 24 agricultural experimental stations (Wada 1963). The numbers represent station numbers.



**5.** Change in the humification degree of NaOH-soluble organic matter due to manuring at 24 agricultural experimental stations and decomposition process of rice straw with respect to humification degree (Wada 1963).

matter of well-rotted manure (straw compost in this experiment). It is qualified to be called "relatively stable organic matter."

- The extra organic matter consists of plant debris, water-soluble organic matter that is adsorbed by soil particles, and tiny fractions rich in microorganisms. Among these components, plant debris exceeds the other two.

This hypothesis was verified by many experiments. Some of the results supporting the hypothesis are summarized:

- The soil of manured plots always contained larger amounts of plant debris than the soil of unmanured plots. The amount of plant debris increased with the amount of manure applied. Components of the plant debris separated from the manured plots at different experiment stations were similar to each other and to plant debris of well-rotted straw compost.

- Water-soluble organic matter of the well-rotted straw compost was adsorbed by soil particles. The adsorbed water-soluble organic matter was not readily decomposed by soil microorganisms and was desorbed with NaF-solution with almost no alteration, even after several weeks of incubation of submerged soil.
- When the decomposition process of rice straw during composting was followed by the change in the humification degree of NaOH-soluble organic matter, it approached a small region in the $\Delta\log K\text{-}K_{400}$ diagram (Fig. 5). This small region coincided with the small region to which all the vectors were directed, representing change in the humification degree of NaOH-soluble organic matter due to manuring.
- $\Delta$CEC/$\Delta$C was constant regardless of soil type. $\Delta$CEC is the increase in CEC (meq/ 100 g soil) due to manuring and $\Delta$C is the increase in organic C (g/100 g soil) due to manuring. The $\Delta$CEC/$\Delta$C had the same value as the CEC/C of the plant debris which was separated from both the soil of the manured plot and the well-rotted straw compost. CEC/C is the CEC expressed by milliequivalents per gram of organic C.

The hypothesis can also clarify the decomposition process of organic debris in rice field soil. The process can be divided into two stages. The first stage starts with the fresh plant debris and ends in “relatively stable organic matter,” which is similar to that in well rotted straw compost. The decomposition process in the first stage is more or less the same in every soil type and continues for more than a year. The second stage starts with the “relatively stable organic matter” and ends in “more stable organic matter,” which is characteristic of each soil type. Management of a soil affects the decomposition process and its products in the first stage, but there is no effect in the second stage.

Recent investigations (Wada et al 1981) of the effects of manuring on the relationship between the amount of easily decomposed organic N *(y)* and the amount of total organic N *(x)* support this consideration (Fig. 6). The amount of easily decomposed organic N was estimated by incubating the air-dried soil sample under submerged conditions at 30° C for 4 weeks. The relationship can be expressed by the formula:

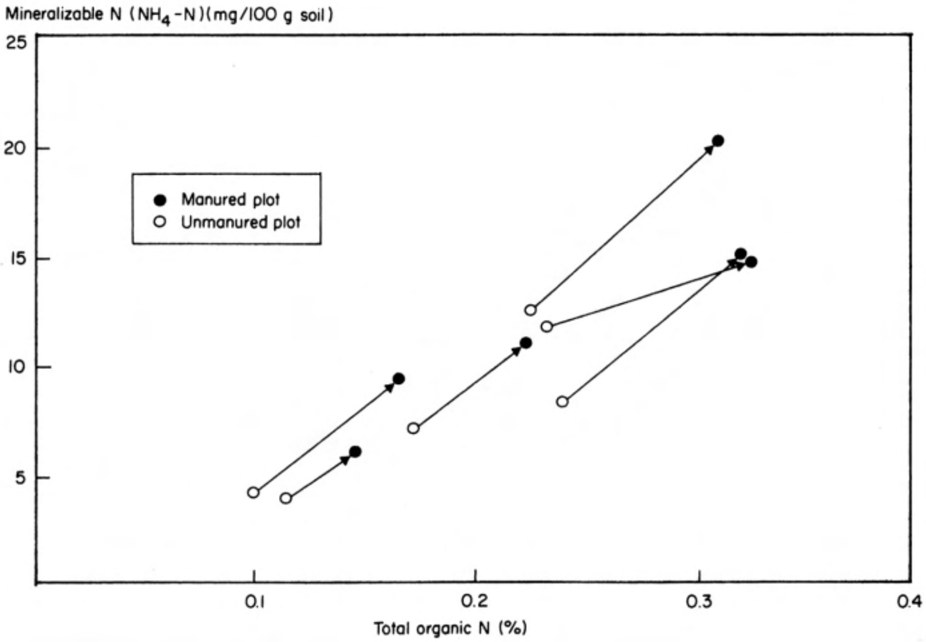
$$y = k(x - a)$$

In this expression, $k$ and $a$ are constants; $k$ is common to all soil types examined and $a$ is characteristic of each soil type. This formula can be modified to show the relationship between the change in the amount of easily decomposed N ($\Delta y$) and the change in the amount of total organic N ($\Delta x$):

$$\Delta y = k\Delta x$$

This formula shows that, in any kind of soil, the same proportion of the extra organic matter is easily decomposed. This is natural if the extra organic matter is the same in nature for any soil.

According to the first formula, $(x-a)$ is the amount of soil organic N that is susceptible and $(a)$ is the amount not susceptible to soil management. The former is the decomposition product in the first stage and the latter the decomposition



**6.** Changes in total organic nitrogen and mineralizable nitrogen due to manuring (Wada et al 1981).

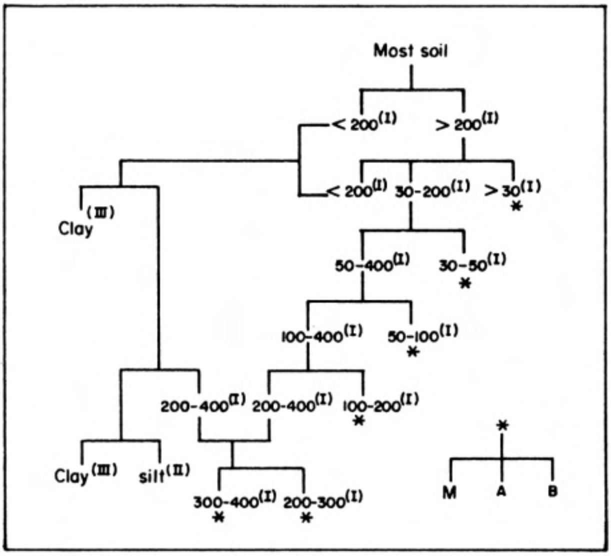
product in the second stage. Figure 6 also shows an improvement in the correlation between the amounts of total organic N and mineralizable N by taking the above-mentioned formula into consideration.

## FEATURES OF ORGANIC DEBRIS IN THE SOIL

Since a considerable part of soil organic matter exists in the form of organic debris, experiments were conducted to obtain more information. Development of a method to separate organic debris was a prerequisite. One method (Wada and Kanazawa 1970) was found especially useful in separating intact plant debris of varying sizes (Fig. 7). This method is based on the fact that, if the particle sizes are the same, organic debris can be separated easily from mineral particles because the former settles much slower in water than the latter.

The separated organic debris was measured for total amount, contents of C and N, chemical composition, humic substances, population and activities of micro-organisms, and micromorphology. The following results were obtained in a series of experiments (Wada 1972, Wada et al 1979, Kanazawa and Takai 1980):

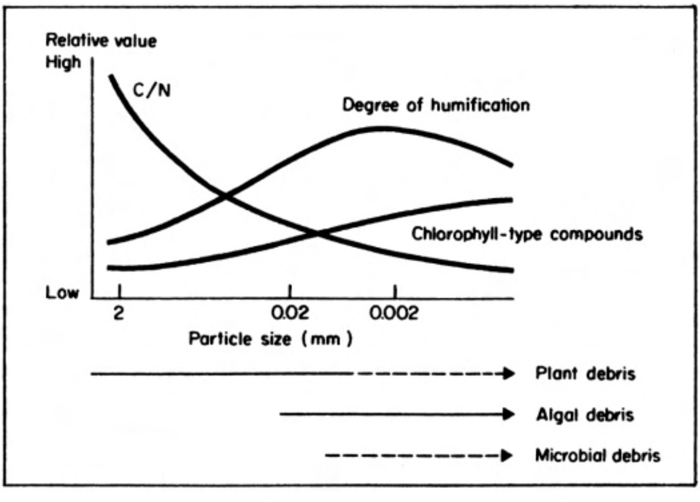
- Total amount of the organic debris larger than 0.037 mm was about one-third of the total organic matter content of the Apg horizon.
- The organic debris larger than 0.037 mm was composed mainly of plant debris. Some algal debris was found in the fine sand-sized fraction.
- Smaller plant debris was more decomposed and more thickly covered with mineral particles. This was also true for algal debris.



**7.** Physical separation of organic debris from soil (Wada and Kanagawa 1970). (I) = mesh, (II) = 400 mesh – 2μ, (III) = 2μ. A = more decomposed plant debris, B = less decomposed plant debris, M = mineral particles.

- Microbial number and activities, including N-fixing, were higher in large, fresh plant debris than in small, more decomposed plant debris.
- Clay-sized fractions were enriched with organic matter which was derived from or related to microorganisms. Population and activities of microorganisms were higher in the clay-sized fractions than in the silt-sized fractions.

Based on this information, particle size distribution of organic debris and main features of each size fraction are illustrated in Figure 8. The fate of the various organic debris fractions is clarified in this figure.



**8.** Particle size distribution of organic debris and some of its features (Wada 1972).

## CHARACTERISTIC DECOMPOSITION PROCESSES IN THE RICE FIELD

In rice fields, rice stubble, weeds, and algae, as well as manure, are important sources of organic matter. The amount of rice stubble and weeds that are plowed under is fairly large. If we estimate the amount of organic C of this debris, we may find it comparable with that of manure, which is commonly applied on rice fields. The fresh plant debris of the rice stubble and the weeds is rapidly decomposed and disintegrated in the submerged soil, and after 1 year its thickness is reduced to less than 1-2 mm (Kimura et al 1980).

In principle, transformation of the organic debris in rice fields is similar to that in dryland fields. However, since the Apg horizon of the rice field is kept strongly reduced during the submergence period, and not fully aerated even during the drainage period, some of the components of the organic debris are not readily decomposed by microorganisms and not readily oxidized by nonbiological reactions, causing them to remain in the soil for a long time. Examples are chlorophyll-type compounds and the components in the lignified tissue of the plant debris. Some of the chlorophyll-type compounds are contained in living akinate. Death and decomposition of the akinate are accelerated when the soil is strongly reduced.

The refractory nature of the lignified tissues and suppression of grazing activities of soil animals in the reduced soil may be the two principal reasons why a large part of organic matter in rice field soil is in plant debris form. Actually, decomposition of the lignified tissues goes on during the drainage period when lignin-decomposing fungi can invade the tissues. But after flooding, these fungi are replaced by anaerobic bacteria, most of which cannot decompose the lignified tissues (Miyashita 1980).

Organic P compounds such as inositol phosphate can be stabilized by strong bonds with $Fe^{3+}$ in the oxidized dryland soil. They are, however, solubilized and decomposed in the submerged and reduced soil of the rice field because the bonds are weakened by reduction of $Fe^{3+}$ to $Fe^{2+}$ (Wada et al 1982).

Nonrefractory components of the organic debris such as sugars, hemicellulose, cellulose, proteins, and peptides are rapidly decomposed, and newly synthesized materials in the decomposition process contribute to the pool of the easily decomposable organic matter.

All of these processes may occur in the first stage of the decomposition of organic debris.

Organic matter in wetland soil differs from that in dryland soil in several respects, mostly attributable to the larger accumulation of “relatively stable organic matter” in wetland soil than in dryland soil.

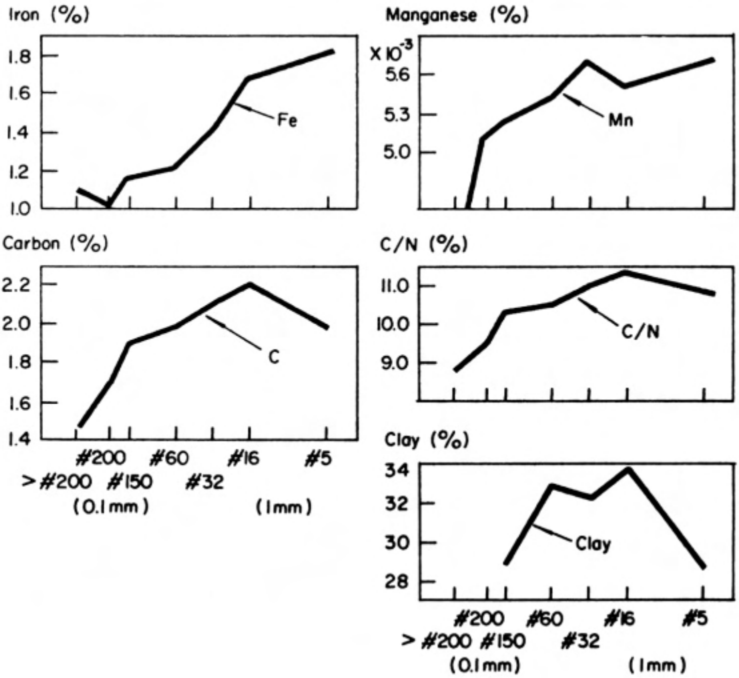
## AGGREGATES AND PLANT DEBRIS

Aggregates of rice field soils are quite different in their significance from those of dryland soils. Few researchers have been interested in the aggregate problem of rice field soils. This is because physical properties such as permeability, aeration, and water-holding capacity, all of which are closely associated with aggregates, are not considered to be so important in wetland rice fields as in dryland fields and because natural aggregates are easily disintegrated in the submerged and puddled soils.

Actually, soil aggregates of varying sizes can be fractioned by first slaking the air-dried soil sample and then sieving it in water (Kawaguchi and Kita 1956). These aggregates are not peds, which are usually surrounded by a natural surface of cutan, but they are formed in nature. The soil particles of these aggregates are held together firmly to withstand the slaking action. In this sense, these aggregates are water-stable compound particles and are regarded as a fundamental unit of chemical and biological reactions in the submerged soil.

The fractionated aggregates were examined microscopically and analyzed for chemical composition and numbers and activities of microorganisms (Wada et al 1974). Both biochemical and chemical properties changed regularly with aggregate size; larger aggregates had more organic matter, larger numbers and higher activities of microorganisms, higher C-N ratio, and higher contents of active Fe oxides and easily reducible Mn oxides (Fig. 9).

These results show that each aggregate might be formed on a framework of plant debris — large aggregates surrounding large plant debris and small aggregates surrounding small plant debris. This supposition is based on the experimental results showing that large parts of soil organic matter exist in the form of plant debris and that chemical and biochemical properties of plant debris vary with size in the same fashion as in the case of the aggregates. Using a microscope to isolate plant debris



**9.** Variation in chemical composition of aggregates with their sizes (Nagano soil) (Wada et al 1974). Mn = easily reducible manganese, Fe = active iron, C = total organic carbon.

from the aggregates, it was confirmed that many aggregates contained plant debris.

The cementing materials of the aggregates seem to be $Fe(OH)_3$ and $MnO_2$ as well as organic matter, because Fe and Mn levels are high in the aggregates.

As large plant debris is rich in substrates for microorganisms, large aggregates are more rapidly reduced than small aggregates when they are submerged.

Decomposition of plant debris occurs inside the aggregates, where the substrates in the plant debris are utilized more efficiently by the microorganisms. Reactions inside the aggregates are more or less independent of those outside the aggregates. In addition, high levels of Fe and Mn in the aggregates may assist the high efficiency of the metabolism inside them. This is because $Fe(OH)_3$ and $MnO_2$ are effective electron acceptors and the contents of these oxidants are higher in large aggregates rich in substrates than in small aggregates poor in substrates.

Fresh plant debris is usually not included in the aggregate, holds soil particles only weakly, and decomposes by itself. Some fresh debris of rice roots is covered with mineral particles which are cemented together with $Fe(OH)_3$. These rice roots may be regarded as intermediates between the plant debris, which exists inside the aggregates, and other fresh plant debris.

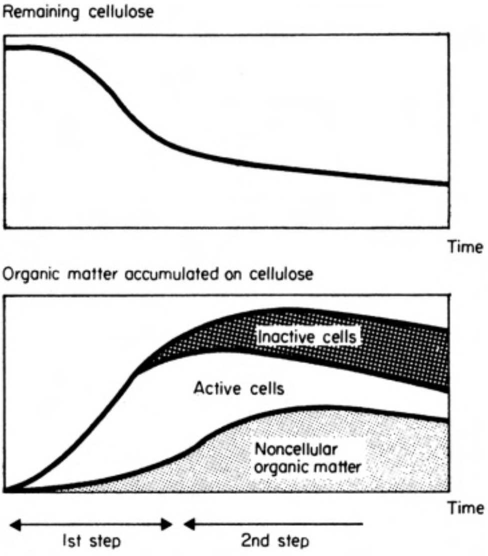
Consequently, when fresh plant debris is decomposed in the soil, the bonds between it and soil particles become stronger, the association of “plant debris-soil particles-microorganisms” becomes closer, and the aggregates formed become more qualified as a unit of chemical and biochemical reactions in rice field soil.

Saito (1981) showed this subject was worthy of proper consideration. In his experiment, he buried a piece of filter paper enclosed in a saran mesh bag in the submerged soil. After proper incubation period, the filter paper was removed from the soil, observed under a microscrope, and its degree of decomposition and microbial biomass were measured. Saito found that the filter paper decomposed in two steps (Fig. 10). First, a few cellulose decomposer species predominated on the filter paper, soil particles were loosely held to the filter paper, and intermediate products of cellulose decomposition were outfluxed from the filter paper and utilized by the microorganisms outside the saran bag. Second, the filter paper was completely covered by various kinds of microorganisms, soil particles were more firmly held to the filter paper, and the intermediate products of the cellulose decomposition such as $H_2$ were utilized by microorganisms inside the saran bag.

The second step of filter paper decomposition can be regarded as an embryonic stage of aggregate formation. Further experiments are needed to clarify the formation process of aggregates in rice fields and their changes in properties. By this type of experiment, details of the decomposition process of plant debris may be more clearly understood because the main part of the process occurs inside the aggregate. Accordingly, both the formation and the significance of aggregates (macro-aggregates) in wetland soil differ greatly from those in dryland soil.

## PLANT DEBRIS AS MICROSITES FOR BIOCHEMICAL REACTIONS

When the general picture of organic debris decomposition and its products in rice fields had become apparent, another series of experiments was begun (Wada 1974, 1975, 1980), the results of which will hopefully lead to founding a new branch of



**10.** Cellulose decomposition in the submerged soil and development of microbial community (Saito 1980).

micropedology — dynamic micropedology — placing particular stress on the characterization of microsites and the processes occurring at the microsites. Two of the experiments are described below.

## Mn deposition

Undisturbed soil samples were collected from the Apg horizon of rice fields several times in a year (Wada et al 1978b). Benzidine solution was added to the soil samples and blue color development was examined under a microscope. (Benzidine was oxidized by $MnO_2$, causing blue color.) During the drainage period, many tiny Mn-mottling were found on and around the plant debris, but during the submergence period, the Mn-mottlings were recognized only in the oxidized layer and other limited places.

The Mn-mottling usually took the form of tiny dots, and most of the filmy Mn-mottlings appeared to be composed of numerous tiny dots.

Among organic debris, fresh plant debris was free from the Mn-mottling, and weakly decomposed organic debris showed strong reaction with benzidine solution.

The form and distribution pattern of the Mn-mottlings suggested that Mn was initially deposited on the colonies of the Mn-oxidizing microorganisms, which fed on the substrates of organic debris, and then $Mn^{2+}$ was nonbiologically oxidized on the surface of preformed $MnO_2$. This supposition was supported by incubating the reduced soil sample in several ways. The results supporting the supposition are:

- One day after incubation at room temperature, many tiny Mn-mottlings could be detected on the surface of the reduced soil paste placed in a petri dish.
- The tiny Mn-mottlings were also formed by incubating the reduced soil suspension, which was dispersed in agar containing $Mn^{2+}$. The number of the Mn-mottling was the same in the soil suspension as in the soil paste, calculated per gram of soil.

- Almost all tiny Mn-mottlings in the soil suspension were attached to organic debris.
- Formation of the tiny Mn-mottling in the soil suspension was inhibited with $NaN_3$ and streptomycin.
- Blue-stained microorganisms were found in the tiny Mn-mottlings.

The supposition that $Mn^{2+}$ is nonbiologically oxidized on the surface of preformed $MnO_2$ was verified by Ross and Bartlett (1981).

Abundant deposition of Mn on and around the weakly decomposed plant debris may play a role in the formation of large soil aggregates with high Mn content.

### Reduction of tetrazolium salts

About 5 g of air-dried soil sample, 50 mg of $CaCO_3$, an appropriate amount of tetrazolium salts, and water were placed in the inverted lid of a petri dish. The bottom of the dish was placed inside the lid and a paraffin seal between the two halves, creating a narrow space. The set-up was incubated at 30°C. Color development was inspected under a microscope (colorless water-soluble tetrazolium salts were reduced to colored water-insoluble formazane). Some of the plant debris, aggregates, and microorganisms in the soil sample were selected and put on a slide for detailed examination at high magnification (200X-1,000X). If lactophenol cotton blue solution was added to the sample, formazane was gradually dissolved, and microorganisms responsible for reduction of tetrazolium were stained blue. The results of the expriments (Wada 1974, 1975, 1980; Wada et al 1976, 1978a) are summarized:

- Organic debris, especially fresh organic debris and some aggregates, provides favorable sites for growth and activities of microorganisms.
- Bacteria are the predominant microorganisms that attack organic debris, but some fungi and actinomycetes can grow on and around the plant debris, even in submerged and reduced soil.
- Microbially active microsites are rich in decomposable carbohydrates as well as decomposable nitrogenous organic compounds.

## REFERENCES CITED

Chairoj, P., M. Kimura, H. Wada, and Y. Takai. 1982. Effects of light on some processes in the submerged soil. Abstract 1982 Meeting, Jpn. Soc. Soil Sci. Plant Nutr. 28:108.

Kanazawa, S., and Y. Takai. 1980. Studies on plant debris in rice paddy soils [in Japanese]. J. Sci. Soil Manure, Jpn. 51:461-467.

Kawaguchi, K., and D. Kita. 1956. A method for determining water-stable aggregate in paddy soil [in Japanese]. J. Sci. Soil Manure, Jpn. 27:262-264.

Kimura, M., N. Tanaka, H. Wada, and Y. Takai. 1980. Quantitative estimation of decomposition process of plant debris in the paddy field, I. [in Japanese]. J. Sci. Soil Manure, Jpn. 51:169-174.

Miyashita, K. 1980. Decomposition process of intact rice root [in Japanese]. Ph D thesis, The University of Tokyo, Tokyo, Japan.

Ross, D. S., and R. S. Bartlett. 1981. Evidence for nonbiological oxidation of manganese in soil. Soil Sci. 132:153-160.

Saito, M. 1981. Microbial ecology of cellulose decomposition in paddy soils [in Japanese]. Ph D thesis, The University of Tokyo, Tokyo, Japan.

Wada, H. 1963. Effects of application of compost on the properties of soil organic matter [in Japanese]. Ph D thesis, The University of Tokyo, Tokyo, Japan.

Wada, H. 1972. Physical fractionation of soil organic matter [in Japanese]. Pages 26-35 *in* Jpn. Soc. Soil Manure, ed. Advances in Soil Science. Vol. 3. Yokendo, Tokyo.

Wada, H. 1974. Chemical and biological changes at microsites of submerged soil [in Japanese]. J. Sci. Soil Manure, Jpn. 47:435-440.

Wada, H. 1975. Micropedological approach to the study of dynamics of paddy soils. JARQ. 9:24-27.

Wada, H. 1980. Growth and activities of microorganisms at microsites of soil [in Japanese]. Pages 205-221 *in* Society for Microbial Ecology, ed. Ecology of Microorganisms, Vol. 7. Japan Scientific Societies Press, Tokyo.

Wada, H., and S. Kanazawa. 1970. Method of fractionation of soil organic matter according to its size and density, I. [in Japanese]. J. Sci. Soil Manure, Jpn. 41:273-280.

Wada, H., K. Iseki, and Y. Takai. 1976. Use of TTC reduction to measure easily decomposable nitrogen in paddy soils [in Japanese]. J. Sci. Soil Manure, Jpn. 47:518-523.

Wada, H., M. Nonaka, and Y. Takai. 1982. Dissolution of organic-P in the submerged soil. Abstract 1982 Meeting. Jpn. Soc. Soil Sci. Plant Nutr. 28:108.

Wada, H., M. Saito, and Y. Takai. 1978a. Effectiveness of tetrazolium salts in microbial ecological studies in submerged soil. Soil Sci. Plant Nutr. 24:349-356.

Wada, H., A. Seirayosakol, and Y. Takai. 1978b. The process of manganese deposition in paddy soils, I. Soil Sci. Plant Nutr. 24:55-62.

Wada, H., K. Inubushi, Y. Uehara, and Y. Takai. 1981. Relationship between total nitrogen and mineralizable nitrogen in soils [in Japanese]. J. Sci. Soil Manure, Jpn. 52:246-252.

Wada, H., H. Ishii, H. Tsuji, and Y. Takai. 1974. Features of water-stable aggregates of paddy soil, I. II. [in Japanese]. J. Sci. Soil Manure, Jpn. 45:204-207, 208-212.

Wada, H., S. Panichsakpatana, M. Kimura, and Y. Takai. 1979. Organic debris as microsite for nitrogen fixation. Soil Sci. Plant Nutr. 25:453-456.

Yoo, I. 1982. Effects of rice straw application on N2-fixation in paddy soils with special reference to phototrophic $N_2$-fixers on surface placed straw [in Japanese]. Ph D thesis, The University of Tokyo, Tokyo, Japan.

## DISCUSSION

LARSON: What is the time scale between the start of formation of an aggregate and the development of the stable aggregate?

*WADA:* I have no reliable data about this. But since the formation and stability of aggregates are closely connected with decomposition of plant debris, and plant debris is mainly derived from rice plants, I guess that formation of aggregates may start a few months after incorporation of the rice plant, and stable aggregates may be formed in a year and remain stable for a few years, though their size may decrease with time. I know a long-term experimental rice field with good “granular structure.” The field has been applied with rice compost for more than 50 years, and the “granular ped” is actually plant debris covered with soil mineral particles.

# ORGANIC MATTER AND SOIL PHYSICAL PROPERTIES

# EFFECTS OF ORGANIC MATTER ON SOIL PHYSICAL PROPERTIES

W. E. Lason and C. E. Clapp

Organic matter influences productivity of soils through the mineralization of nutrients, its high cation exchange and water-holding capacities, and its ability to improve soil physical properties. This paper discusses the components of organic matter in soils and how organic matter influences physical properties. Soil organic matter components range in complexity and decomposability from native soil organic matter and plant residues, to manure and other organic wastes, to soil organic chemical additives. The characterization of these components and the understanding of their complex reactions with soil inorganic materials will help us to interpret their effects on soil physical properties. Many measurements are used to denote soil structure, including porosity, bulk density, and aggregation. The impact of the structure of a soil may be expressed in terms of the content and transmission of water, air, and heat, as well as soil strength.

Organic matter contributes much to the productive capacity of soil. Nutrients are mineralized during decomposition of organic matter. Organic matter has a high cation exchange capacity, high water-holding capacity, the capacity to chelate cations, and the ability to improve the physical characteristics of soils.

Organic matter is composed of many substances that are often complexed with the fine mineral fraction in soils. These organic compounds may be transient or rather long-lasting, depending upon their resistance to microbial decomposition. Some organic substances are combined with the clay fraction in aggregates so that they are not accessible to microbial decomposition.

While it is commonly recognized that organic matter imparts a desirable physical condition to soils, the mechanisms by which it reacts have not been well documented. Likewise, the impact of organic matter on desirable physical properties is not well understood.

The purpose of this paper is to discuss the components of organic matter in soils and how organic matter influences soil physical properties.

---

Contribution from the Soil Science Department, Univ. of Minnesota. St. Paul, MN 55108, and the Soil and Water Management Research Unit, USDA-ARS, St. Paul. Sci. J. Ser. Paper No. 13,069 of the Minnesota Agric. Exp. Stn.; Professor and head, Department of Soil Science, University of Minnesota; and Research Chemist, USDA-ARS, St. Paul, and Professor, Dept. of Soil Science, University of Minnesota.

## ORGANIC MATTER

The organic components of soil range in complexity and decomposability from native soil organic matter to crop residues, to manures and other organic wastes, to chemical additives. Constituents have been isolated, fractionated, purified, mixed with soil inorganics such as clay or sand, and characterized as to soil chemical, microbiological, or physical processes.

### Native soil organic matter

The analytical approach to the chemistry of soil organic matter began with Schreiner and Shorey (1910), continued through the fractionation procedures of Waksman (1938), and has gained momentum with the research of Schnitzer (1978). An alternative approach — studying properties of synthetic model organic substances — has been the subject of experiments by Flaig et al (1975). Other reviews of both the general and specific nature and properties of soil organic matter have been presented by Bremner (1951, 1954), Kononova (1966, 1975), Allison (1973, and Greenland and Hayes (1978).

Soil organic matter represents a particular stage in the continuous exchange of C, H, O, N, P, and S between living material and soil minerals. An equilibrium condition usually exists whereby, as new organic matter is formed, a portion of the older material is mineralized. The two main processes — both microbial in origin — are 1) the degradation of plant and animal residues with modification of their composition and properties, and 2) the synthesis of new microbial cells, which in turn die and are turned over by other microorganisms. In view of the diversity of both organic materials and microorganisms, it is evident that there is wide variation in the soil organic fraction. Soil organic matter distribution in soils can generally be attributed to several factors: 1) climate and vegetation (Jenny 1941) and cropping (Haas et a1 1957), 2) horizon (Broadbent 1953), and 3) human intervention such as manure application (Russell 1973).

The composition of soil organic matter is essentially defined in terms of the precursor plant tissue components, i.e., polysaccharides, lignins, and proteins. The polysaccharides, represented by cellulose, hemicelluloses, and polyuronides, make up the major fraction of plant material, but after undergoing microbial transformations, exist as only 5-25% of the soil C (Swincer et al 1969). Carbohydrate chemists earlier believed that most soil polysaccharides were of microbial origin (Forsyth 1950); however, more recent work by Cheshire (1977) has suggested that specific monosaccharide-containing structures may come predominantly from plants. The fraction derived from plant lignin represents another large component which has been highly altered by microbial activity. The resistant portion of soil organic matter resembles lignin in some properties, but attempts to isolate lignin oxidation products from soil by chemical procedures proved futile (Gottlieb and Hendricks 1945). Other exhaustive degradation procedures by Schnitzer ( 1978) have produced a host of aromatic monomer “building-blocks,’’ some of which resemble lignin-like substances. The alternative approach of chemical or biological synthesis of humic materials has been carried out by Flaig et al (1975) and Martin and Haider (1977). The third important plant precursor component — protein — can be classified as the soil organic N fraction, representing up to 5% of the organic matter of mineral soils. Proteins as such have not been isolated from soils; however, evidence for the presence of peptides and large amounts of amino acids exists (Stevenson and Butler 1965. Stevenson 1982).

A more recent classification scheme for soil organic matter involves two major groups (Kononova 1966,1975): 1) unaltered materials such as fresh and older debris, and 2) transformed products (humus) that bear no morphological resemblance to the original material. Hayes and Swift (1978) have further subdivided the humified products into 2a) amorphous, polymeric, brown-colored humic substances based on solubility (humic acids, fulvic acids, and humins), and 2b) recognizable classes of compounds that are synthesized by microorganisms or modified from the original debris (polysaccharides, polypeptides, and altered lignins).

### Crop residues

Crop residues, including unharvested plant parts such as maize stover, cereal straw and stubble, legume stalks, grass thatch, leaves, and most plant roots, represent a sizable pool of material for microbial decomposition into soil organic matter. About 400 million metric tons of above-ground crop residues are produced each year by the nine leading crops in the United States (Larson et al 1978). (Maize, wheat, and soybean account for 75% of the total residues, in a ratio of 10:7:5.) Residues from all nine crops contain up to 4 million t of N, representing about 40% of the N of current fertilizer applications to all crops. In addition to the importance of crop residues as starting materials for microbially produced soil humic substances, other significant uses for crop residues must be considered, such as: reducing runoff, erosion, and sediment transport; maintenance of adequate infiltration rates: prevention of surface crusting: improvement of soil aggregation; and transport and retention of water, heat, and air in the soil.

A study that illustrates the relationship between soil organic matter and the amount of residue added was conducted on a Typic Hapludoll in southwest Iowa (Larson et al 1972). From 0 to 16 t/ha of maize and alfalfa residues were added for 11 consecutive years and plowed under each autumn. Maize was grown each year. After 11 years, the organic C content was a linear function of the amount of residue added. It was estimated that about 5 t/ha was needed to maintain the initial 1.8% C in the surface soil.

### Manures and other organic wastes

Farm manure, green manures, composts, and sewage sludges provide another major source of organic food for soil microorganisms. These materials are usually related to either stabilizing the structure of cultivated soils or providing N for crop production. The value of farm manure can be summarized as a benefit only realized when combined with other factors of good soil management (Salter and Shallenberger 1939). Green manures — legumes or nonlegumes grown primarily to conserve or improve productivity of the soil — can be important in sustaining levels and benefits of soil organic matter and N (Bradfield 1954). Composts consist of a variety of organic materials that have been subjected to decomposition before being added to soil. The chief advantage of composting before mixing with soil is one of physical condition. The unrotted material holds little water and is coarse and fibrous, but the compost holds water and is friable. For rice soil management, compost application is the best method for recycling K and Si in crop residues, but not N, because of temporary immobilization (Tanaka 1978). In the long run, however, it is possible to build the N-supplying power of soil by increasing its humus content with application of crop residues or compost. Sewage sludges and other municipal and agricultural wastes hold promise of benefiting soil organic matter. Large quantities of these materials have traditionally been incinerated or deposited in land-fills. With the recent interest in decreasing air and groundwater pollution, agricultural scientists are advocating utilization of these wastes on cropped land rather than just disposal of them (Dowdy et al 1976, Duncomb et al 1982). The composition of waste materials must be determined before land application, though, to avoid potentially hazardous high levels of trace metals and toxic organic compounds.

In general, for any organic waste from manures to sludges, soil and crop management practices will largely control the nature of the chemical and physical processes that occur (Kardos et al 1977). Before applying waste to land, one should know its chemical, physical, and microbiological properties; the topographical and climatological features of the area; the soil chemical and physical properties; the long-range land-use plans; cropping plans; crop nutrient requirements and elemental sensitivities; and public reaction or sentiment. With this information, management systems can be developed to optimize effective waste utilization and recycling.

### Chemical additives

Use of organic and inorganic chemicals as soil conditioners has reappeared after a brief flurry of activity and interest in “Krilium” and related compounds in the early 1950s (Ruehrwein and Ward 1952). The initial impetus was shortlived, mainly because of economics, but more recent interest has been in control of soil erosion by wind and water. The effectiveness of various chemicals as soil conditioners was summarized by DeBoodt (1972) and Gardner et al (1975). The chemical and physical reactions of soil-conditioning polymers, as well as the mechanisms of their activity, were covered by Emerson (1956). The more recent use of compounds like PVA was discussed by Carr and Greenland (1975). Particular mention should be made of the special utilization of soil conditioners in developing countries, where materials such as bitumens and polyacrylamide are being found effective in reducing evaporation, reclaiming saline soils, and preventing water and wind erosion (DeBoodt 1975). Soil conditioning gives soils the needed physical properties to allow plant growth, fight erosion, or save water. The products and techniques to incorporate soil conditioners into the soil are now economically justified in certain well-defined cases.

## PHYSICAL PROPERTIES

Soil structure is often defined as the arrangement of the particles in a soil and of the pore spaces located among the particles. The solid particles in a soil may be close- or open-packed as individuals, or arranged in aggregates. In coarse-textured soils the particles may act largely as individuals, whereas in medium- and fine-textured soils the particles are usually aggregated.

Many measurements are used to denote soil structure, including porosity, aggregation, and bulk density. The impact of the structure of a soil may be expressed in terms of the content and transmission of water, air, and heat, as well as soil strength.

### Porosity

Bulk density and total porosity values for various soils and porous materials are given in Table 1. Note that bulk density for mineral soils varies from 1.12 to 1.90 g/cm$^3$ and the fraction of the total soil volume occupied by pores (porosity) varies from 0.58 to 0.28. Organic soils (Histosols), mineral soils high in organic matter, and paddy soils may have bulk densities of less than 1.0 g/cm$^3$. Bulk densities of temperate-region soils usually range from 1.2 to 1.8 g/cm$^3$.

Pores in soils range in size over several orders of magnitude, as is illustrated in Table 2. While various descriptions of soil pores have been proposed, a system of nomenclature based on pore function seems most useful (Greenland 1977) and is also included in Table 2.

Greenland (1979) suggested that a soil should contain a) a proportion of pores of $2.5 \times 10^{-4}$ m or more in diameter, since most plant roots are of this size, b) 10% or more by volume of pores greater than $5 \times 10^{-6}$ m to allow water to drain freely through the soil; and c) 10% by volume of pores from $5 \times 10^{-7}$ to $5 \times 10^{-5}$m, because these pores store water for plant use. Figure 1 illustrates the pore size distribution for two soils as calculated from water content suction measurements. The ranges of transmission, storage, and residual pore sizes are given in the figure.

Pore sizes are usually calculated from a soil water matric potential curve using the capillary rise equation (Marshall and Holmes 1979). The computed pore sizes are a convenient and good estimation in soils with a stable structure during water content changes. The minimum pore size, which can be reliably estimated from water content matric potential curves, is about $5 \times 10^{-4}$ m. In swelling soils and soils with unstable structure, calculations of pore sizes from water content matric potential

**Table 1. Range of values$^a$ found in bulk density and total porosity for various soils and porous materials.**

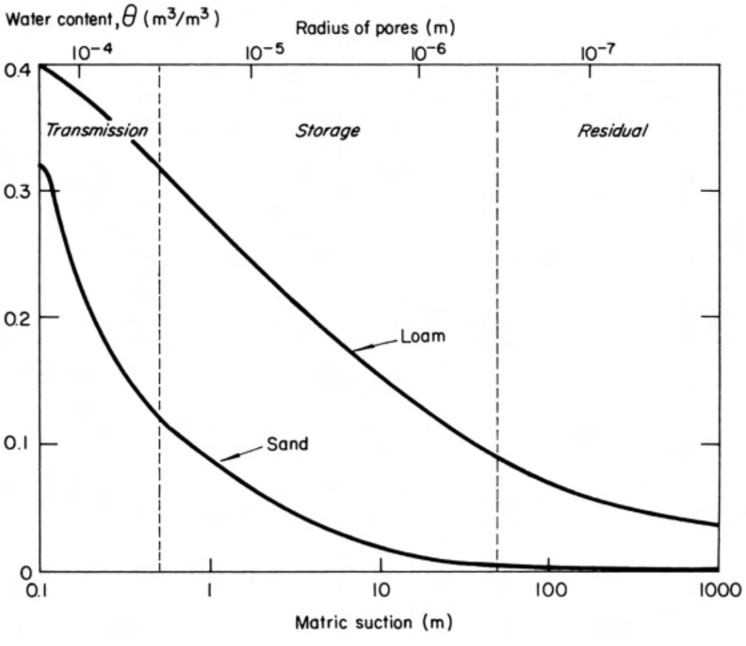
| Sample | Bulk density (g/cm$^3$) | Total porosity (cm$^3$/cm$^3$) |
|---|---|---|
| Peat in Minnesota, USA | 0.40 | 0.70 |
| Surface soil of wet clay | 1.12 | 0.58 |
| Surface soil of loam texture | 1.28 | 0.52 |
| Spheres of uniform size in open packing | 1.39 | 0.48 |
| Subsoil of sandy texture | 1.61 | 0.39 |
| Sandy loam soil compacted by heavy traffic | 1.90 | 0.28 |
| Spheres of uniform size in closest packing | 1.96 | 0.26 |

$^a$All values except those for peat taken from Marshall and Holmes (1979). Mineral particle density is taken as 2.65 g/cm$^3$.

**Table 2. Soil pores of different sizes and functions, Size is expressed as equivalent cylindrical diameter.**

| Size (m) | Function[n] | Example[b] |
|---|---|---|
| $10^{-2}$ | Fissure | Spaces as large as this are commonly formed between the clods of newly plowed soils. Cracks in dry clay soils can reach widths of this order of magnitude. |
| $10^{-3}$ | | Pores of about this size and smaller are formed between aggregates of finely tilled soil, as for a seedbed. |
| $10^{-4}$ | Transmission | Pores between spherical particles $6.5 \times 10^{-4}$ m in diameter in closest packing have this size. Roots will not extend into rigid pores smaller than this. |
| $10^{-5}$ | Storage | Pores larger than about $1.5 \times 10^{-5}$ m are drained in most soils that can be said to be at field capacity. |
| $10^{-6}$ | | Pores down to this size are accessible to bacteria. |
| $10^{-7}$ | Residual | Water in pores of about this size or larger is available to plants in nonsaline soil. (Corresponds to 1.5 MPa suction.) |
| $10^{-8}$ | Bonding | When micropores are treated as slits between parallel plates, about half the pore space in dried aggregates of clay soil an commonly be attributed to plate separations of $1 \times 10^{-8}$ or less. |
| $10^{-9}$ | | This is about the thickness of 3 layers of water molecules on a clay surface. |

[a] From Greenland (1977). Division between pores are not precise. For convenience, the divisions may be taken to occur at $5 \times 10^{-4}$, $5 \times 10^{-5}$, $5 \times 10^{-7}$, and $5 \times 10^{-9}$.0 [b] Adapted from Marshall and Holmes (1979).



**1.** Size distribution of pores and their function as given by the water characteristics of 2 soils (adapted from Marshall and Holmes 1979).

curves are of doubtful value. Greenland (1980) recently discussed other methods of estimating pore sizes.

## Soil aggregation

A soil aggregate can be considered a naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates. Martin et al (1955) thoroughly reviewed soil aggregation studies, including attempts to measure aggregate stability as related to crop yields. Another review by Harris et al (1966) covered dynamics of soil aggregation with respect to organic matter and microbial activities. Much worthwhile research centering on formation or production of aggregates as contrasted with chemical or biochemical stabilization of aggregates has still left many unanswered questions as to the overall relation of soil organic matter, aggregate structure, and soil tilth.

The work of Emerson (1959, 1964) illustrated how wet strength and stability of soil crumbs was related to permeability. Modification of this “chemical hammer” technique by Clapp and Emerson (1965) gave evidence of two groups of organic stabilizing agents — polysaccharides and humic colloids — which were active in grassland and forest soils, as opposed to charged polysaccharides mainly present in cultivated soils. These experiments led to the classification scheme of Emerson (1967) for soil aggregates based on their coherence in water.

The diagrammatic arrangement of clay domains, organic matter, and quartz particles in a soil crumb, as suggested by Emerson (1959), has led to many attempts to show clay-organic polymer interactions and bonding mechanisms. Adsorption studies of dextrans on montmorillonite by Clapp et al (1968) and Olness and Clapp (1975) showed interlameller absorption and shielding of polymers by clays. Further studies of clay-polysaccharide complexes by Clapp and Emerson (1972) were carried out to test adsorption and bonding mechanisms of uncharged, negatively charged (carboxyl), and positively charged (amino) polymers to clay and to elucidate some results from previous experiments on the role of polysaccharides in stabilizing soil aggregates.

Porosity characteristics of air-dried soil aggregates were changed significantly by different crop rotations and cropping practices in England (Dettmann and Emerson 1959; Currie 1961, 1966; see Table 3). A large reduction in fractional total porosity was found for cultivated soils compared with permanent grass management, as was a reduction of stability in 0.05 M NaCl (indicated by $K_2/K_1$ in Table 3) and stability in water. The $D_c/D_o$ values suggested that aeration within the arable aggregates was limiting. Greater values of porosity complexity for the arable aggregates indicated a microstructure more restrictive to gas diffusion. Diffusion within a tilled soil would also be dependent on the interaggregate porosity created by tillage.

Emerson and Dettmann (1959) found that when aggregates (3-5 mm in diameter) of the permanent grass plot were remolded by puddling at the sticky point, the water stability decreased to that of the natural cultivated aggregates. Moreover, they found no change in water stability because of a similar remolding treatment of similarly sized cultivated aggregates. Thus, they concluded that the remolding did not affect the aggregation of the clay fraction but disrupted the mechanism for bonding silt and

**Table 3. Aggregate porosity, stability in 0.05 M NaCl ($K_2/K_1$), water stability, air permeability ($D_c/D_o$), and porosity complexity as affected by long-term (100 years) management of calcareous Rothamsted silt loam.**[a]

| Management | Fractional total porosity | $K_2/K_1$ ($\times 10^{-2}$) | Water stability[b] (%) | $D_c/D_o$ | Porosity complexity |
|---|---|---|---|---|---|
| Permanent grass | 0.310 | 87 | 94 | 0.12 | 3.29 |
| Arable-mangolds-no fym | 0.171 | 5 | 1 | 0.04 | 4.94 |
| Arable-mangolds-fym | – | 18 | – | – | – |

[a] From Larson and Allmaras (1971). [b] Percentage of 3- to 5-mm aggregates retained on 1-mm sieve.

sand particles in the permanent grass sod. It was shown that remolding destroys structural shrinkage and increases somewhat the range of normal shrinkage. Because remolding did not change the stability of the arable aggregates, these aggregates could not have contained pores that exhibited structural shrinkage.

Changes in fractional porosity because of management appeared to be less on coarse-textured soils than on medium-textured soils. Compared to the Rothamsted soil, Woburn sandy loam showed smaller changes of fractional porosity attributable to use of farmyard manure (Currie 1966) than Broadbalk silt loam. These changes were accompanied by smaller differences in stability in 0.05 M NaCl. On the Broadbalk silt loam, managed for >100 years (Currie 1962), the inorganic N fertilizer and manure treatments showed greater fractional porosity than did the plot receiving neither fertilizer nor farmyard manure. The amount of crop growth and therefore the amount of plant residue on unmanured and unfertilized plots was also much lower than on manured and fertilized plots. Thus, approximately similar results may be obtained with manure or with the residue that results from increased growth.

In an irrigated Mollisol (low in organic matter) in Nebraska under intensive cropping, dry bulk density decreased and the fractional porosity of the aggregates increased when manure and alfalfa were included in the rotation as compared with potatoes, grain, and sugar beets alone (Mazurak et al 1953). Increases in organic matter and aggregate porosity and decreases in dry bulk density were about equal for 1 t/ha of farmyard manure per year of 3 years of alfalfa in a 6-year rotation. Soil structural improvements were as great with manure alone as when manure and alfalfa were combined.

The age of grass stands was related to the dry bulk density of the 0- to 76-cm depth of a Mollisol in western Nebraska by Mazurak et al (1960, 1963; see Table 4). Density decreased with age of stand both under grass and after 4 subsequent years of fallow - wheat cropping sequence. Associated with these decreases of density were increases in stability and water entry rates both under grass and after 4 years of fallow - wheat.

The evidence indicates that increasing amounts of organic matter in soils will usually be accompanied by increased aggregate porosity, lowered aggregate density, and a narrower range in aggregate size distribution, which will result in lowered soil bulk density. Changes in stability of soil structure are more pronounced than changes in organic matter. The effects of organic matter on soil aggregation are most evident on soils of intermediate charge where other cementing agents are low.

**Table 4. Effect of length of grass stand on the density and other soil properties and residual length of grass stand as evaluated by changes in density and other properties in subsequent fallow-wheat sequence on a very fine sandy loam in Nebraska.**[a]

| Age of grass stand at end of 2nd 10-year cycle (yrs) | Soil properties at end of 2nd 10-year cycle | | | | Soil properties after subsequent 4 years of fallow - wheat sequence | | |
|---|---|---|---|---|---|---|---|
| | Dry bulk density ($g/cm^3$) | Organic matter (%) | GMD of $H_2O$ stable aggregates (μm) | $H_2O$ entry rate after 120 min (cm/h) | Dry bulk density ($g/cm^3$) | GMD of $H_2O$ stable aggregates (μm) | $H_2O$ entry rate after 120 min (cm/h) |
| 0 | 1.36 | 1.6 | 55 | 1.0 | 1.33 | 57 | 0.9 |
| 2 | 1.38 | 1.8 | 54 | 1.8 | 1.30 | 57 | 1.5 |
| 4 | 1.36 | 2.0 | 57 | 2.8 | 1.28 | 58 | 1.9 |
| 6 | 1.31 | 2.2 | 71 | 2.6 | 1.27 | 61 | 2.2 |
| 8 | 1.30 | 2.3 | 84 | 3.2 | 1.28 | 68 | 2.1 |
| 10 | 1.24 | 2.7 | 141 | 4.8 | 1.22 | 69 | 2.6 |

[a] From Larson and Allmaras (1971).

## Compaction and bulk density

Submerged rice soils are usually either compacted or puddled, or both, to decrease the water loss from leaching. Compaction usually refers to the reduction in soil bulk density caused by a static or transient load applied normal to the soil surface. Puddling refers to mechanical work done on a soil associated with normal stresses and the tangential stresses of shear.

Compaction influences most of the important phenomena taking place in soils. However, the state of compaction alone, as expressed by bulk density, is not always a good indicator of a soil's physical behavior, because it is a macro measurement and does not adequately express the pore arrangements and their continuity. As a macro measurement, bulk density, along with soil texture, is a useful and readily measured index of a soil's behavior.

Several attempts have been made to predict the density (packing) of mixtures of particles from their concentrations and other physical properties in pure systems (Westment and Hugill 1932, White and Waltoin 1937). These models have been used to predict the bulk density of multicomponent glass bead systems or tricomponent field soil (Bodman and Constantin 1965, Staple 1975). Predictions from these models were good only when the mixtures consisted of particles that had severalfold differences in their diameter. In many instances, the models were successful in some test systems and not in others.

Gupta and Larson (1979b) developed a random-packing model that utilized soil-particle size distribution, average equivalent particle and cavity radii, bulk and particle densities, and concentrations of soil mineral and organic fractions. The model predicts random-packing, maximum, and minimum bulk densities of soils. The random-packing model estimates the normal bulk densities found in tilled soils. In one experiment the standard error of the estimated bulk density was 0.15 g/cm$^3$. Highest bulk densities are found in soils with a wide range in particle sizes (e.g., coarse-textured soils). Applications of the random-packing model may delineate horizons within a soil profile susceptible to pan formation. Maximum and minimum bulk densities are limiting values. They indicate the approximate extremes in densities that are of value in comparison with field-measured values.

The packing model of Gupta and Larson (1979b) most accurately predicts bulk density of coarse-textured soils when particle size distribution and particle density are used as the inputs. On fine-textured aggregated soils the model is a better predictor if aggregate size distribution and aggregate density are used as inputs (Gupta and Larson 1982). Using the model, predicted hulk densities were 1.08 (measured 1.09) and 1.35 (measured 1.44) g/cm$^3$ for geometric mean diameters of aggregates of 9.1 and 1.8 mm, respectively. This range in geometric mean diameter and bulk density is within the range of values that have been observed from variations in organic matter (Larson and Allmaras 1971).

The model demonstrates that organic matter can influence bulk density of soils by decreasing aggregate density, by increasing the size, and by narrowing the range in aggregate diameters.

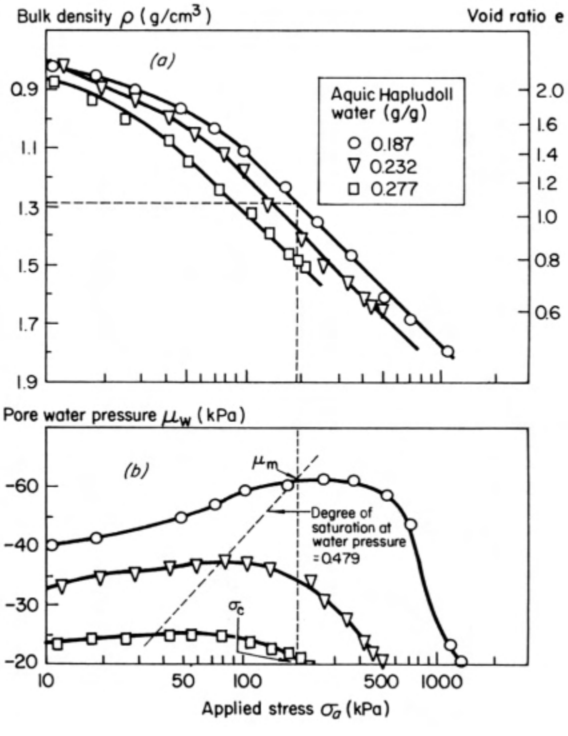
The compression of soils from an applied load will depend on the magnitude of the load and the geometry of the system. Larson and Gupta (1980) and Larson et al

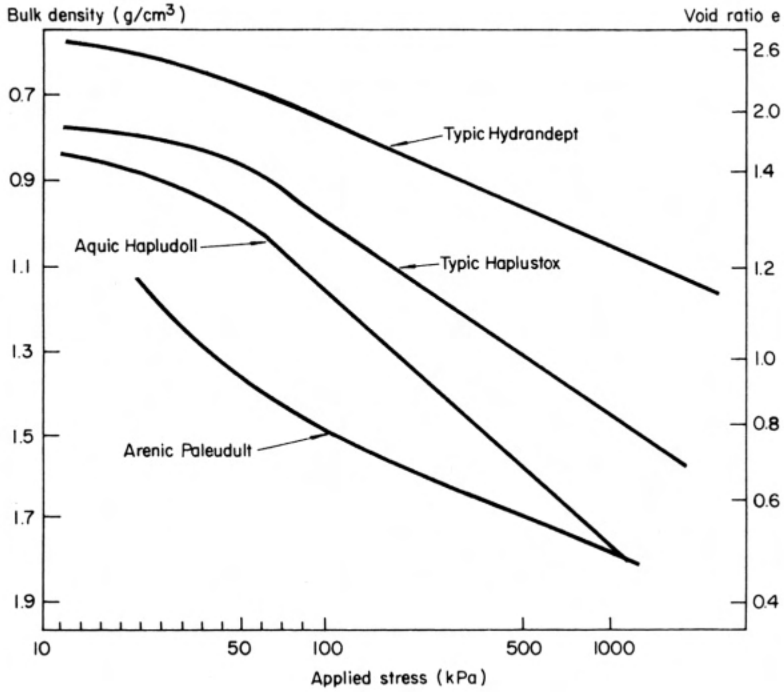
(1980) measured the compression characteristics of a large number of world soils using a one-dimensional compression apparatus.

Soil compression curves ($\rho$ vs. $\sigma_a$) for an Aquic Hapludoll at several water contents are shown in Figure 2a (Larson and Gupta 1980). The curves are linear over much of the applied mechanical stress range, and curves for different water contents are parallel over the range about 5 to 100 kPa.

During compression of unsaturated agricultural soils, the pore water ($\mu_m$) pressure decreases to a minimum (becomes more negative), and then increases as the applied mechanical stress increases (Fig. 2b, Larson and Gupta 1980). The pore water pressure-log applied stress curves for a given soil with different water contents are similar in shape but vary in scale. The degree of water saturation at which minimum pore water pressure occurs ($\mu_m$) appears to be a constant for a given soil. This degree of saturation increases with soil clay content up to about 33% clay and then remains nearly constant at 0.60. The pore water pressure-log applied stress curves for different water contents of a given soil, when normalized, fit a common curve. For different soils, the log of applied stress corresponding to $\mu_m$, when normalized with respect to the log of stress at saturation, increases with clay content up to about 33% clay and then remains constant at 0.78. It appears that, as the applied stress increases beyond the point of $\mu_m$, soil aggregates are sheared and their integrity destroyed. The stress corresponding to the point of $\mu_m$ is hypothesized as the maximum stress that can be applied to a soil during cultivation or by vehicular

**2.** Bulk density $\rho$, void ratio $e$, and pore water pressure $u_w$, as influenced by applied stress $\sigma_a$ for an Aquic Hapludoll at 3 water contents.





**3.** Soil compression curves for a Typic Hydrandept, Typic Haplustox, Aquic Hapludoll, and Arenic Paleudult at a pore water pressure of –30 kPa.

traffic without destroying the aggregate structure. We have termed the stress corresponding to the $\mu_m$ as the critical stress $s_c$. In submerged rice soils, where the objective is to decrease soil volume to reduce water transmission, it may be desirable to exceed the critical stress.

Figure 3 illustrates measured compression curves for four soils with different clay compositions and textures (Larson et al 1980). The curves were all determined at $s_m$ of approximately –30 kPa. In the Typic Hydrandept from Hawaii, USA, the weathered products consist of allophane. The Typic Haplustox from Brazil is highly weathered soil containing largely kaolinite and iron oxides in its clay fraction. The Aquic Hapludoll from Minnesota, USA, contains montmorillonite and hydrous mica in its clay fraction, and the Arenic Paleudult from North Carolina, USA, is a sandy soil (1.4% clay) with kaolinite as its dominant clay mineral.

From the data in Figure 3 one would expect that organic matter would be most effective in reducing the compressibility of soils of intermediate charge and where other cementing agents are not pronounced. The Typic Hydrandept and Typic Haplustox in Figure 3 are probably less compressible than the Aquic Haplustox, because their aggregate structure is cemented with iron. The Arenic Paleudult is not aggregated because of low clay content and low charge.

Increasing content of organic matter tends to reduce the amount of compaction from a given applied load. Soane (1975) found that for 58 samples of surface soils in

Scotland, increasing amounts of organic matter reduced the bulk density statistically by the following relationship:

$$\rho_b = 1.86 - 0.55\,M$$

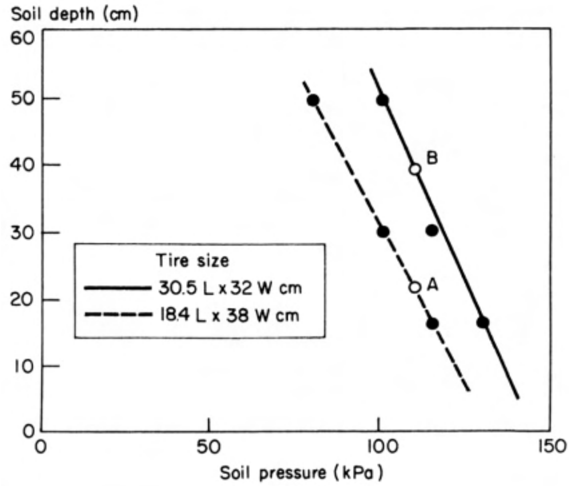
where $\rho_b$ is the maximum bulk density by the Proctor method over a range from 1.3 to 1.8 g/cm$^3$ and $M$ is the organic matter over a range from 2 to 10%. From Soane's work, it appears that the critical stress $\sigma_c$ for a given soil would be increased as the organic matter content of the aggregates increase.

At a given normal stress on the soil surface per unit area, the depth of penetration of the stress will depend on the geometry of the area over which the stress is applied. Thus, stresses from wide tractor wheels will penetrate deeper and compaction will penetrate to greater depths than from narrow wheels even though the stress per unit area is the same. This principle is illustrated in Figure 4 (Taylor et al 1978). If the total load is the same, increasing the tire width will decrease the pressure at a given depth. This relationship can be determined by comparing points A (wide tire) and B (narrow tire) in Figure 4. Thus, in paddy soils the geometry of the compacting tool as well as the load is important in determining the bulk density distribution.

High organic matter content increases the soil's resistance to puddling (Ghildyal 1982). The degree of puddling from a given treatment is dependent upon cultural practices, soil, and implement used. High clay content facilitates puddling, with kaolinitic clay being more difficult to puddle than Ca-saturated montmorillonite clays. Puddling increases the dry bulk density and reduces the soil to a series of individual particles and small aggregates. While puddling or soil compaction, or both, may be desirable for paddy rice production, the destruction of soil aggregates may be undesirable for succeeding nonpaddy crops.

In summary, increasing amounts of organic matter usually reduce the compressibility of soils when compared at a constant water content. The critical stress $\sigma_c$ is increased as water content increases. This conclusion agrees with a large amount of

**4.** Soil pressures at several depths under 2 tire sizes on a Norfolk sandy loam (Typic Paleudult). The interface pressure at the soil surface was 83 kPa for the smaller tire and 80 kPa for the larger(adapted from Taylor et al 1978).



other information, which shows that increasing amounts of organic matter will increase aggregate strength.

### Soil water

Organic matter has an influence on the amount of retention and transmission of water in soils. Gupta and Larson (1979a) developed regression models for estimating the retention of water in a group of soils and sediments and then tested the model against 61 soils from the central United States (mostly Mollisols and Alfisols). Using their regression equation ($r = 0.96$) for a silt loam (25% sand, 50% silt, 25% clay, bulk density 1.4 g/cm$^3$) and assuming the soil had 2 and 7% organic matter results in fractional soil water contents at 10 kPa suction of 0.491 and 0.516 cm$^3$/cm$^3$, respectively. At 1,500 kPa suction, the fractional water contents are 0.245 and 0.256 cm$^3$/cm$^3$ for 2 and 7% organic matter, respectively. Thus, using Gupta and Larson's equation the estimated increase in available water retention due to increase in organic matter from 2 to 7% would be small (1.4%).

Lal (1979) reported that the available water percentage (difference between 10 and 1,500 kPa suction) for the surface horizons of 11 toposequences from south and western Nigeria was represented by the equation $y = 2.35x + 8.32$ ($r = 0.63$) where $y$ is the available water and $x$ is the organic C percentage. Again, assuming organic matter levels of 2 and 7%, the difference in available water using Lal's equation is sizable — 6.8%. The soils used by Lal from Nigeria were Alfisols, Oxisols, and Entisols.

Organic matter changes may also affect the bulk density of the soil. Using Gupta and Larson's (1979a) equation for the same soil as listed above and assuming that a) the 2% organic matter soil has a bulk density of 1.5 g/cm$^3$, and b) the 7% organic matter soil has a bulk density of 1.3 g/cm$^3$, the fractional water retention at 10 kPa suction would be 0.467 and 0.540, respectively, and at 1,500 kPa suction 0.242 and 0.259 cm$^3$/cm$^3$, respectively. Thus, the available water would be 0.225 cm$^3$/cm$^3$ for the 2% organic matter soil, and 0.281 cm$^3$/cm$^3$ for the 7% organic matter soil, or an increase of 0.056 cm$^3$/cm$^3$. The data just cited indicate that organic matter's greatest influence on water retention may be through soil structural changes, i.e., through pore size and amount differences both within and between aggregates.

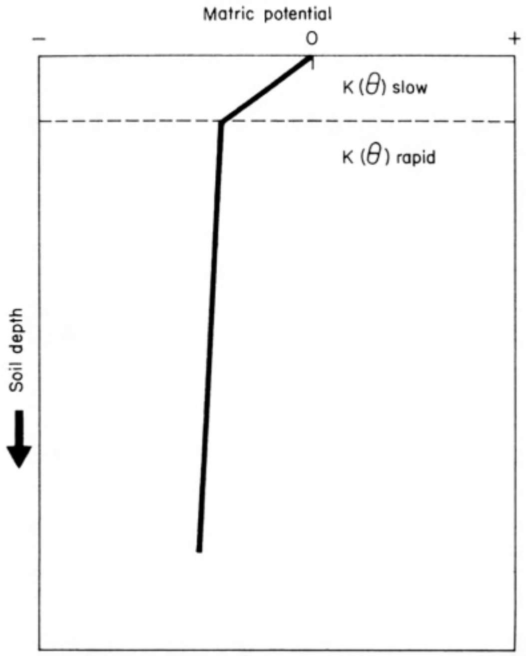
The much larger influence of organic matter on available soil water retention, estimated from Lal's equation as compared with Gupta and Larson's equation, is probably related to the effect of organic matter on aggregation. The medium-textured soils and sediments of the eastern United States, from which Gupta and Larson's equations were developed, were largely sandy soils or medium-textured soils and sediments with active clays. In the case of the sands with very low cation exchange capacities, organic matter will have little effect on aggregation. The medium-textured soils had relatively high cation exchange capacities and probably were well aggregated at all organic matter contents. In the Nigerian soils used by Lal (1979), the cation exchange capacities were probably moderate, where bonding of inorganic particles by organic matter might be large.

Gupta et al (1977) found that incorporation of digested sewage sludge increased soil water at all suctions on a Udorthentic Haploboroll (2% clay). Most of the increase was due to the increase in the amount of water sorbed (1,500 kPa suction) by the organic matter. There was no appreciable change in the available water capacity (10 minus 1,500 kPa) from the organic matter levels. The organic matter content varied from about 0.9 to 5.3%. They also found that saturated hydraulic conductivity increased with increasing organic matter content. However, unsaturated conductivity and soil-water diffusivity decreased at any water content as organic matter increased. This behavior of soil is important with respect to water storage. particularly in the wet tropics and arid zones. While higher saturated conductivities increase the intake of water during heavy rains, lower unsaturated hydraulic conductivities decrease the water loss due to evaporation.

The depth of compaction or puddling is an important consideration in water transmission through soils. In a submerged soil with a thin compacted layer at the soil surface, the dense layer will have a positive soil water potential at the soil surface, whereas a negative soil water potential will occur at the lower boundary of the dense later (Eduards and Larson 1969, Sharma et a1 1981). The gradient from positive to negative may occur over a short distance (Fig.4). Sharma et al (1981) found that hydraulic conductivity and water flux were greater during simulated rain from virgin soils than from cultivated soils (Mollisols, Alfisols, and Entisols). Matric potential drop across the surface seal was sometimes but not always greater in the cultivated soils. Presumably, the virgin soils were higher in organic matter. The matric potential drop was greater on a soil with a puddled surface than on one dispersed by simulated rain.

The illustrative diagram in Figure 5 has a number of implications in paddy soils. If a given transmission rate is desired, it can be achieved by. manipulating the hydraulic conductivity [K(Θ)] rate of the upper layer, or by changing the thickness of the upper

**5.** Idealized soil water potential in a 2-layered soil with a thin film of water on the surface K (Θ) refers to the hydraulic conductivity.



layer. In wetland fields where rice is grown in rotation with other crops, it may be advantageous to destroy only the aggregated structure in a very thin layer. Through tillage for the following crop, the aggregated lower layer can then be brought to the surface. If the soil is continuously under wetland cultivation, it may be more practical to increase the thickness of the upper layer. Crop residues on the surface or incorporated near the soil surface are not conducive to development of slowly permeable layers by compaction or puddling.

Cracking has a number of important implications in water transmission. Larson and Allmaras (1971) presented data showing that grassland soil aggregates exhibit considerable structural shrinkage upon drying, whereas arable soils lower in organic matter do not. Structural shrinkage is that stage of shrinkage starting with a water-saturated soil where the bulk volume change is less than the volume of water lost. Because aggregates higher in organic matter show greater structural shrinkage, the bulk soil may crack less on drying than aggregates with low organic matter, assuming other conditions are constant.

## Aeration

Aeration of the root zone influences the growth of most cultivated crops, with rice being a major exception. In the respiration of roots $O_2$ is consumed and $CO_2$ is given off. Usually the content of $O_2$ or the diffusion rate within the soil is used as a measure of aeration status.

In well-aerated soil the composition of the soil air approaches that of the atmosphere (20.96% $O_2$, 0.03% $CO_2$). In poorly aerated soils the $O_2$ content is decreased and the $CO_2$ content increased. A general rule of thumb expressed by Penman (1940) relates gas diffusion in soil to the diffusion in air:

$$D/D_o = 0.66\ E_a$$

where $D$ is the diffusion coefficient in soil, $D_o$ the diffusion coefficient in air (oxygen $2.26 \times 10^{-5}$ $m^2/s$ at 25° C), and $E_a$ is the fraction of soil volume occupied by air. The coefficient 0.66 approximates the impedance of air for flow into a tortuous and poorly connected pore system. The diffusion rate in aggregates compared with that in air, $D_c/D_o$, was 0.12 on soils cropped to permanent grass, compared with 0.04 on arable soils cropped to mangolds (Table 3).

Roots and microorganisms in soils are separated from the soil air by water films. Thus, part of the path for diffusion of $O_2$ and $CO_2$ diffusion is through water. Hence, diffusion coefficients for the gas phase are not necessarily critical for plant growth. Lemon and Erickson (1952) used a Pt microelectrode inserted in the soil and measured the $O_2$ diffusion rate to simulate air diffusion to a root. Subsequent work has shown that the method is a relative rather than an intrinsic measure of the $O_2$ diffusion rate.

Greenwood (1975) considered that soils with $E_a$ >0.1 are likely to be adequately aerated and that an $O_2$ content of <5% in the soil air is likely to affect plant growth.

Organic matter can influence the $O_2$ available to roots by affecting the porosity of the soil through its influence on aggregation. Readily decomposable organic matter in the soil can consume $O_2$ and give off $CO_2$ and thus make less $O_2$ available to plant roots.

## Heat

The thermal properties of soils reflect the varying proportions of air, water, organic matter, and mineral matter. The relevant properties of soil constituents are given in Table 5.

The volumetric heat capacity, $pc$ of the whole soil may be estimated from the properties of the constituents by:

$$\rho c = \Sigma\Theta_i (\rho c)_i$$

where $\Theta_i$ is the content of constituent *i* expressed as a volumetric fraction of the soil.

Organic matter differences in soils can influence thermal properties by their effects per se, and by the effects of organic matter on the proportions of water, air, and mineral fractions (Cruse et al 1980). Usually a soil becomes darker with increasing organic matter and hence has a lower reflection coefficient. The reflection coefficient for a dark-colored Mollisol is usually about 0.15 but can vary by 0.03 or more depending on soil color.

The combination of lower thermal conductivity and higher specific heat at any time (due to higher water content) on higher organic matter contents acts as a buffer to sudden temperature changes. Thus, maximum and minimum daily temperature in Minnesota, USA, were 3-4° C lower and higher, respectively, on soil having 5.3% organic matter compared with soil having 0.9% organic matter (Gupta et al 1977).

Organic matter in the form of surface crop residues will have a major influence on the temperature of the soil (Allmaras et al 1964). Mulches of crop residues influence soil temperature by:

- acting as an insulating layer on the soil surface, reducing the amount of heat that enters the soil;
- increasing the reflection coefficient at the surface if the reflection coefficient of the mulch exceeds that of the unmulched soil; and
- reducing evaporation.

The last-mentioned effect counteracts the previous two as regards soil temperature, since a smaller fraction of the total heat generated at the surface is used as latent heat of vaporization and sensible heat constitutes the larger fraction compared with the unmulched soil.

In temperate regions the reduction in soil temperature is directly proportional to the fraction of soil covered by plant residue. Cruse et al (1980) proposed the

**Table 5. Thermal properties of soil constituents.**[a]

| Constituent | Specific heat capacity (kJ/kg per K) | Density (kg/m$^3$) | Volumetric heat capacity (kJ/m$^3$ per K) | Thermal conductivity (W/m per K) |
|---|---|---|---|---|
| Air (20°C) | 1.0 | 1.2 | 1.2 | 0.025 |
| Water | 4.2 | $1.0 \times 10^3$ | $4.2 \times 10^3$ | 0.6 |
| Quartz | 0.8 | $2.7 \times 10^3$ | $2.0 \times 10^3$ | 8.8 |
| Clay minerals | 0.8 | $2.7 \times 10^3$ | $2.0 \times 10^3$ | 2.9 |
| Soil organic matter | 2.5 | $1.1 \times 10^3$ | $2.7 \times 10^3$ | 0.25 |

[a] From de Vries (1963).

following equation for calculating soil temperature differences between a bare and residue-treated soil as function of absorbed solar radiation:

$$T_r = T_s - (L\text{-}1)(X - S_s)(K)(I_t/I_s)$$

where

$T_r$ = 5-cm soil temperature on a residue-treated soil (°C)
$T_s$ = 5-cm soil temperature on the standard soil (°C)
$L$ = measured daily incoming solar radiation (langleys/ day)
1 = daily incoming solar radiation at the winter solstice when ($T_s$-$T_r$) is assumed to be 0°C (langleys/ day)
$S_s$ = reflection coefficient of the standard soil (0.15)
$X$ = reflection coefficient of tilled soil
$K$ = constant (°C day/ langley)= 0.05
$I_t$ = soil thermal inertia of the tilled soil (cal / ° C per $cm^2$ per 0.5 s)
$I_s$ = soil thermal inertia of the standard soil (cal / ° C per $cm^2$ per 0.5 s)

In flooded paddy soils the temperature of the water has an important effect on rice growth and aquatic plants (Ghildyal 1982). The temperature of the water is sometimes regulated by water depth, changing periods of irrigation, and intervals of drainage. Dressing of carbon black and mulching with crop residues have also been used.

## Soil strength

Organic matter affects the strength of a soil through its effect on soil water as well as its effect on bulk density, soil aggregation, and structure. Soil strength can be measured in a number of ways, including shear strength, tensile strength, probe penetration, and modulus of rupture.

Cruse and Larson (1977) have shown that the detachment of soil particles from raindrop splash is related to the shear strength of the soils at suctions of 0 to 2.5 kPa, and that an organic polymer (PVA), when added to the soil, materially increases the shear strength. Additions of PVA increased both the angle of internal friction and the cohesion. Presumably, organic matter with natural polysaccharides also increases a soil’s shear strength and resistance to erosion. Kandiah (1979) showed that the critical shear strength of an illitic soil was increased by the organic matter content when the SAR (sodium-adsorption ratio) was 2.0 but had little influence at high SAR. Critical shear strength was defined as that shear stress required for zero erosion.

Dowdy (1972) found that additions of PVA increased the tensile strength and tensile strain energy of montmorillonite films at constant water suctions. The strength of the films was increased as the molecular weight of the PVA increased. Yuan and Zhao (1981) demonstrated that the modulus of rupture as measured by the crushing of cylindrical soil samples was markedly influenced by the content of organic matter.

## REFERENCES CITED

Allison, F. E. 1973. Soil organic matter and its role in crop production. Elsevier Sci. Publ. Co., New York, NY. 637 p.

Allmaras, R. R., W. C. Burrows, and W. E. Larson. 1964. Early growth of corn as affected by soil temperature. Soil.Sci. Soc. Am. Proc. 28:271-275.

Bodman, G. B., and G. K. Constantin. 1965. Influence of particle size distribution on soil compaction. Hilgardia 36:567-591.

Bradfield, R. 1954. Organic matter maintenance: Desirable or feasible. Proc. Soil Microbiol. Conf., Purdue. 19 p.

Bremner, J. M. 1951. Review of recent work on soil organic matter. I. J. Soil Sci. 2:67-82.

Bremner, J. M. 1954. A review of recent work on soil organic matter. II. J. Soil Sci. 5:214-232.

Broadbent, F. E. 1953. The soil organic fraction. Adv. Agron. 5:153-183.

Carr, C. E., and D. J. Greenland. 1975. Potential application of polyvinyl acetate and polyvinyl alcohol in the structural improvement of sodic soils. Pages 47-63 *in* Soil conditioners. Soil Sci. Soc. Am. Spec. Publ. No. 7. Soil Sci. Soc. Am., Madison, Wisconsin.

Cheshire, M.V. 1977. Origins and stability of soil polysaccharide. J. Soil Sci. 28:l-10.

Clapp, C. E., and W. W. Emerson. 1965. The effect of periodate oxidation on the strength of soil crumbs. I. Qualitative studies. II. Quantitative studies. Soil Sci. Soc. Am. Proc. 29:127-134.

Clapp, C. E., and W. W. Emerson. 1972. Reactions between Ca-montmorillonite and polysaccharides. Soil Sci. 114:210-216.

Clapp, C. E., A. E. Olness, and D. J. Hoffmann. 1968. Absorption studies of a dextran on montmorillonite. Trans. 9th Int. Congr. Soil Sci., Adelaide, Australia. 1:627-634.

Cruse, R. M., and W. E. Larson. 1977. Effect of soil shear strength on soil detachment due to raindrop impact. Soil Sci. Soc. Am. J. 41:777-781.

Cruse, R. M., D. R. Linden, J. K. Radke, W. E. Larson, and K. Larntz. 1980. A model to predict tillage effects on soil temperature. Soil Sci. Soc. Am. J. 44:378-383.

Currie, J. A. 1961. Gaseous diffusion in the aeration of aggregated soils. Soil Sci. 92:40-45.

Currie, J. A. 1962. The importance of aeration in providing the right conditions for plant growth. J. Sci. Food Agric. 13:380-385.

Currie, J. A. 1966. The volume and porosity of soil crumbs. J. Soil Sci. 17:24-35.

DeBoodt, M. (ed.) 1972. Proceedings of the symposium on the fundamentals of soil conditioning. Mededelingen Fakulteit Landbouwwetenschappen, Rijksuniversiteit, Gent. Vol. 37(3):897-1167.

DeBoodt, M. 1975. Use of soil conditioners around the world. Pages 1-12 *in* Soil conditioners. Soil Sci. Soc. Am. Spec. Publ. No. 7. Soil Sci. Soc. Am., Madison, Wisconsin.

Dettmann, M. G., and W. W. Emerson. 1959. A modified permeability test for measuring the cohesion of soil crumbs. J. Soil Sci. 10:215-226.

de Vries, D. A. 1963. Thermal properties of soils. Pages 210-235 *in* W. R. van Wijk (ed.) Physics of plant environment. North-Holland, Amsterdam.

Dowdy, R. H. 1972. Effects of hydroxyl-containing organics on the strength and strain energy characteristics of montmorillonite. Soil Sci. Soc. Am. J. 36:162-166.

Dowdy, R. H., R. E. Larson, and E. Epstein. 1976. Sewage sludge and effluent use in agriculture. Pages 138-153 *in* Land application of waste material. Soil Conserv. Soc. Am., Ankeny, IA.

Duncomb, D. R., W. E. Larson, C. E. Clapp, R. H. Dowdy, D. R. Linden, and W. K. Johnson. 1982. The effects of liquid wastewater sludge application on crop yield and water quality in a closed watershed. J. Water Pollut. Control Fed. 54:1185-1193.

Edwards, W. M., and W. E. Larson. 1969. Infiltration of water into soils as influenced by surface seal development. Trans. Am. Soc. Agric. Eng. 12:463-465, 470.

Emerson, W. W. 1954. The determination of the stability of soil crumbs. J. Soil Sci. 5:233-250.

Emerson, W. W. 1956. Synthetic soil conditioners. J. Agric. Sci. 47:117-121.

Emerson, W. W. 1959. The structure of soil crumbs. J. Soil Sci. 10:235-244.

Emerson, W. W. 1967. A classification of soil aggregates based on their coherence in water. Aust. J. Soil Res. 5:47-57.

Emerson, W. W., and M. G. Dettmann. 1959. The effect of organic matter on crumb structure. J. Soil Sci. 10:227-234.

Flaig, W., H. Beutelspacher, and E. Rietz. 1975. Chemical composition and physical properties of humic substances. Pages 1-129 *in* J. E. Gieseking (ed.) Soil components. Vol. 1, Springer-Verlag, Berlin.

Forsyth, W. G. C. 1950. Studies on the more soluble complexes of soil organic matter. 2. The composition of the soluble polysaccharide fraction. Biochem. J. 46:141-146.

Gardner, W. R., W. C. Moldenhauer, C. E. Clapp, W. H. Gardner, M. M. Mortland, and C. I. Rich (eds.) 1975. Soil conditioners. Soil Sci. Soc. Am. Spec. Pub. No. 7. Soil Sci. Soc. Am., Madison, WI. 186 p.

Ghildyal, B. P. 1982. Nature, physical properties and management of submerged rice soils. Pages 121-142 *in* 12th Int. Congr. Soil Sci., Symposium papers II, New Delhi.

Gottlieb, S., and S. B. Hendricks. 1945. Soil organic matter as related to newer concepts of lignin chemistry. Soil Sci. Soc. Am. Proc. 10:117-125.

Greenland, D. J. 1977. Soil damage by intensive arable cultivation: temporary or permanent? Phil. Trans. R. Soc. London, B, 281:193-208.

Greenland, D. J. 1979. Structural organization of soils and crop production. Pages 47-56 *in* R. Lal and D. J. Greenland (eds.) Soil physical properties and crop production in the tropics. John Wiley and Sons, New York, NY.

Greenland, D. J. 1980. Recent progress in studies of soil structure, and its relation to properties and management of paddy soils. Pages 42-58 *in* Proceedings of symposium on paddy soil. Springer-Verlag, Berlin.

Greenland, D. J., and M. H. B. Hayes. 1978. The chemistry of soil constituents. John Wiley and Sons, New York, NY. 469 p.

Greenwood, D. J. 1975. Measurement of soil aeration. Pages 261-272 *in* Soil physical conditions and crop production. Min. Agric. Fish. and Food, London, Tech. Bull. No. 29.

Gupta, S. C., R. H. Dowdy, and W. E. Larson. 1977. Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. Soil Sci. Soc. Am. J. 41:601-605.

Gupta, S. C., and W. E. Larson. 1979a. Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. Water Resour. Res. 15:1633-1635.

Gupta, S. C., and W. E. Larson. 1979b. A model for predicting packing density of soils using particle-size distribution. Soil Sci. Soc. Am. J. 43:758-764.

Gupta, S. C., and W. E. Larson. 1982. Modeling soil mechanical behavior during tillage. Pages 151-178 *in* Predicting tillage effects on soil physical properties and processes. Soil Sci. Soc. Am., Madison, WI.

Haas, H. J., C. E. Evans, and E. F. Miles. 1957. U.S. Dep. Agric. Tech. Bull. 1164. 111 p.

Harris, R. F., G. Chesters, and O. N. Allen. 1966. Dynamics of soil aggregation. Adv. Agron. 18:107-169.

Hayes, M. H. B., and R. S. Swift. 1978. The chemistry of soil organic colloids. Pages 179-320 *in* D. J. Greenland and M. H. B. Hayes (eds.) The chemistry of soil constituents. John Wiley and Sons, New York, NY.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill, New York, NY. 281 p.

Kandiah, A. 1979. Influence of soil properties and crop cover on the erodibility of soils. Pages 475-487 *in* R. Lal and D. J. Greenland (eds.) Soil physical properties and crop production in the tropics. John Wiley and Sons, New York, NY.

Kardos, L. T., C. E. Scarsbrook, and V. V. Volk. 1977. Recycling elements in wastes through soil-plant systems. Pages 299-324 *in* L. F. Elliott and F. J. Stevenson (eds.) Soils for management of organic wastes and waste waters. Soil Sci. Soc. Am., Madison, Wisconsin.

Kononova, M. M. 1966. Soil organic matter. Its nature, its role in soil formation and in soil fertility. 2nd ed. Pergamon Press, Oxford. 544 p.

Kononova, M. M. 1975. Humus of virgin and cultivated soils. Pages 475-526 *in* J. E. Gieseking (ed.) Soil components, VI. 1. Springer-Verlag, Berlin.

Lal, R. 1979. Physical characteristics of soils of the tropics: Determination and management. Pages 7-44 *in* R. Lal and D. J. Greenland (eds.) Soil physical properties and crop production in the tropics. John Wiley and Sons, New York, NY.

Larson, W. E., and R. R. Allmaras. 1971. Management factors and natural forces as related in compaction. Pages 367-427 *in* Compaction of agricultural soils. Am. Soc. Agric. Eng., St. Joseph, Missouri.

Larson, W. E., C. E. Clapp, W. H. Pierre, and Y. B. Morachan. 1972. Effects of increasing amounts of organic residues on continuous corn. II. Organic carbon, nitrogen, phosphorus, and sulfur. Agron. J. 64:204-208.

Larson, W. E., and S. C. Gupta. 1980. Estimating critical stress in unsaturated soils from changes in pore water pressure during confined compression. Soil Sci. Soc. Am. J. 44:1127-1132.

Larson, W. E., S. C. Gupta, and R. A. Useche. 1980. Compression of agricultural soils from eight soil orders. Soil Sci. Soc. Am. J. 44:450-457.

Larson, W. E., R. F. Holt, and C. W. Carlson. 1978. Residues for soil conservation. Pages 1-15 *in* W. R. Oschwald (ed.) Crop residue management systems. Spec. Publ. No. 31. Am. Soc. Agron., Madison, Wisconsin.

Lemon, E. R., and A. E. Erickson. 1952. The measurement of oxygendiffusion in the soil with a platinum microelectrode. Soil Sci. Soc. Am. Proc. 16:160-163.

Marshall, T. J., and J. W. Holmes. 1979. Soil physics. Cambridge University Press, Cambridge. 345 p.

Martin, J. P., and K. Haider. 1977. Decomposition in soil of specifically $^{14}$C-labeled DHP and corn stalk lignins, model humic acid-type polymers, and coniferyl acohols. Pages 23-32 *in* Proc. IAEA-FAO-Agrochemical Symposium (Braunschweig), Vol. 2.

Martin, J. P., W. P. Martin, J. B. Page, W. A. Raney, and J. D. DeMent. 1955. Soil aggregation. Adv. Agron. 7: 1-37.

Mazurak, A. P., W. Kriz, and R. E. Ramig. 1960. Rates of water entry into a Chernozem soil as affected by age of perennial grass sods. Agron. J. 52:35-37.

Mazurak, A. P., and R. E. Ramig. 1963. Residual effects of perennial grass sod on physical properties of a Chernozem soil. Soil Sci. Soc. Am. Proc. 27:592-595.

Mazurak, A. P., A. W. Zingg, and W. S. Chepil. 1953. Effect of 39 years of cropping practices on wind erodibility and related properties of an irrigated Chestnut soil. Soil Sci. Soc. Am. Proc. 17:181-185.

Olness, A. E., and C. E. Clapp. 1975. Influence of polysaccharide structure on dextran adsorption by montmorillonite. Soil Biol. Biochem. 7:113-118.

Penman, H. L. 1940. Gas and vapour movements in the soil. I. The diffusion of vapours through porous solids. J. Agric. Sci. 30:437-462.

Ruehrwein, R. A., and D. W. Ward. 1952. Mechanism of clay aggregation by polyelectrolytes. Soil Sci. 73:485-492.

Russell, E. W. 1973. Soil conditions and plant growth. 10th ed. Longman, London. 849 p.

Salter, R. M., and C. J. Shallenberger. 1939. Farm manure. Ohio State Agric. Exp. Stn. Bull. 605. 69 p.

Schnitzer, M. 1978. Humid substances: Chemistry and reactions. Pages 1-64 *in* M. Schnitzer, and S. U. Khan (eds.) Soil organic matter. Elsevier Sci. Publ. Co., New York, NY.

Schreiner, O., and E. C. Shorey. 1910. Chemical nature of soil organic matter. US. Dep. Agric. Bur. Soils Bull. 74. 48 p.

Sharma, P. P., C. J. Gantzer, and G. R. Blake. 1981. Hydraulic gradients across simulated rain-formed soil surface seals. Soil Sci. Soc. Am. J. 45:1031-1034.

Soane, B. D. 1975. Studies on some physical properties in relation to cultivation and traffic. Pages 160-182 *in* Soil physical conditions and crop production. Min. Agric. Fish. and Food, London, Tech. Bull. No. 29.

Staple, W. J. 1975. The influence of size distribution on the bulk density of uniformly packed glass particles. Soil Sci. Soc. Am. Proc. 39:404-408.

Stevenson, F. J. 1982. Humus chemistry. Genesis, composition, reactions. John Wiley and Sons, New York, NY. 443 p.

Stevenson, F. J., and J. H. A. Butler. 1965. Chemistry of humic acids and related pigments. Pages 534-557 *in* G. Eglinton and M. T. J. Murphy (eds.) Organic geochemistry. Springer-Verlag, Berlin.

Swincer, G. D., J. M. Oades, and D. J. Greenland. 1969. Extraction, characterization and significance of soil polysaccharides. Adv. Agron. 21:195-235.

Tanaka, A. 1978. Role of organic matter. Pages 605-620 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

Taylor, J. H., E. C. Burt, and A. C. Bailey. 1978. Traction and compaction of big tractors. Am. Soc. Agric. Eng., paper No. 78-1029. p.

Waksman, S. A. 1938. Humus. Origin, chemical composition, and importance in nature. 2nd ed. Williams and Wilkins Co., Baltimore, Maryland. 526 p.

Westment, A. E. R., and H. R. Hugill. 1932. The packing of particles. J. Am. Ceram. Soc. 13:767-779.

White, H. E., and S. F. Walton. 1937. Particle packing and particle shape. J. Am. Ceram. Soc. 20:155-156.

Yuan, Jian-fang, and Yue-hua Zhao. 1981. Effect of water conditions and organic matter on modulus of rupture of paddy soils. Pages 689-693 *in* Proceedings of symposium on paddy soil. Springer-Verlag, Berlin.

## DISCUSSION

CHAUDHRY: What is the effect of organic matter decomposition from different sources in both decomposed (composted) and undecomposed conditions on the physical soil properties?

*LARSON;* It was agreed during the general discussion that there is a need for further studies on the effects of different organic materials. Besides, there is still a need to assess the percentage of organic matter that must be built up in paddy soils under different cropping systems.

SINGH: 1. What will happen if the depth of water ponding at the surface of a 2-layer system, as shown by you, is large?

2. Will the critical bulk density beyond which the aggregates collapse change with varying organic matter content of the soil?

*LARSON:* 1. There will still be a potential decrease across the slowly permeable layer. The magnitude will depend upon the depth of the ponded layer and the soil characteristics.

2. The critical stress will be increased with increasing organic matter content of the soil when compared at the same water contents.

NAGAR: Do you have any experience in working with tropical soils, and what is the significance of your work for tropical climatic conditions?

*LARSON:* We have worked with a large number of tropical soils in our laboratory, but I have not worked in the field with tropical soils. In our soil compression work, the concepts we report apply to all fine-grained soils. The differences in degree of compression are reported.

HUNDAL: 1. In a given soil, is there a particular level of organic matter beyond which additions of organic matter do not bring appreciable change in physical properties?

2. In your model studies on relating available water capacity to organic matter, what were the lower and upper limits of the available water range?

*LARSON:* 1. I am sure that there is a point where further increases in organic matter do not bring appreciable changes in physical properties. The point will vary with soil properties.

2. Our studies were on soils ranging from about 5 to 25% available water capacity.

# EFFECTS OF ORGANIC AND MINERAL FERTILIZATION ON SOIL PHYSICAL PROPERTIES AND HYDROPHOBICITY OF SOIL ORGANIC MATTER

Norio Nakaya and Satoru Motomura

Accumulated organic matter in the soil originating from long-term application of organic materials improved the physical properties of paddy soils, particularly by decreasing the solid ratio, bulk density, specific gravity, and crushing strength; increasing the liquid ratio and porosity caused mainly by increase of capillary pores; developing water-stable aggregates; and improving Atterberg limits.

Dry soil showed hydrophobicity because the contact angles of dry soils, which had been considered hydrophilic, were appreciably greater than zero.

Moist and dry soils were resistant to wetting mainly because of the presence of organic matter. In moist soils the infiltration was slowest at pF 4.2 because of the hydrophobicity of soil organic matter.

Knowledge of water repellency is necessary in evaluating the effects of organic matter on soil physical properties.

It is said that soil organic matter improves the physical properties of soil. The main improvements to paddy soils include development of soil structure, decrease of soil hardness, formation of water-stable aggregates, increase of water retentivity, and improvement of consistency and soil tilth (Yamashita 1967, Kubota 1971, Maeda 1974, Motomura and Nakaya 1980).

This paper reports results of some studies on soil physical properties from five long-term paddy field experiments in Japan with special reference to organic and mineral fertilization and to wetting resistance caused by soil organic matter.

## EFFECTS OF ORGANIC AND MINERAL FERTILIZERS ON SOIL PHYSICAL PROPERTIES

The physical properties of paddy soils are affected by topography (including depth of groundwater table), mode of deposition, parent materials (particle size distribu-

---

National Institute of Agricultural Sciences, Kannondai 3-1–1, Yatabe, Tsukuba, Ibaraki 305, Japan; and Tropical Agriculture Research Center, Kannondai 2-1-2, Yatabe, Tsukuba, Ibaraki 305, Japan.

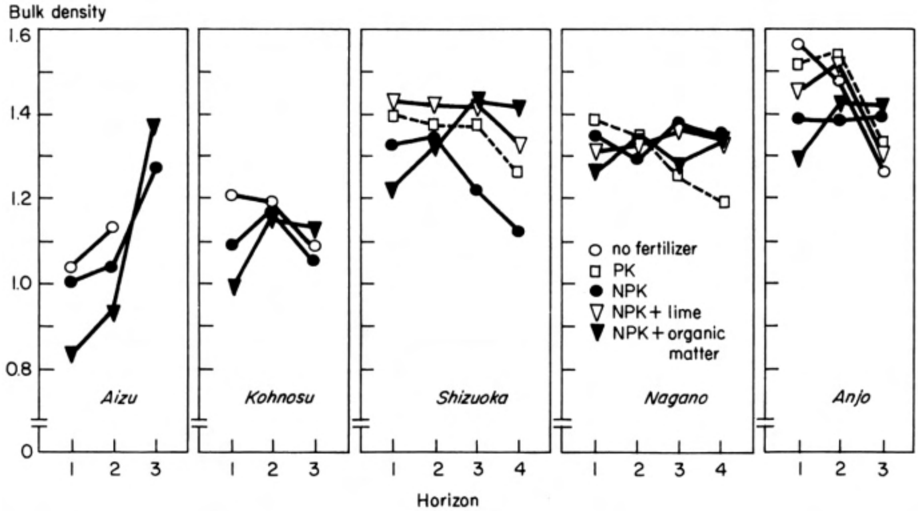
tion, kind and quantity of clay minerals), gleization, development of plowsole, and artificial soil management including fertilization.

Organic matter plays an important role in the permeability to air and water, water retentivity, and consistency of soils (Kubota 1971, Maeda 1974). Thus the application of such organic materials as rice straw, compost, and farmyard manure to soil contributes considerably to the improvement of soil physical properties. However, the effect of the application varies remarkably with such factors as kind and amount of applied organic materials, and soil and climate conditions.

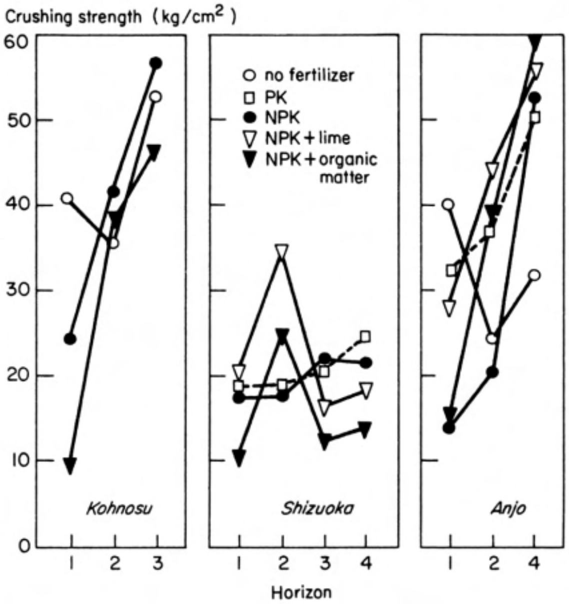
The effect of organic and mineral fertilizers on soil physical properties was examined with soil samples from five long-term paddy field experiments in Japan, which differed in soil and climate conditions: 1) Aizu (57 years, gley soil), 2) Kohnosu (52 years, gray lowland soil), 3) Nagano (29 years, gray lowland soil), 4) Shizuoka (28 years, gray lowland soil), and 5) Anjo (52 years, yellow soil).

Each field consisted of three to five plots that received compost + NPK fertilizers, NPK + lime, NPK, PK, or no fertilizer.

The bulk densities of the soils in the plots are summarized in Figure 1. The bulk density was smallest in Aizu gley soil and increased as the soil type became more oxidative (i.e., Kohnosu < Shizuoka < Nagano < Anjo). The bulk density of topsoils decreased with application of organic materials. The effects were quite noticeable in Aizu, Kohnosu, and Anjo soils, but insignificant in Nagano soil. This tendency was recognized also in the plowsole, with relatively small differences among the treatments. In the subsoil there was no significant difference among the treatments. The bulk density of topsoils, which were intensely influenced by fertilization management, decreased in Aizu soil by 0.138 per 1% increase in total C content of the soil, in Kohnosu soil by 0.181, in Nagano soil by 0.233, in Shizuoka soil by 0.256, and in Anjo soil by 0.266.



**1.** Bulk densities of paddy soils in long-term fertilization experiment fields.



**2.** Crushing strength of paddy soils in long-term fertilization experiment fields.

Crushing strength data are summarized in Figure 2. The topsoils were generally smaller; especially in the NPK + compost plots and the NPK plots, which were rich in organic matter content, the crushing strength decreased remarkably. Organic matter thus decreases crushing strength. Crushing strength of the topsoils decreased by 24 kg/cm$^2$ per 1% increase in total C content in Kohnosu soil, by 9.8 kg/cm$^2$ in Shizuoka soil, and by 20.9 kg/cm$^2$ in Anjo soil (Table 1).

Detailed results of the other soil physical properties are omitted from this report. However, the correlations of total C content of the topsoils with the physical properties after harvesting are summarized in Table 1. They showed similar tendencies to the correlations with bulk density and the crushing strength; in the organic material application plot, especially, the soil physical properties were recognizably improved through decrease of the solid ratio and specific gravity, increase of liquid ratio and porosity (mainly by increasing the capillary pore), development of water-stable aggregates, and improvement of consistency. Saturated water permeability improved slightly with the application of organic materials.

These improvements are considered to be related to the accumulation of soil organic matter originating from continuous application of organic materials and from the large amounts of rice plant roots and stubble. The NPK plots also had better soil physical properties than the PK or no-fertilizer plots because of the accumulation of soil organic matter originating from large amounts of rice plant roots and stubble. On the other hand, the application of lime, which promotes decomposition of soil organic matter, scarcely improved soil physical properties.

The physical properties of Aizu gley soil, located in a cold climate, and Kahnosu gray lowland soil, located in an area with a high groundwater table, were improved by the accumulation of organic matter. On the other hand, the effect of application

**Table 1. Correlation between total carbon content of topsoils and physical properties after harvesting.[a]**

| | Aizu | | Kohnosu | | Nagano | | Shizuoka | | Anjo | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *r* | *a* | *r* | *a* | *r* | *a* | *r* | *a* | *r* | *a* |
| Solid ratio (%) | –0.935* | –4.6 | –0.985** | –5.9 | –0.886 | –7.8 | –0.879** | –7.8 | –0.855* | –8.6 |
| Liquid ratio (%) | 0.981** | 5.6 | 0.934* | 3.7 | 0.453 | – | 0.808* | 6.2 | 0.926** | 7.4 |
| Air ratio (%) | –0.654 | –1.0 | 0.914* | 2.3 | 0.631 | 5.7 | 0.371 | – | 0.148 | – |
| Bulk density | –0.962** | –0.138 | –0.972** | –0.181 | –0.860 | –0.233 | –0.903** | –0.256 | –0.870* | –0.266 |
| Specific gravity | –0.978** | –0.059 | –0.750 | –0.055 | –0.646 | –0.041 | –0.887** | –0.097 | –0.860* | –0.080 |
| Total porosity (%) | 0.935* | 4.6 | 0.985** | 5.9 | 0.886 | 7.8 | 0.879** | 7.8 | 0.855* | 8.6 |
| pF 0 ~ 1.5 (%) | –0.654 | –1.0 | 0.474 | – | 0.697 | 3.1 | 0.905** | 3.6 | –0.401 | – |
| pF 1.5 ~ 2.7 (%) | –0.072 | – | 0.736 | 4.1 | 0.371 | – | 0.009 | – | 0.639 | 3.2 |
| pF 2.7 ~ 4.2 (%) | 0.910* | 4.8 | 0.893 | 4.8 | 0.910* | 3.2 | 0.922** | 5.4 | 0.708 | 2.4 |
| pF 4.2 < (%) | 0.304 | – | –0.580 | – | –0.295 | – | –0.326 | – | 0.975** | 5.7 |
| Aggregate > 5 mm (%) | 0.691 | 5.9 | –0.892 | –6.3 | –0.984** | –7.9 | 0.786 | 22.5 | 0.845* | 10.7 |
| Liquid limit[b] (%) | 0.905* | 6.9 | 0.338 | – | 0.681 | 4.3 | 0.972*** | 7.5 | 0.969** | 6.4 |
| Plastic limit[b] (%) | 0.565 | 4.3 | 0.888 | 3.1 | 0.992*** | 4.3 | 0.930** | 7.6 | 0.722 | 3.5 |
| Plasticity index[b] | 0.636 | 2.5 | –0.225 | – | 0.001 | – | –0.051 | – | 0.677 | 2.9 |
| Shrinkage limit[b] (%) | 0.789 | 3.0 | 0.842 | 2.5 | 0.201 | – | 0.758 | 3.9 | 0.766 | 4.1 |
| Shrinkage ratio | –0.881 | –0.083 | –0.854 | –0.053 | –0.809 | –0.075 | –0.810* | – 0.106 | –0.766 | –0.138 |
| Crushing strength[c] (kg/cm$^2$) | – | – | –0.877 | –24.0 | – | – | –0.847* | –9.8 | –0.644 | –20.9 |

[a] *r* = correlation coefficient, *a* = changes in soil physical property per 1% increase of total carbon content, * = 10%, ** = 5%, *** = 1%. [b] Air dried soil. [c] Oven-dried soil.

of organic materials was not noticeable in Nagano gray lowland soil, whose good drainage prevented organic matter from accumulating.

Consequently the effect of fertilization with organic materials on soil physical properties was obvious in the topsoils, which were able to accumulate organic matter, only slightly noticeable in the plowsole, and scarcely felt in the subsoil.

## HYDROPHOBICITY OF SOIL

### Water repellency of dry soil

Although the superficial properties of soil particles have scarcely been studied, soil particles have generally been considered completely wettable. Fallen leaves, straw, and fungal hyphae are generally water repellent, and dried peat floats on water. Furthermore, the humic acid extracted from soils is difficult to wet again after being thoroughly dried. So, are soils containing humified substances of organic materials water repellent or not?

In arid or semiarid zones of the world a number of poorly wettable soils were found (Jamison 1945, van’t Woudt 1954, Bond 1964, DeBano and Letey 1969, Scholl 1971). They repel water much as bird feathers do, and it is difficult for irrigated or rain water to infiltrate them. Their water repellency depends mainly upon soil organic matter coating the soil particles (Bond 1964, DeBano and Letey 1969, van't Woudt 1954). Japan, too, has dry brown forest soil that is difficult to wet with water (Mashimo 1960, Ohmasa 1951). However, these water-repellent soils are considered exceptional, because most soils are thought to be completely hydrophilic.

Instead of the preconceived idea that soils, except certain water-repellent ones, are completely wettable, it has been hypothesized that soils are not completely wettable but are relatively resistant to wetting (Nakaya et al 1977, 1981).

The existing methods for measuring water repellency of soils (Jamison 1945, Letey et al 1962, Emerson and Bond 1963) could not measure from complete nonwettability to complete wettability with a single procedure. Furthermore, each method had different units for the expression of water repellency. That is the reason why much research had been directed to only extremely nonwettable soils distributed locally. It was therefore necessary to establish a method for measuring the degree of water repellency of soils, preferably one that enables measurement of water repellency over a wide range, from completely wettable to completely nonwettable.

In very wettable soils, the capillary rise of water is very high; conversely, in nonwettable soils, there is scarcely any capillary rise. In a procedure modified from the method of Emerson and Bond (1963), it was found that nonwettable soils became fully wettable when heated at 250° C. From the ratio of the maximum height of capillary rise in a sample dried at 105°C to that in a sample heated to 250° C, the water repellency of a soil sample can be represented by the value of the contact angle. Hence, heating of soils at 250° C was adopted instead of heating sand at 500° C, proposed by Emerson and Bond (1963). The term “water repellency” is defined in this report as relative nonwettability by water of the soil particle surface. The soil sample is completely wettable if the contact angle is 0° and completely nonwettable if it is 180°.

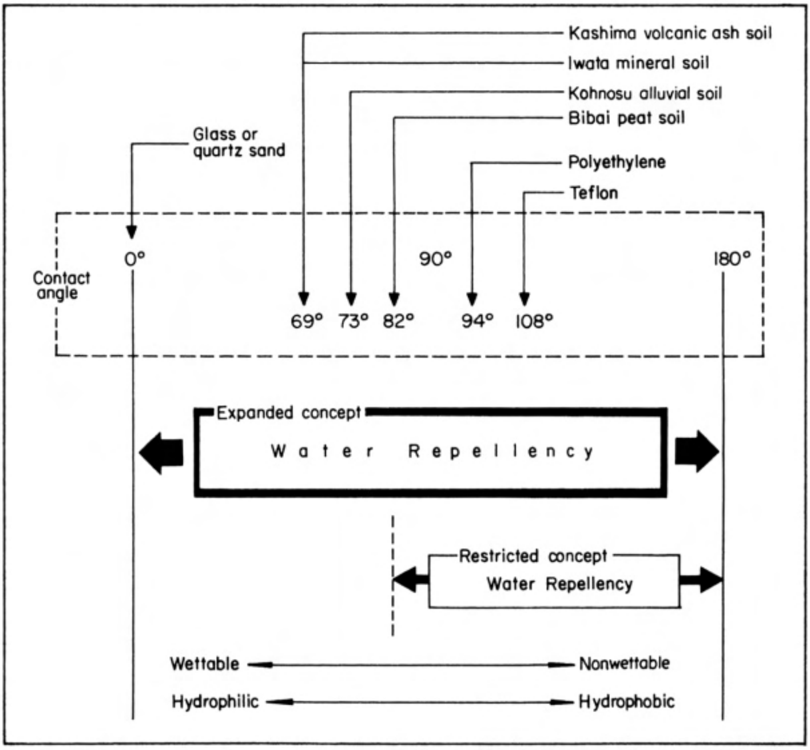
The expanded concept of water repellency proposed in this report is shown in Figure 3. Soils that have been considered equally hydrophilic show very different wettability, and their contact angles are not at all 0°. For reference, the contact angle of glass or quartz sand to water is 0°; that of teflon, the most hydrophobic plastic, 108° ; and that of polyethylene, 94°. The contact angles of soils tested were rather nearer to plastic than to glass or quartz.

It is concluded that a dry soil cannot be fully hydrophilic as long as organic matter is present.

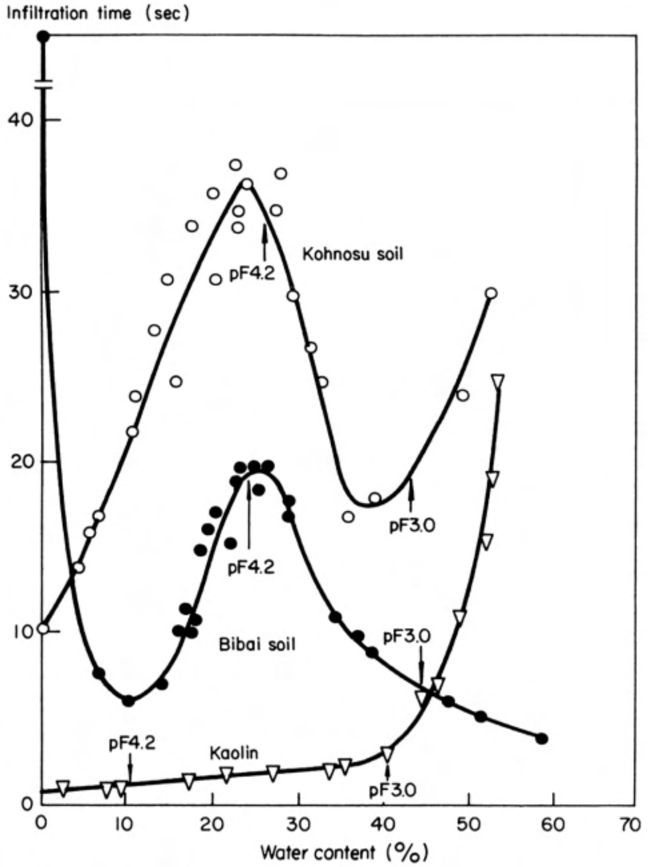
### Effect of water repellency of moist soil

Dry soils show resistance to wetting with water. However, soils in field conditions, unlike glass or plastic, contain moisture. So, explaining whether moist soils show resistance to wetting or not is useful in elucidating the mechanism of water repellency on the basis of the physical properties of moist soils.

It was anticipated that the infiltration of soils by water would be significantly influenced by their water repellency. Soils with a larger contact angle were expected to be infiltrated more slowly than those with a smaller contact angle. Infiltration is improved by an increase in the porosity of soil, which is caused through development of soil structure by soil organic matter (Parr and Bertrand 1960), but nonwettability



**3.** Expanded concept of water repellency as expressed by contact angles of soils.

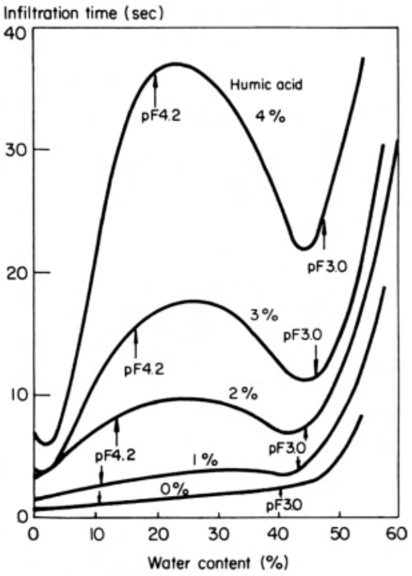


**4.** The relation between infiltration time and water content.

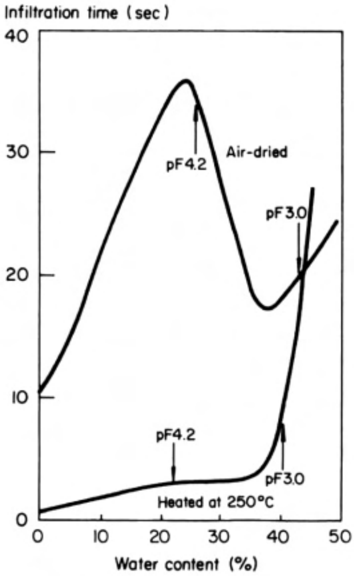
or water repellency, a superficial property of soil particles, has not been considered in this relation.

Hence, the effect of water repellency on infiltration of water into soil was investigated. Soil samples whose natural structure had been destroyed by remolding with a soil knife were used to minimize the influence of the soil structure or cracks on infiltration. Fungal hyphae are thought to be a prominent factor affecting water movement in soils, but, because the purpose of this experiment was to determine the effect of soil organic matter other than microorganisms upon soil physical properties, soil samples were treated with $HgCl^2$ to prevent the occurrence of fungal hyphae. The length of time that one water drop could remain on the soil surface was used as an index of the water repellency of moist soil.

Figure 4 shows the effect of a decrease in moisture content on infiltration in Kohnosu alluvial paddy soil, Bibai peat paddy soil, and kaolin. Infiltration of water into soils that contain organic matter became slower above pF 3.0. At pF 4.2 the infiltration was slowest. In kaolin, which does not contain organic matter, the infiltration slowdown at pF4.2 was not recognized (Fig. 4); however, the infiltration at pF 4.2 of a mixture of kaolin and humic acid, which is very hydrophobic after drying, became slower with increasing humic acid content (Fig. 5). The infiltration



**5.** Infiltration time of mixtures of kaolin and humic acid.



**6.** Infiltration time of Kohnosu soil heated at 250° C.

slowdown at pF 4.2 of the soil that became fully hydrophilic when heated at 250° C was not recognized (Fig. 6). Thus it is clear that the presence of organic matter in moist soil decreases the infiltration rate, i.e., the soil resists wetting.

The infiltration of soils at pF 4.2 was slower in the wetting process where dry samples were wetted than in the drying process where wet samples were dried. But in the case of kaolin, the infiltration slowdown at pF 4.2 was not recognized in either process. From these facts it appears that the air entrapped by organic matter disturbs infiltration.

It is concluded that soil organic matter shows hydrophobicity above pF 3.0 and that it becomes most hydrophobic at pF 4.2.

## DISCUSSION

Even if soil organic matter decreases bulk density, develops structure, improves water retentivity, and improves permeability to air and water, its hydrophobicity remarkably restricts these physical properties. For example, soil pores present due to organic matter cannot function to retain water if the water is repelled. Water repellency is thus a crucial factor when considering soil physical properties.

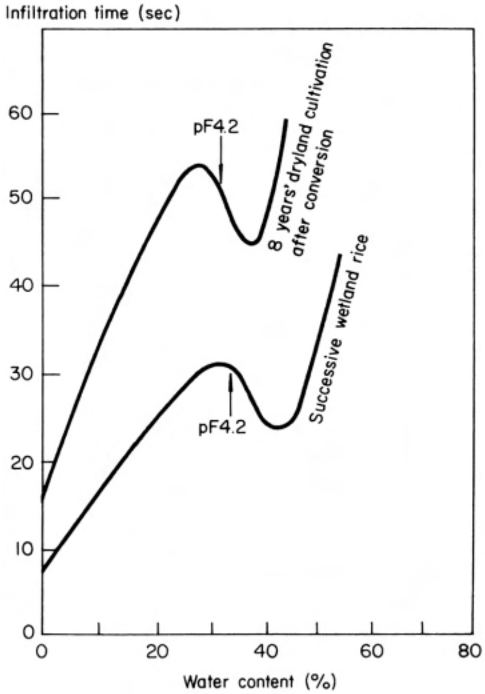
The air phase remaining in the pores of hydrophobic soil functions efficiently to maintain a balance between water and air in the soil, which is important for plant growth. A stable aggregate develops when water cannot approach the hydrophobic part of soil in the cycle of wetting and drying. Coexistence of water, air, organic matter, and inorganic matter should develop and stabilize soil aggregates and thus develop soil structure.

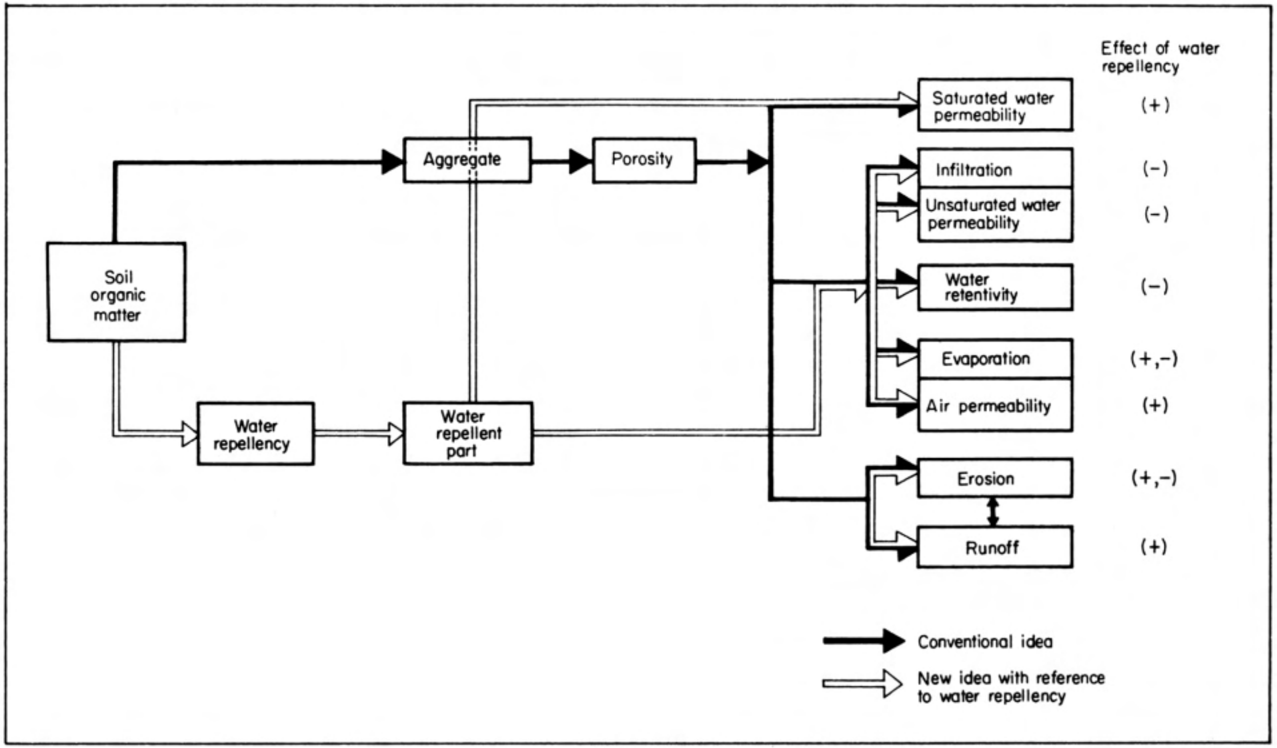
Wettability was determined by Scholl (1971) at 1/3 and 15 bars moisture tension and air-dry conditions, with the 15-bar level showing the greatest resistance to wetting. Also, Mashimo (1960) found that the dry brown forest soil in Japan was extremely difficult to wet above pF 3–4 because of fungal hyphae. Their results agree closely with those described in this paper. Furthermore, Mashimo (1960) also reported that nonwettability was caused by fungal hyphae.

Thus soil organic matter, by increasing porosity through development of the soil, promotes infiltration, but soil organic matter, which is hydrophobic, restricts infiltration. The net effect of organic matter upon infiltration in the field is a function of these two contradictory factors.

Moisture content with the value of pF 4.2 is generally referred to as the "permanent wilting point;" this report suggests that this moisture content could prevent water movement in soil. Even in Japan, the moisture content of surface soils frequently amounts to pF 3 or more. In arid or semiarid zones in the world, soils are thought to be dried often above pF 4.2. In this case, the water repellency must be considered for efficiency of utilization of soil moisture and irrigation or rain water. For example, according to the results of furrow irrigation for dryland rice plants on mineral soil, reported by Nomoto and Nakamura (1959) and Yokoi (1965), an upward capillary rise of water into ridges did not take place easily, and moisture content of the ridges corresponded to the wilting point. One possible explanation for this phenomenon is that the mineral soil showed slow infiltration because of the hydrophobicity of the soil organic matter.

**7.** Relation of infiltration between successive paddy cultivation and 8 years' dryland cultivation after conversion.





**8.** Flow chart of soil physical properties related to water repellency.

On the other hand, making use of water repellency could save water and provide an index of control of water.

Many investigations have dealt with unsaturated water flow, but this phenomenon has not been satisfactorily explained. For example, studies concerning unsaturated water flow have considered sizes and distribution of porosity but not the hydrophobicity of soil particles caused by soil organic matter.

Hydrophobicity offers some new insights into the solution of problems concerning not only water movement in dryland fields whose water flow is unsaturated but also changes of water movement from saturated water flow (paddy field) to unsaturated water flow (dryland field) in the conversion from paddy field to dryland field, a phenomenon that has been promoted in Japan to restrict rice production.

Figure 7 shows an example of infiltration slowdown at pF 4.2 after the conversion. This slowdown resulted from the increased hydrophobicity of the soil organic matter caused by drying. Therefore, if a paddy field is dried for dryland crop production, measures against slow infiltration at pF 4.2 should be taken.

When organic materials such as rice straw are applied to soils poor in organic matter content, infiltration becomes difficult at pF 4.2.

Hydrophobicity restricts water movement in unsaturated water flow. On the other hand, saturated water flow is not affected by water repellency, but may be improved by the formation or stabilization of soil aggregates due to hydrophobicity.

A flow chart of the effects of water repellency upon soil physical properties is shown in Figure 8. In addition, it is supposed that water repellency influences cohesion, Atterberg limits, dispersion, etc. of soil; however, the mechanisms have not not been studied. The concept of water repellency of soils provides new inputs for water management under field conditions. Water repellency of soils should be considered in evaluating the effects of organic matter upon soil physical properties.

## REFERENCES CITED

Bond, R. D. 1964. The influence of the microflora on the physical properties of the soils. II. Field studies on water repellent sands. Aust. J. Soil Res. 2:123-131.

DeBano, L. F., and J. Letey (eds.). 1969. Water repellent soils. University of California, Riverside. 354 p.

Emerson, W. W., and R. D. Bond. 1963. The rate of water entry into dry sand and calculation of the advancing contact angle. Aust. J. Soil Res. 1:9-16.

Jamison, V. C. 1945. The penetration of irrigation and rain water into sandy soils of Central Florida. Soil Sci. Soc. Am. Proc. 10:25-29.

Kubota, T. 1971. Effects of organic matter on Atterberg limits with relation to the stability of soil structure [in Japanese, English summary]. Sci. Soil Manure, Jpn. 42:7-11.

Letey, J., J. Osborn, and R. E. Pelishek. 1962. Measurement of liquid-solid contact angles in soil and sand. Soil Sci. 93:149-153.

Maeda, K. 1974. The physical properties of the paddy field soil treated with the successive application of rice straw [in Japanese]. Soil Physical Conditions and Plant Growth, Jpn. 30:33-38.

Mashimo, Y. 1960. Studies on the physical properties of forest soil and their relation to the growth of Sugi *(Cryptomeria japonica)* and Hinoki *(Chamaecyparis obtusa)* [in Japanese, English summary]. For. Soils Jpn. Rep. 11:1-182.

Motomura, S., and N. Nakaya. 1980. The effect of long-term fertilization on the physical properties of the paddy soils [in Japanese]. Abstr. I980 Meeting, Soc. Sci. Soil Manure, Jpn. 26:5 p.

Nakaya, N., H. Yokoi, and S. Motomura. 1977. The method for measuring of water repellency of soil. Soil Sci. Plant Nutr. 23:417-426.

Nakaya, N. 1981. The moisture characteristics of soils in relation to organic matter and water repellency [in Japanese, English summary] Bull. Natl. lnst. Agric. Sci. Jpn. B 32:l-74.

Nomoto, K., and H. Nakamura. 1959. Effect of irrigation on upland rice plant [in Japanese, English summary]. Bull. 2nd Agro. Div., Tokai-Kinki Natl. Agric. Exp. Stn. Jpn. 1:52-67.

Ohmasa, M. 1951. Studies on beech forest soils [in Japanese. English summary]. For. Soils Jpn. Rep. 1:1-243.

Parr, J. F., and A. R. Bertrand. 1960. Water infiltration into soils. Adv. Agron. 12:311-363.

Scholl, D. G. 1971. Soil wettability in Utah Juniper Stands. Soil Sci. Soc. Am. Proc. 35:344-345.

van’t Woudt, B. D. 1954. On factors governing subsurface storm flow in volcanic ash soils, New Zealand. Trans. Am. Geophys. Union. 35:136-144

Yamashita, K. 1967. The effects of the prolonged application of farmyard manure on the nature of soil organic matter and chemical and physical properties of paddy rice soils [in Japanese, English summary]. Bull. Kyushu Agric. Exp. Stn. Jpn. 13:113-156.

Yokoi, H. 1965. Studies on soil water of irrigated mineral soil [in Japanese, English summary]. Bull. Tokai-Kinki Natl. Agric. Exp. Stn. Jpn. 12:l-26.

# EFFECTS OF ORGANIC MATTER MANAGEMENT ON LAND PREPARATION AND STRUCTURAL REGENERATION IN RICE-BASED CROPPING SYSTEMS

S. K. De Datta and S. S. Hundal

Wetland rice culture common to Asia results in soil structure deterioration and creates a poor physical environment in the soil for dryland crops in a rice-based cropping system. Good management and recycling of organic matter from crop residues and organic manures improve soil tilth and help regenerate favorable soil structure for the dryland crops.

Incorporating organic matter into the soil improves its structure through increased aggregation, which favorably influences tillage properties, crusting, water infiltration, moisture retention, drainage, aeration, temperature, and root penetration. In silty soils, organic matter decreases slaking sensitivity, whereas in wet clay soils, it increases resistance of the soil mass to plastic deformation. Adding organic matter may alter soil shrinkage properties, improve tilth, and reduce draft requirements for preparing the seedbed for dryland crops.

Greater benefits are obtained by adding organic matter to heavy soils and soils with poor structure than to light-textured soils and soils with good inherent structure. The paper reviews research on the role of organic matter management in the maintenance of soil structure. It suggests critical research needs for further investigation.

Organic matter plays a prominent role in sustained productivity of tropical soils under continuous cultivation. Soils in the rice-growing regions of tropical Asia are generally low in organic matter, and the need for judicial management and recycling of organic matter is very important. The beneficial roles of organic matter in increasing the level of soil fertility and improving soil physical conditions are well recognized. Addition of organic matter to soils has been practiced since ancient times to increase crop yields and maintain soil productivity.

---

Agronomist and head, and postdoctoral fellow, Department of Agronomy, International Rice Research Institute, P.O. Box 933, Manila, Philippines.

In order to meet increasing food demands, intensive systems of crop production are advocated to increase total crop yield from a given piece of land. An increase in cropping intensity implies the inclusion of an additional rice crop or dryland crop in the existing cropping pattern. More than two-thirds of the rice area in Asia is cultivated under wetland rice culture, in which soil is plowed wet, puddled, and kept flooded during the duration of the rice crop. Wetland rice culture destroys soil structure and presents a poor soil physical environment for the dryland crops following rice. Attaining optimum yields of dryland crops grown in sequence with wetland rice requires regeneration and maintenance of soil structure favorable to the dryland crops. How the land is prepared for rainfed rice culture determines the amount of energy required, the cropping intensity, and the nutrient and water availability. Information on the physical properties of rainfed rice soil related to these parameters is limited in a rice-based cropping system (De Datta and Barker 1978). In this paper, the role of organic matter management in seedbed preparation and structural regeneration of soil in the rice-based cropping systems will be reviewed.

## RICE-BASED CROPPING SYSTEMS IN ASIA

Rice-based cropping systems practiced in Asia can be categorized into rainfed and irrigated. Based on the practice of rice crop culture, the rainfed category may be subdivided into dryland and wetland systems. Dryland (or upland) rice commonly refers to the rice culture that does not seek accumulation of water on the soil surface, whereas wetland (or lowland) rice culture encourages accumulation of water on the soil surface by providing levees around the fields to impound rain water. Nearly 80% of the total rice area in Asia is planted to wetland rice, while dryland rice constitutes about 13% (Huke 1982). Some of the dryland areas in Asia are planted to a single rice crop per year; in others, one or more dryland crops are intercropped, relay cropped, or sequentially cropped with rice. In wetland rice areas, rice is grown during the main monsoon season, and dryland crops are grown in sequence with rice during the premonsoon and the postmonsoon moist periods. The irrigated rice-based cropping systems in Asia invariably use wetland rice culture, where rice is grown in puddled soil, primarily as a transplanted crop. Nearly 32% of the rice receives irrigation in South and Southeast Asia (De Datta 1981).

Field experiments at IRRI have suggested that cropping system and crop residue management affect soil consistency, with pronounced effects on the range of soil moisture optimal for tillage in a sandy clay loam soil. In the same experiments, cultivation of the sandy clay loam soil decreased the apparent specific volume (ASV) after land preparation compared to the ASV before land preparation, resulting in a negative $\Delta$ASV (Table 1). The incorporation of leguminous crop residues at 11 t/ha during land preparation for dryland rice caused soil to be more compact than did incorporation of nonleguminous crop residues at 14 t/ha (Fagi and De Datta 1982). Leguminous crop residues decomposed faster, and their beneficial physical effects, if any, were shortlived.

Cropping patterns in wetland rice soils are determined by the amount and distribution of rainfall, availability of irrigation water, climate, hydrology, and the

**Table 1. Changes in apparent specific volume (DASV) and porosity of sandy loam soil as affected by cropping system and crop residue management.[a] IRRI, 1979 wet season.**

| Cropping system and crop residue management | DASV ($cm^3/g$) | Change in porosity (%) |
|---|---|---|
| After soybean followed by cowpea | | |
| residue incorporated | –0.051 d | –3 a |
| residue mulched | –0.023 bc | –1 a |
| After maize followed by sorghum | | |
| residue incorporated | –0.033 cd | –1 a |
| residue mulched | –0.020 abc | –1 a |
| Weedy fallow | –0.010 ab | 5 a |

[a] In a column, means followed by a common letter are not significantly different at the 5% level.

land and soil environments. Three types of cropping patterns are commonly recognized:

1. Rice - fallow,
2. Rice - dryland crop or rice - rice - dryland crop, and
3. Continuous rice for some years followed by dryland crop for a few years.

The main source of crop residues in pattern 1 is rice straw. For example, in northern Japan, where cold winters prevail, only one rice crop is grown, and the rice straw is composted before application (Dei 1975). In the second pattern, where the crop residues consist of rice straw and residues from dryland crops, incorporation of rice straw is the chief method of residue management in Japan. Tanaka (1973) summarized the various methods of utilization of rice straw in rice-growing countries. Straw is primarily returned to soil as compost in Japan, Korea, and China; burned in the Philippines, Thailand, Indonesia, and Malaysia; used as animal feed or bedding in India, Bangladesh, Sri Lanka, Pakistan, Burma, and Egypt; and incorporated into the soil or burned in the USA, Australia, and the southern European countries. Other means of straw disposal include use as fuel, mulch, roofing, and packing material, and in paper manufacture.

## ORGANIC MATTER MANAGEMENT SYSTEMS

### Crop residues

Residues from crops constitute a major resource for organic matter recycling in crop production. Management of crop residues can be classified into: surface crop residues, such as straw mulched on the soil surface and standing residues of the previous crop; incorporation of residues; complete removal of residues; and burning of crop residues.

Different systems of residue management influence soil water content, soil temperature, soil strength, soil aeration, and crop response to varying degrees (Van Doren and Allmaras 1978). Favorable effects of crop residues on soil water conservation, soil temperature, and crop response have been reported by several investigators (McCalla and Army 1961, Unger and Parker 1968, Larson et al 1970, Hundal and De Datta 1982). The physical parameters of soil strength and aeration are inversely related to soil water content changes in so far as they are influenced by the crop residues. The introduction of no-tillage farming systems encourages maintenance of crop residues on the soil surface and helps build up organic matter and control of soil erosion by wind and water.

The unfavorable effects of crop residues have also been recognized, primarily in temperate regions where their presence on the soil surface reduces springtime soil temperatures and reduces evaporation, delaying soil drying and planting in poorly drained soils such as those in the midwestern USA. The presence of crop residues has also been reported to tie up soil N during initial decomposition, but such adverse effects are more likely to happen in temperate areas than in tropical Asian countries. In the past, long-term systematic studies on evaluation of crop residue management in situ and their effects on soil physical properties in rice-based cropping systems have been nonexistent and, therefore, need attention.

### Bulky organic manures

In the past, farmyard manure (FYM) and compost have been extensively used in Japan, Korea, China, and India. In recent years, with the increase in use of inorganic fertilizers and the scarcity of labor in industrialized Japan and Korea, use of inorganic fertilizers has declined considerably. However, in China and India, where labor is less costly, bulky manures are still widely used to supplement inorganic fertilizers. In India, a major proportion of animal excretions (cow dung) is being used for fuel; however, in China nearly all animal and human wastes are composted or treated in bio-gas production systems and the residues are returned to the soil. Long-term experiments on the use of bulky organic manures in India have demonstrated the beneficial role of organics in the maintenance of soil productivity. In these experiments, the primary emphasis was given to yield performance of different crops and soil fertility evaluations with comparatively little emphasis on simultaneous evaluation of soil physical parameters and tillage properties of soils.

### Green manuring

Green manuring is practiced extensively in China in rotation with rice to maintain soil fertility. Nearly 10 million ha covering one-third of the rice area in China are planted to green manure crops during the winter season. Milk vetch is the dominant green manure crop and covers nearly 75% of the area. Other crops used for green manuring in China include vetches, broad bean, and *Sesbania.* In other Asian countries, various crops commonly used for green manuring include sunnhemp *(Crotalaria juncea),* guar *(Cyamopsis tetragonoloba).* and dhaincha *(Sesbania aculeata)* in India, and ipil-ipil *(Leucaena leucocephala)* in the Philippines. Green manuring is not widely practiced in other South and Southeast Asian rice-growing countries. A green manure crop requires fertilizer and water inputs and takes land out of grain production for its duration. The economic benefits largely control its adoption as a general practice in these countries.

Incorporation of green manure crops into the soil has been shown to increase organic C, total N, and crop yields (Williams et al 1957, Havangi and Mann 1970, Gu and Wen 1981). The favorable effects on soil physical properties of incorporating organic matter from green manure crops have been reported in the the literature

(Williams et al 1957, Biswas et al 1970, Havangi and Mann 1970, Hundal et al 1971). Green manuring is not recommended in poorly drained soils as it may result in the accumulation in the soil of toxic substances that affect rice yields adversely (Sahoo et al 1970).

In some areas, azolla is applied to rice fields to supply N. The large biomass of azolla also supplies organic matter to the soil. Azolla application to rice is common in China, where it covers about 9% of the total green-manured area (Gu and Wen 1981).

## EFFECTS OF FLOODING AND PUDDLING ON SOIL STRUCTURE IN WETLAND RICE-BASED CROPPING SYSTEMS

Soil structure is adversely affected by the practices of flooding and puddling in wetland rice culture. When an aggregated soil is wetted with excess water, the soil aggregates experience reduction in both intra- and inter-aggregate cohesion (Koenigs 1961). The decrease in cohesive forces at saturation results from increased thickness of water films surrounding the soil particles and loss of contact points between the soil aggregates. Wetting also leads to air entrapment and unequal swelling of the soil aggregates. These factors favor breakdown of the soil aggregates; however, the degree of stability of the aggregate is controlled by binding forces that differ with the type of clay and the nature of organic and inorganic complexes.

The process of puddling by wet plowing and harrowing operations exerts mechanical forces on the wet aggregates, resulting in their further disintegration. The degree of puddling is controlled largely by the mechanical composition of the soil, type of clay minerals, organic matter content, and the exchangeable cations. Soils containing clay and silt are easier to puddle than a sandy soil. Furthermore, soils containing swelling clays, such as montmorillonite, can be puddled more easily than those containing kaolinite (Buehrer and Rose 1943). Saturation of soil with $Na^+$ has been shown to facilitate puddling more than when $Ca^{2+}$ is the dominant cation (McGeorge 1937). An increase in level of organic matter in a soil results in an increasing degree of resistance to puddling (Buehrer and Rose 1943). Koenigs (1963) attributed effects of organic matter to the binding action of organic bonds between clay polyplates. An increase in organic matter decreases the slaking sensitivity of silty soils and increases the resistance to plastic deformation in heavy clay soils (Boekel 1963).

Puddling, in general, destroys soil aggregation (McGeorge 1937, Kawaguchi et al 1956) and results in decreased macroporosity, an increase in microporosity (Bodman and Rubin 1948, Jamison 1953), an increase in bulk density (Bodman and Rubin 1948, Dutt 1948), an increase in moisture retention (Jamison 1953, De Datta and Kerim 1974), reduced soil aeration (Aomine and Shiga 1959), and reduced hydraulic conductivity (Varade and Ghildyal 1967). These physical conditions of the puddled soil are antagonistic to the growth of dryland crops following rice. For example, in parts of southeastern China, triple croppings of rice - rice - wheat or rice - rice - green manure are grown — rice being a natural crop due to prolonged waterlogging in those areas. However, with triple cropping, the plow layer becomes thin and compact as a result of aggregate destruction. As a result, permeability of water in the plow layer decreases, which affects wheat growth (Yi et a1 1980). However, it is not clear how green manure in the rotation affects the soil's physical properties. In order to encourage optimum growth of crops in rotation with rice, the soil structure must be regenerated to a satisfactory level for the dryland crops.

## REGENERATION OF SOIL STRUCTURE

The adverse physical conditions of the soil produced as a result of changeover from granulated to the puddled system can be reversed provided that the moisture content is first lowered below the lower plastic limit (Koenigs 1963). Drying of a puddled soil induces the capillary forces to help re-establish contact between primary clay particles, which provide the essential mechanism of the restructuring process in soils. Fragmentation of the puddled soil mass into smaller units upon drying, followed by their stabilization, leads to regeneration of soil structure. In rice-based cropping systems of Asia, restructuring the puddled soil has received little attention from researchers. Various factors control the regeneration of soil structure, including the role of soil texture and clay mineralogy; the role of ferric hydroxides during oxidation in the soil following wetland rice; the rate and degree of soil drying; depth, timing, and types of tillage operations; and organic matter management. These factors need more critical investigation.

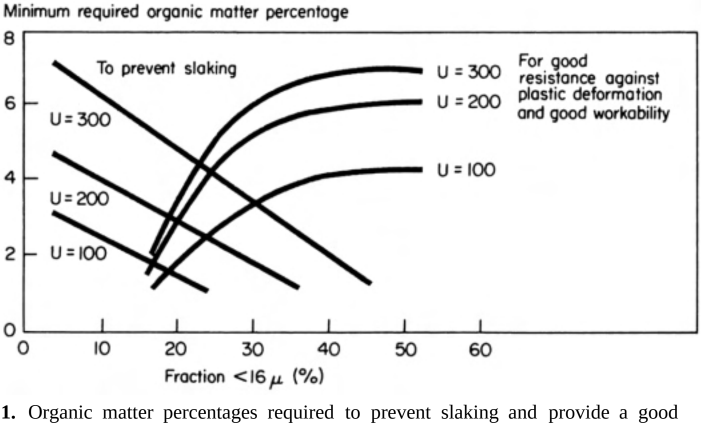
Alternate drying and wetting of puddled soil regenerates soil structure by affecting soil cracking, differential swelling, explosions of entrapped air, and softening the puddled soil mass leading to granulation. In temperate regions, freezing and thawing during winter and spring result in similar effects by breaking down larger clods into granular structures. The role of organic matter in improving soil structure is well recognized. Robinson and Page (1951), working with a puddled soil, observed that addition of colloidal humified organic matter increased regeneration of soil structure and aggregation upon wetting and drying. A 40-year field study compared green manuring with a control of no green manure at the Central Agricultural Experiment Station, Konosu, Japan (Dei and Maeda 1973). Green manuring resulted in a well developed aggregated structure in the plowed layer of a paddy field, whereas the control field showed a large and compact blocky soil structure. The introduction of dryland crops in rotation with rice has also improved soil physical conditions (Ikeda and Harada 1956, Takahashi and Shibusawa 1956, Mahapatra and Sadanandan 1973, Yi et al 1980, Li and Li 1981, Xu 1981). The dryland crops grown after rice promote soil granulation through their extensive root systems. Dutt (1948) observed increased aggregation when a rye or vetch crop was grown on the puddled soil; however, the greatest aggregation was obtained with straw mulch up to 1 year after puddling.

## ORGANIC MATTER AND TILLAGE PROPERTIES OF SOILS

In general, there is a close correlation between the amount of organic matter in soils and soil tilth. Long-term cultivation of soils low in organic matter leads to deterioration in soil structure. The presence of abundant organic matter markedly decreases any harmful effects of cultivation and actually widens the optimum moisture range at which cultivation can take place without, harmful effects. In finer textured soils, where physical effects of organic matter are more important than the chemical ones, soil tilth is affected favorably by addition of organic matter. In sandy soils, the beneficial effects of organic matter addition result largely from an increase in moisture-holding capacity due to the higher level of available nutrients in the organic matter.

Organic matter influences the shrinkage (Lauritzen 1948) and plastic behavior of soils (Odell et al 1960, Boekel 1963). When a wet soil undergoes drying, two phases of shrinkage are recognized. The first phase is the “normal shrinkage” range, in which the reduction in the bulk soil volume is proportional to the reduction in soil water content. In this case, the volume vacated by soil water is not made available for air entry. The second phase of “residual shrinkage” succeeds normal shrinkage and is characterized by air occupying the pore spaces emptied by water removal. Soils showing an absence of normal shrinkage suffer less from puddling and do not experience poor soil aeration. Lauritzen (1948) reported that the addition of organic matter in the form of alfalfa meal to a silt loam and a clay soil was effective in eliminating “normal soil shrinkage” and favorably affected soil aeration.

An increase in organic matter content decreases the slaking sensitivity in silty soils and increases the resistance to plastic deformation (puddling) caused by the mechanical forces in wet clay soils (Boekel 1963). These favorable effects of organic matter were related to the observation that an increase in organic matter content increased the soil consistency limits (upper and lower plastic limits) to a greater extent than the corresponding increase in field capacity of the soil expressed at — 100 cm of soil matric potential. Boekel assumed the soil to be resistant to slaking if the upper plastic limit exceeded field capacity by at least 3%. Alternatively, good soil resistance to plastic deformation was assumed as long as field capacity did not exceed the lower plastic limit by more than 3%. Results reported by Boekel (1963) are reproduced in Figure 1, showing the organic matter contents required for prevention of slaking and for resistance to plastic deformation in soils of varying mechanical composition. As clay content decreases and fineness of sand fraction



**1.** Organic matter percentages required to prevent slaking and provide a good resistance to plastic deformation by mechanical forces and a good soil workability (source: Boekel 1963).

**Table 2. Soil strength in relation to soil density and moisture.**[a]

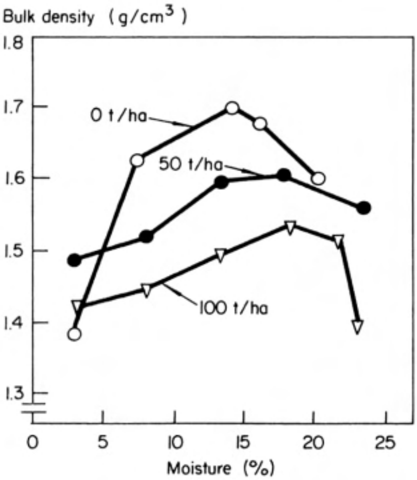
| Dry bulk density ($g/cm^3$) | Soil moisture (%) | Maximum shear strength (bars) |
|---|---|---|
| 1.10 | 28 | 0.344 |
| 1.40 | 28 | 0.618 |
| 1.22 | 18 | 0.895 |
| 1.56 | 18 | 1.790 |

[a] Source: Bateman et al (1965).

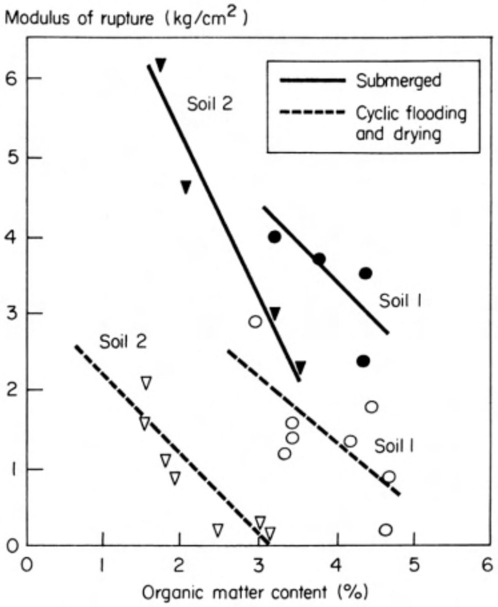
increases, higher levels of organic matter are required to prevent slaking. On the other hand, higher organic matter was required with increasing clay content and fineness of sand fraction to resist plastic deformation.

For insertion of dryland crops into a rice-based cropping system, puddled clay soils planted to wetland rice are allowed to dry before land preparation for the dryland crop. On drying, the clay soil undergoes an increase in soil density or compaction and an increase in soil strength (Chancellor 1971). Shear strength of the soil at similar moisture contents has been shown to increase with an increase in bulk density (Table 2), as reported for a silty clay loam by Bateman et al (1965). However, the importance of bulk density per se on the draft force of agricultural implements remains to be established.

Russel et al (1952) reported bulk density vs moisture content relations using the Proctor test on a silt loam soil after 25 years of continuous horse manure applications at 0, 50, and 100 t/ha per year. Their results (Fig. 2) showed that soil receiving higher rates of manure attained lower bulk densities than the untreated soil at equivalent moisture contents. Also, the maximum densities occurred at greater moisture contents in the treated soil compared to the control. These results indicate that the Proctor test response from organic matter additions to a soil was similar to the response commonly observed by increasing clay content and fineness of soil texture.



**2.** Proctor soil compaction curves showing the effect of manure application on the susceptibility to compaction of Sassafras silt loam (source: Russel et a1 1952).



**3.** Effect of organic matter content and incubation water regime on modulus of rupture of dried soil cores from a permeable wetland rice soil (soil 1) and a red earth (soil 2) (adapted from Yuan and Zhou 1981).

The modulus of rupture in paddy soils is influenced by additions of organic matter, by moisture regime, and by the mechanical properties of the soil. In a laboratory incubation study from China (Fig. 3), additions of organic matter in the range of 1-5% using rice straw or milk vetch reduced the modulus of rupture on soil cores by as much as 40-80%. At equivalent soil organic matter contents, the value of modulus of rupture was higher in flooded soil than in soil subjected to intermittent flooding and drying over a 4-month period. Tiarks et a1 (1974) reported modulus of rupture values in a silty clay loam 3 years after application of cattle feedlot manure. Their results showed that application of 0, 90, 180, and 360 t manure/ha per year to the 10-cm soil depth resulted in modulus of rupture values of 0.60, 0.47, 0.29, and 0.08 bars, respectively.

In a Japanese study, Miki and Mori (1966) applied compost or incorporated rice straw at 10 t/ha for 3 years. They found an increase in the number of clods less than 1 cm in diameter and a decrease in those greater than 3 cm after plowing and harrowing. They also found a large increase in aggregates greater than 0.5 mm.

In an Iowa study on a silty clay loam having good initial physical conditions, additions of up to 16 t organic matter/ ha for 13 consecutive years failed to show any visual changes in soil tilth (Morachan et a1 1972). The energy of aggregate rupture and infiltration was not affected significantly.

Actual field measurements of drawbar pull (draft force) made with a dynamometer in soils of different texture and management were reported by Low and Piper (1973). Application of farmyard manure reduced the draft force, but to a smaller extent than the soil maintained in grass sod for several years. The reduction in draft force was related to stability of aggregates, increased pore space, and decreased apparent density of soil clods (Table 3).

**Table 3. Effect of farmyard manure (FYM) application on draft force and soil properties in a loam soil.**[a]

| Treatment | Drawbar[b] pull (kN) | Organic matter (%) | Apparent density (g/cm$^3$) | Total porosity (%) | Air-filled volume at field capacity (%) |
|---|---|---|---|---|---|
| FYM | 1.52 | 4.0 | 1.34 | 48.6 | 9.5 |
| Control | 1.66 | 3.0 | 1.38 | 46.9 | 8.3 |

[a] Adapted from Low and Piper (1973). FYM applied for 6 consecutive years at 75 t/ha per year. [b] Draft force recorded during plowing at 15-cm depth using a single-furrow plow.

The most important soil property associated with draft requirements of tillage tools is the soil strength, which characterizes the mechanical properties and behavior of soil based on soil parameters of friction, shearing strength, and resistance to deformation and rupture. Unfortunately, information on parameters of this type is generally lacking in most studies of soil compaction and draft requirements associated with crop production systems (Gill 1971). The effects of organic matter on soil strength parameters related to tillage properties of soils have not been critically evaluated and need attention by researchers.

## ORGANIC MATTER AND SOIL STRUCTURE

Soil organic matter affects most of the physical, chemical, and biological properties of soils. It affects the soil physical environment through its influence on soil aggregation, which in turn influences soil crusting, water infiltration, moisture content, drainage, aeration, temperature, microbial activities, and root penetration. In this way, application of organic matter acts indirectly to improve the physical condition of the soil. The major impact of soil structure is associated with compaction, aeration, and root development. As the percentage of organic matter decreases in a given soil, the bulk density increases with a significant decrease in aeration porosity. The combination of increased density and decreased aeration restricts root development, impairs normal absorption by the roots, and impedes microbiological activity.

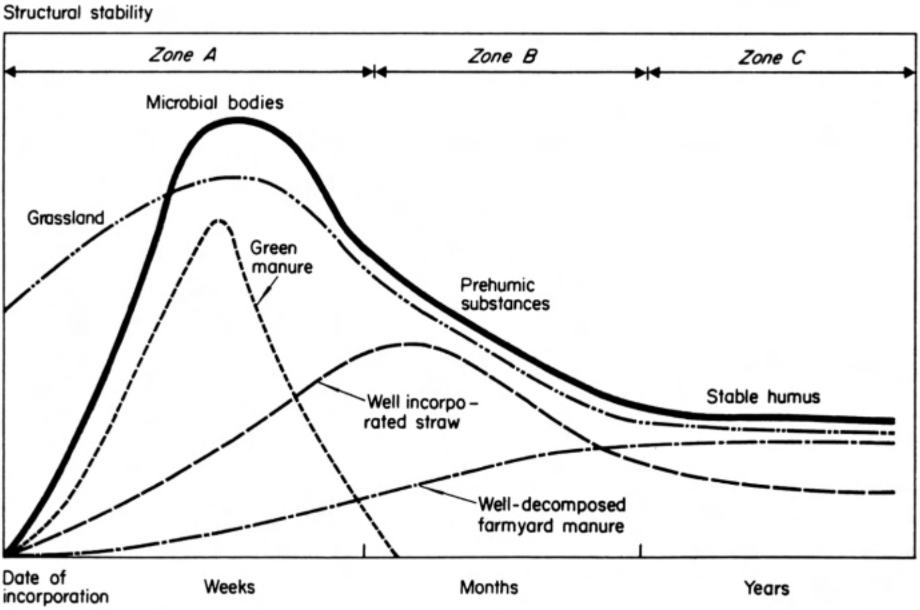
The action of organic matter on soil structure is difficult to measure, as it varies with soil texture and clay type. The physical properties of humus have much more importance in the clay-textured soils than in sandy soils, whereas in sandy soils the importance of the chemical properties of humus is greater in both temperate and tropical climates (Primavesi 1968).

### Soil aggregation

The dominant role of organic matter in improving soil structure through formation and stabilization of soil aggregates has been amply demonstrated (Allison 1973). Several organic materials promote soil aggregation, but their effects vary greatly with the amount and frequency of application, nature and composition of organic materials, stage and rate of decomposition, soil moisture content, and soil type, among others. Greenland (1965) and Theng (1974) studied and reviewed the various mechanisms involved in aggregate stability.

Monnier (1965) discussed the role of crop residues, full or partially decomposed manure, green manuring, and meadow cultivation on the structural stability of soil. In the evolution of organic matter he divided soil structural stability into three phases corresponding to successive phases of microbial bodies, prehumic products, and humus (Fig. 4). Easily decomposable materials very low in humus (e.g., green manure) produce short but intense effects that correspond to the first phase. Well-decomposed manure, on the other extreme, has long-term effects and maintains a basic level of stability. Grassland provides both prehumic and humic phases, thus maintaining and increasing soil structure stability. It is well established that quality rather than quantity of organic matter is more important in structural improvement of soils (Kumar and Ghildyal 1969, Biswas et al 1970, Allison 1973). Not all kinds of organic matter are active stabilizing agents. For example, undecomposed crop residues and well-rotted manures and composts are not especially effective. The soil aggregates are stabilized chiefly by microbial gums produced during decomposition of the organic matter. These gums consist mostly of polysaccharides, polyuronides, cellulose, humus breakdown products, and other linear organic polymers (Allison 1973).

Green manure crops are readily decomposed and result in faster aggregate stabilization after their incorporation into the soil. Biswas et al (1970) found that, in a sandy loam soil in rice - fallow rotation, green manuring with sunnhemp compared to FYM application during a 10-year period gave the maximum beneficial response in terms of soil aggregate stability. Williams et al (1957) reported



**4.** Schematic representation of various phases of soil structural stabilization by different kinds of organic matter (source: Monnier 1965).

**Table 4. Water-stable soil aggregates >2 mm in diameter in relation to the use of organic materials and soil conditioners in a pot experiment.**[a]

| Treatment | Aggregates (%) |
|---|---|
| Krilium (soil conditioner) | 71 |
| Rice straw | 63 |
| Compost | 48 |
| Control | 39 |

[a] Source: Oh (1964).

green manuring after rice harvest during a 5-year period to increase rice yields and reduce the harmful effect of N tieup by straw during the subsequent rice crop.

Martin and Waksman (1940) reported that organic materials, which are more resistant to decomposition, have a more lasting effect on soil aggregation. In a study using rice husk, wheat straw, millet (*Pennisetum typhoideum*), guar, berseem (*Trifolium alexandrinum*), and sawdust as sources of organic matter in a sandy loam and a sandy clay loam, Verma and Singh (1974) found that after 16 weeks of incubation in the laboratory, millet and wheat straw were the best aggregating materials. In another field study, rice straw applied 2 weeks before puddling resulted in better aggregation than FYM application (Chaudhary and Ghildyal 1969). They also observed greater aggregation 60 and 120 days after puddling than immediately after puddling for rice. In a Korean laboratory incubation study, Oh (1964) observed greater aggregation with rice straw than with compost (Table 4) and ascribed the lower aggregate stability of compost-treated soil to the well-decomposed nature of the compost. Mahapatra and Sadanandan (1973) observed that growing a wetland rice crop in a rice - rice rotation in an alluvial sandy loam decreased aggregation from its initial high values. Including a dryland crop of maize or potatoes in the rotation and applying FYM at 12 t/ha to maize or at 20 t/ha to potatoes resulted in improved aggregation of the soil after two cropping cycles (Table 5).

Many studies of soil aggregation have been made where crop residues were incorporated into the plow layer. There have been few studies on the beneficial effects of organic matter when crop residues are used as mulch on the soil surface. Allison (1973) concluded that organic residues left on the soil surface may be as valuable in aggregate formation as if they were thoroughly mixed with the soil. The leaching products from the decaying mulches probably furnish all of the polysac-

**Table 5. Effect of intensive cropping on percent of water stable aggregates >0.25 mm in diameter.**[a]

| Crop pattern[a] | Aggregates (%) | | |
|---|---|---|---|
| | Initial status | After first cycle | After second cycle |
| Rice - rice - potato | 59 | 19 | 31 |
| Rice - rice - maize | 59 | 16 | 29 |
| Rice - rice | 59 | 21 | 21 |

[a] Adapted from: Mahapatra and Sadanandan (1973). The dryland crops of maize and potato received farmyard manure at 12 and 20 t/ha, respectively.

charides and related substances needed for use as aggregating cements, while the other physical factors (such as wetting and drying, growing crop roots, etc.) serve primarily as aggregate formers.

Wilson and Fisher (1946) reported increased aggregation by increasing amounts of organic matter up to 2% organic C from dried white vetch in a Lintonia silt loam containing 1.04% organic C. On the other hand, in Olivier silt loam with high initial aggregation and an organic C content of 1.40%, additions of organic matter did not result in greatly enhancing aggregation.

Thus, it seems that little improvement can be expected from the addition of organic matter to soils of good initial soil structure. Baver (1958) indicated the maximum beneficial physical effects of organic matter to be expected in poorly aggregated soils low in clay and organic C contents.

### Other soil physical properties

Soil organic matter plays a significant role in aggregation and related soil physical properties controlling soil water-air relations. In India, Biswas et al (1970) reported results from adding FYM, groundnut cake, and green manure (providing 45 kg N/ha per year) in a rice-fallow rotation for 10 years in an alluvial sandy loam. The organic manures improved water-stable aggregation, hydraulic conductivity, and water retention characteristics, with green manure showing the most benefits. In another study, increasing FYM application from 17.4 to 69.7 t/ha per crop in a maize - wheat rotation resulted in improved structure and increased water retention as well as decreased bulk density of the sandy loam soil (Biswas et a1 1971). Similarly, in a sandy clay loam soil, application of FYM at 15 t/ ha for 3 years in a rice - wheat rotation increased the organic C and total N (Formoli and Prasad 1979). The effects were greater when FYM was applied to both rice and wheat rather than to one crop.

Heavy application of organic manures has increased organic C content and decreased bulk density (Klute and Jacob 1949, Russel et a1 1952, Miki and Mori 1966. Biswas et a1 1971, Tiarks et a1 1974). increased hydraulic conductivity (Miki and Mon 1966, Tiarks et a1 1974, Gupta et a1 1977), and increased moisture retention (Biswas et a1 1971, Morachan et a1 1972, Gupta et a1 1977). The reported effects on available water capacity of the soil of adding organic matter are often contradictory. An increase in available water capacity was reported by Salter and Haworth (1961), Biswas et a1 (1971), and Miki and Mori (1966), whereas Klute and Jacob (1949), Havangi and Mann (1970), and Gupta et a1 (1977) found no positive response to adding organic matter.

Jamison (1953) stated that adding organic matter to well-drained soils does not affect their capacity to store available water released between–0.06 and –15 bar soil matric potentials. Some exceptions to this rule are the coarse-textured soils that have very low capacity to store available water. Improvement of these soils with organic matter additions is mostly a matter of dilution of a material of low water holding capacity with one of a fair capacity. In fine-textured soils, aggregation is usually accompanied by an increase in air capacity, but with no increase in available water capacity because of increased macropores that drain at tensions below 0.06 bar or because of an increase in micropores that drain at tensions much greater than 15 bars. Salter and his associates (Salter and Haworth 1961, Salter et a1 1967) report

**Table 6. Effect of application of green manure on physical properties of a paddy soil after 3 annual applications.**[a]

| Treatment | Penetration resistance (kg/cm$^2$) | Bulk density (g/cm$^3$) | Total porosity (%) | Non-capillary porosity (%) | Water-holding capacity (%) |
|---|---|---|---|---|---|
| Check | 31 | 1.23 | 54 | 4.4 | 38 |
| Azolla | 28 | 1.11 | 58 | 4.5 | 46 |
| Check | 31 | 1.25 | 53 | 7.0 | 35 |
| Common water hyacinth | 26 | 1.20 | 55 | 6.8 | 40 |
| Check | 32 | 1.18 | 56 | 8.8 | 39 |
| Rice straw | 26 | 1.14 | 57 | 6.1 | 42 |

[a] Source: Gu and Wen (1981).

that application of FYM at 50 t/ha per year for 6 years to a sandy loam soil increased the available water capacity of the soil. They contend that failure to detect increases in available water capacity in other comparable reports in the literature was due to failure of techniques for evaluating the upper and lower limits of available water rather than to lack of increase in available water capacity of an organic matter-amended soil. Most studies reporting no increase in available water capacity employed 0.33 bar as the upper limit of available water, which may not be realistic for coarse-textured soils.

Incorporation of green manures (azolla and common water hyacinth) and rice straw during a 3-year period has been shown (Table 6) to reduce bulk density and resistance to penetration and increase total porosity and water-holding capacity. But it produced no differences in noncapillary porosity in a paddy soil from China (Gu and Wen 1981). Incorporation of crop residues from corn stalks and alfalfa at 0, 2, 4, 8, and 16 t/ha during 13 consecutive years in a silty clay loam soil in Iowa, USA, increased C content, wet aggregate stability, and soil moisture retention (Morachan et al 1972).

Heavy applications of organic manures may also influence the thermal and hydraulic properties of the soils. In a field study, Gupta et al (1977) reported that application of sewage sludge at 0, 112, 225, and 450 t/ha to a sandy soil increased soil organic matter content from 1 to 5%. Increasing organic matter in the soil increased its specific heat capacity, but resulted in decreased thermal conductivity, decreased unsaturated hydraulic conductivity, and decreased soil-water diffusivity.

## REFERENCES CITED

Allison, F. E. 1973. Soil organic matter and its role in crop production. Elsevier, Amsterdam. 637 p.

Aomine, S., and Y. Shiga. 1959. Soil fabrics of the plowed layer of flooded rice fields. Soil Plant Food 5:64-72.

Bateman, H. P., M. P. Naik, and R. R. Yoerger. 1965. Energy required to pulverize soil at different degrees of compaction. J. Agric. Eng. Res. 10:132-141.

Baver, L. D. 1968. The effect of organic matter on soil structure. Pages 383-413 *in* Study week on organic matter and soil fertility. John Wiley & Sons, Inc., New York.

Biswas, T. D., B. L. Jain, and S. C. Mandal. 1971. Cumulative effect of different levels of manures on the physical properties of soil. J. Indian Soc. Soil Sci. 19:31-37.

Biswas, T. D., M. R. Roy, and B. N. Sahu. 1970. Effect of different sources of organic manures on the physical properties of the soil growing rice. J. Indian Soc. Soil Sci. 18:233-242.

Bodman, G. B., and J. Rubin. 1948. Soil puddling. Soil Sci. Soc. Am. Proc. 13:27-36.

Boekel, P. 1963. The effect of organic matter on the structure of clay soils. Neth. J. Agric. Sci. 11(4):250-263.

Buehrer, T. F., and M. S. Rose. 1943. Studies in soil structure. V. Bound water in normal and puddled soils. Arizona Agric. Exp. Stn. Tech. Bull. 100.

Chancellor, W. J. 1971. Effect of compaction on soil strength. Pages 190-212 *in* Compaction of agricultural soils. Monograph, Am. Soc. Agric. Engr. St. Joseph, Mich.

Chaudhary, T. N., and B. P. Ghildyal. 1969. Aggregate stability of puddled soil during rice growth. J. Indian Soc. Soil Sci. 17:261-265.

De Datta, S. K. 1981. Principles and practices of rice production. John Wiley & Sons, New York. 618 p.

De Datta, S. K., and R. Barker. 1978. Land preparation of rice soils. Pages 623-648 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

De Datta, S. K., and M.S.A.A.A. Kerim. 1974. Water and nitrogen economy of rainfed rice as affected by soil puddling. Soil Sci. Soc. Am. Proc. 38(3):515-518.

Dei, Y. 1975. The effects of cereal crop residues on paddy soils. ASPAC Food and Fert. Tech. Ctr. Ext. Bull. 49. 29 p.

Dei, Y., and K. Maeda. 1973. On soil structure of plowed layer of paddy field JARQ 7:86-92.

Dutt, A. K. 1948. Puddling and other treatments in relation to soil structure and crop growth. J. Am. Soc. Agron. 40:324-330.

Fagi, A. M., and S. K. De Datta. 1982. Physical properties of rainfed wetland rice soils as affected by cropping system and crop residue management. (Unpublished paper)

Formoli, G. N., and R. Prasad. 1979. Effects of farmyard manure and phosphorus in rice-wheat rotation. J. Agric. Sci. Camb. 92:359-362.

Gill, W. R. 1971. Economic assessment of soil compaction. Pages 431-456 *in* Compaction of agricultural soils. Monograph, Am. Soc. Agric. Eng. St. Joseph, Mich.

Greenland, D. J. 1965. Interaction between clays and organic compounds in soils. Part I. Mechanisms of interaction between clays and defined organic compounds. Soils Fert. 28:415-425. II. Adsorption of soil organic compounds and its effect on soil properties. Soils Fert. 28:521-532.

Gu, Rong-shen, and Qi-xiao Wen. 1981. Cultivation and application of green manure in paddy fields of China. Pages 207-219 *in* Proceedings of symposium on paddy soil, 19-24 Oct. 1980, China.

Gupta, S. C., R. H. Dowdy, and W. E. Larson. 1977. Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. J. Soil Sci. Soc. Am. 41:601-605.

Havangi, G. V., and H. S. Mann. 1970. Effect of rotations and continuous application of manures and fertilizers on soil properties under dry farming conditions. J. Indian Soc. Soil Sci. 18:45-50.

Huke, R. E. 1982. Rice area by type of culture: South, Southeast, and East Asia. International Rice Research Institute, Los Baños, Philippines, 32 p.

Hundal, S. S., and S. K. De Datta. 1982. Effect of dry season soil management on water conservation for the succeeding rice crop in a tropical soil. Soil Sci. Soc. Am. J. 46 (in press)

Hundal, S. S., S. S. Prihar, and N. S. Randhawa. 1971. Effect of crop rotations on the physical properties of the soil. J. Res. (PAU) VIII (3):320-326.

Ikeda, M., and I. Harada. 1956. Studies on soils in the transferring cultivation of paddy and upland field. Int. Congr. Soil Sci. 6th (Paris) C:507-513.

Jamison, V. C. 1953. Changes in air water relationships due to structural improvement of soils. Soil Sci. 76:143-151.

Kawaguchi, K., D. Kita, and K. Kyuma. 1956. A soil core sampler for paddy soils and some physical properties of the soils under waterlogged condition. Soil Plant Food 2(2):92-95.

Klute, A., and W. C. Jacob. 1949. Physical properties of Sassafras silt loam as affected by long time organic matter additions. Soil Sci. Soc. Am. Proc. 14:24-28.

Koenigs, F. F. R. 1961. The mechanical stability of clay soils as influenced by moisture conditions and some other factors. Versl. landb. oriderz. 67.7 171 p.

Koenigs, F. F. R. 1963. The puddling of clay soils. Neth. J. Agric. Sci. 11:145-156.

Kumar, V., and B. P. Ghildyal. 1969. Effect of some organic materials on the regeneration of soil structure in a lateritic puddled paddy soil. Riso 18(2):105-108.

Larson, W. E., W. C. Burrows, and W. O. Willis. 1970. Soil temperature, soil moisture, and corn growth as influenced by mulches of crop residues. Trans. 7th Int. Congr. Soil Sci. VI(29):629-637.

Lauritzen, C. W. 1948. Apparent specific volume and shrinkage characteristics of soil materials. Soil Sci. 65:155-179.

Li, Shi-jun, and Xue-yuan Li. 1981. Stagnancy of water in paddy soils under the triple cropping system and its improvement. Pages 509-516 *in* Proceedings of symposium on paddy soil, 19-24 Oct. 1980. China.

Low, A. J., and F. J. Piper. 1973. Some examples of effect of soil physical conditions on tractive effort required during plowing. J. Sci. Food Agric. 24:1011-1020.

Mahapatra, I. C., and N. Sadanandan. 1973. Effects of multiple cropping on some of the physical and chemical properties of upland alluvial rice soils. Int. Rice Comm. Newsl. 22(1):26-34.

Martin, J. P., and S. A. Waksman. 1940. Influence of microorganisms on soil aggregation and erosion. Soil Sci. 50:29-47.

McCalla, T. M., and T. J. Army. 1961. Stubble mulch farming. Adv. Agron. 13:125-196.

McGeorge, W. T. 1937. Studies on soil structure: Some physical characteristics of puddled soils. Arizona Agric. Exp. Stn. Tech. Bull. 67.

Miki, K., and T. Mori. 1966. Effect of incorporated organic matter such as compost, rice straw, mixed clover-grasses residues and alfalfa residues on the fertility of mineral soil. II. Changes of soil physical and chemical properties with application of the organic matters [in Japanese, English summary]. Bull Tokai-Kinki. Natl. Agric. Exp. Stn. 15:112-124.

Monnier, G. 1965. Effect of organic matter on soil structural stability [in French, English summary]. Ann. Agron. 16:471-534.

Morachan, Y. B., W. C. Moldenhauer, and W. E. Larson. 1972. Effects of increasing amounts of organic residues on continuous corn. I. Yields and soil physical properties. Agron. J. 64:199-203.

Odell, R. T., T. H. Thornburn, and L. J. McKenzie. 1960. Relationships of Atterberg limits to some other properties of Illinois soils. Soil Sci. Soc. Am. Proc. 24:297-300.

Oh, W. K. 1964. Effect of compost and fresh rice straw on the production of paddy rice. Res. Rep. Off. Rural Dev. Korea 7:1-16.

Primavesi, A. 1968. Organic matter and soil productivity in the tropics and subtropics. Pages 653-666 *in* Study week on organic matter and soil fertility. John Wiley and Sons, Inc., New York.

Robinson, D. O., and J. B. Page. 1951. Soil aggregate stability. Soil Sci. Soc. Am. Proc. 15:25-29.

Russel, M. B., A. Klute, and W. C. Jacob. 1952. Further studies on the effect of long-time organic matter additions on the physical properties of Sassafras silt loam. Soil Sci. Soc. Am. Proc. 16:156-159.

Sahoo, R., A. K. Bandyopadhya, and B. B. Nanda. 1970. Effect of organic manures with and without drainage on rice yield, nutrient uptake and soil aggregation. J. Indian Soc. Soil Sci. 18:51-55.

Salter, P. J., and F. Haworth. 1961. The available water capacity of a sandy loam soil. II. The effects of F. Y. M. and different primary cultivations. J. Soil Sci. 12:335-342.

Salter, P. J., G. Berry, and J. B. Williams. 1967. The effect of F. Y. M. on matric suctions prevailing in a sandy loam soil. J. Soil Sci. 18:318-328.

Takahashi, H., and V. Shibusawa. 1956. Physical properties of the soil in relation to the alternate use of land for lowland and upland crops. Proc. Crop Sci. Soc. Jpn. 25:24-27.

Tanaka, A. 1973. Methods of handling the rice straw in various countries. Int. Rice Comm. Newsl. 22:l-20.

Theng, B. K. G. 1974. The chemistry of clay-organic reactions. London: Hilger.

Tiarks, A. E., A. P. Mazurak, and L. Chesnin. 1974. Physical and chemical properties of soil associated with heavy application of manure from cattle feedlots. Soil Sci. Soc. Am. Proc. 38:826-830.

Unger, P. W., and J. J. Parker, Jr. 1968. Residue placement effects on decomposition, evaporation, and soil moisture distribution. Agron. J. 60:469-472.

Van Doren. D. M., Jr., and R. R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. Pages 49-83 *in* W. R. Oschwald (ed.) Crop residue management systems. American Society of Agronomy, Madison, Wisconsin.

Varade, S. B., and B. P. Ghildyal. 1967. Mechanical impedance and growth of paddy in artificially compacted lateritic sandy loam soil. J. Indian Soc. Soil Sci. 15(3):157-162.

Verma, S. M., and N. T. Singh. 1974. Effect of some indigenous organic materials on soil aggregation. J. Indian Soc. Soil Sci. 22:220-225.

Williams, W. A., D. C. Finfrock, L. L. Davis, and D. S. Mikkelsen. 1957. Green manuring and crop residue management in rice production. Soil Sci. Soc. Am. Proc. 21:412-415.

Wilson, H. A., and W. C. Fisher. 1946. Aggregate increase and stability in two Louisiana soils. Soil Sci. Soc. Am. Proc. 10:30-33.

Xu, Qi. 1981. Cropping system in relation to fertility of paddy soils in China. Pages 220-229 *in* Proceedings of symposium on paddy soil, 19-24 Oct. 1980, China.

Yi, Hseung, Qi Xu, Xian-liang Yao, and Zhao-liang Zhu. 1980. Effect of cropping system on the fertility of paddy soils [in Chinese, English summary]. Pages 116-119 *in* Acta Pedalogica Sinica 17.

Yuan, Jian-fang, and Yue-hua Zhou. 1981. Effect of water conditions and organic matter on modulus of rupture of paddy soils. Pages 689-693 *in* Proceedings of symposium on paddy soil, 19-24 Oct. 1980, China.

## DISCUSSION

PALANIAPPAN: Increasing temperature, moisture, and N content tend to increase — to an optimum level — the rate of decomposition of organic matter in the soil. You have reported that leguminous matter disappears much faster than rice and farmyard manure. If, however, urea or any other source of N is added for the management of the main crop, it tends to speed the rate of decomposition of both straw and farmyard manure. Therefore it may not be proper to recommend a certain source of organic matter as a fast-disappearing type or a long-lasting one. That would be true only if you do not add any inorganic N to the soil.

*DE DATTA:* There are distinct differences among rates of decomposition of different organic matter sources in wetland rice soils. However, that rate of decomposition appears to be faster if N is applied to the main crop and the residue is subsequently incorporated.

PALANIAPPAN: Biocide usage generally tends to destroy microorganisms in the soil and may upset decomposition and mineralization. Further, some biochemical reactions that might occur as a result of biocide use may affect the quality of protein in the rice grains. Have you thought of these effects?

*DE DATTA:* Most herbicides used on rice in this region, particularly the nonselective herbicide paraquat, are short-lived and there is no serious residual effect.

CANNEL: Could you comment further on the role of a dry mulch layer in conserving soil water? A traditional view was that it was effective, but later some discredited that idea. Is it posssible to generalize using some guiding principles, or is the effect to some extent site specific?

*DE DATTA:* All our data on the benefits of dry soil mulch and soil mulch have been consistent. Both practices conserve moisture, shorten the growing period, and help early stand establishment. All of these data, however, were collected on one soil at the IRRl farm. These techniques should be evaluated elsewhere.

YOSHIDA: Among the parameters of soil physical properties, which ones are most likely to affect rice yield increase as a result of the application of organic matter to the soil?

*DE DATTA:* Organic matter influences several soil physical properties simultaneously such as aggregation, pore-size distribution, bulk density, porosity, moisture retention, etc. In wetland rice, soil properties that are related to favorable water movement in the soil such as pore-size distribution would be the most important.

FLAIG: Have linear polymers (krilium) been used for structural regeneration of the soil in rice-based cropping systems?

*DE DATTA:* To our knowledge, soil conditioners (linear polymers) are not being used for structural regeneration in Asia. One laboratory study reported from Korea is presented in Table 4 of our paper. Due to limitations in field application, cost, and short-lived beneficial effects, linear polymers are not currently popular in rice-based cropping systems.

OH: What size, or what proportion of different sized aggregates are good for wetland rice growth?

*DE DATTA:* Under wetland rice culture the aggregation status of soil is of minor importance if the soils have good internal drainage. In poorly-drained soils, an increase in aggregation would help improve percolation and larger aggregates would be preferred. But, it is impossible to say that there is one size or proportion of aggregate sizes good for rice growth.

# EFFECTS OF DRAINAGE ON THE CHARACTERISTICS OF PADDY SOILS IN CHINA

Yun-sheng Cheng

In China, the rice yield varies considerably. For heavy paddy soils, it is the water regime, not always the content of organic matter, that to a greater extent restricts yields. Only through the improvement of the soil water regime can added organic matter become beneficial. To attain this end, field drainage is one of the important measures. It contributes to the improvement of the physical conditions of paddy soils and to the enhancement of fertility as well.

Once drained, the moisture in paddy soil decreases rapidly. Drainage promotes cohesion of soil particles and makes the soil increase in bulk density and in hardness. Moreover, drainage helps improve soil aeration conditions as a result of increasing the gaseous fraction. A higher amount of $O_2$ in soil air and in percolation water is favorable to the renewal of the soil environment for plant growth. Consequently, drainage of paddy soils may lead to improved development of plant roots, with an increase of 10-20% in yield.

China has a long history of wetland rice cultivation over a vast area, from Hainan Island in the southern tropical zone to Heilongjiang in northern frigid-temperate zone, and from Taiwan Province in the east to Xinjiang and Xizang in the west, for a total of some 26 million ha. Rice fields account for 28.4% of the total area planted to grain crops in the whole country, and rice production makes up 43.3% of the total grain output (Editorial Committee of Almanac of China's Agriculture 1981).

Rice yields vary from 2 to 10 t/ha. Low yields are common in about 26% of all paddy soils, which comprise four major types — settling compact paddy soils, cold muddy paddy soils, heavy clayey paddy soils, and toxic paddy soils — covering areas of 2.61, 1.96, 1.63, and 0.33 million ha, respectively (Xiao 1981). For settling compact paddy soils, the principal constraints on higher yield are coarser particle composition and higher content (over 40%) of coarse silt (0.01-0.05 mm). After soil preparation, these coarse particles quickly become deposited, making the soil compactly settled and giving it a consequently lower level of fertility. For cold muddy paddy soils, low yields are attributed to a high groundwater table, poor

---

Institute of Soil Science, Academia Sinica, P.O. Box No. 821, Nanjing, China.

drainage conditions, low soil temperature, an excessive amount of reducing substances, poor aeration conditions, and a low content of available nutrients. For heavy clayey paddy soils, which are derived chiefly from alluvial and lacustrine deposits, are heavy in texture, and commonly contain more than 30% clay, poor yields are attributed to generally small pore spaces, which are poor in aeration and permeability, although good in water retention capacity. In toxic paddy soils many S compounds can be formed into sulfuric acid under oxidizing conditions and can create a low pH of 2-3, which is harmful to the growth of plants (Institute of Soil Science, Academia Sinica 1978).

To improve the last three of these soils, promote their fertility, and increase rice yields, it is essential to provide proper drainage and lower the groundwater table, thereby improving aeration in the root layer. Drainage is not only conspicuously effective in improving soil characteristics, but also a practical technique in growing high-yield rice (Institute of Soil Science, Academia Sinica 1961; Cheng and Zhao 1963; Fujian Agricultural College 1976; Agricultural Bureau of Wuxi County, Jiangsu Province, and Dongting Experiment Unit, Institute of Soil Science, Academia Sinica, 1976; Yang et al 1979; Hseung et al 1980).

In countries like Japan, India, and the Philippines, drainage of paddy soils receives great attention (Ezaki 1976, Pande 1976, Wickham and Singh 1978, Brady 1981). In China also, most farmers have had extensive experience in water management of paddy fields. Different irrigation and drainage techniques have been used for different soils at different times to increase production. Before the 1950s the agrarian land was run in a decentralized way, and therefore irrigation and drainage systems could not be scientifically planned. Then large-scale water conservation projects were started, chiefly using open ditches, which accounted for 10% of the land area and required a considerable number of laborers. In the beginning of the 1960s, such methods as mole drainage and tile drainage were studied as means first to eliminate and control harmful waterlogging in dryland soils and then to drain paddy fields (Tongle Experiment Unit, Institute of Soils and Fertilizers, Agricultural Academy of Guangdong Province 1977; Yang et al 1978; Changshu Farm Land Hydraulic Station, Jiangsu Province 1979; Cheng 1981; Huang 1982). The present drainage practice in paddy fields combines open ditches with mole or tile drains and is progressing from the surface drainage afforded by open ditches to the underground drainage provided by mole or tile drains. This development will be specially significant not only in increasing rice yields under intensified farming systems, but also in raising the land utilization rate to heightened mechanization and to the economization of water consumption and labor.

## EFFECTS OF ORGANIC MATTER AND WATER REGIME ON PHYSICAL PROPERTIES OF PADDY SOIL

At the time of rice planting, the paddy soil is generally under submerged conditions. However, the water regime in the soil varies with the topography of the field's location in general and with yearly variations in the water table in particular. The importance of the water table varies with different crops, and the effect on dryland soils is greater than on paddy soils. Drainage conditions also inevitably affect the

**Table 1. Effects of topography and water regime on organic matter content of paddy soils.**[a]

| Location | Topography | Samples (no.) | Water regime | Organic matter (%) |
|---|---|---|---|---|
| Jiangsu | Plain | 11 | Waterlogged | 3.47 |
| | | 26 | Well-drained | 2.20 |
| Jiangxi | Mountainous | 12 | Waterlogged | 3.23 |
| | | 19 | Well-drained | 3.08 |
| Guangdong | Hilly | 6 | Waterlogged | 3.12 |
| | | 4 | Well-drained | 2.21 |

[a] Source: Institute of Soil Science, Academia Sinica (1961).

decomposition and accumulation of organic matter. Table 1 shows that the content of organic matter in paddy soil is related to the soil water regime in the same way in a variety of topographies; there is always a greater accumulation of organic matter in poorly drained paddy soils than in well-drained ones.

Although there are various rotation systems involving rice cultivation in China, they can be divided into two major patterns: rice - dryland crop and continuous cropping rice. The period of submergence under the rice - dryland crop system is shorter than that under continuous rice cultivation, and these different water regimes will thus exert different effects on the organic matter content. In South China the amount of organic matter is higher in paddy soil under continuous rice cultivation than in soil under the rice - dryland crop system, evidently because of different water regimes (Table 2). Although the application of organic manure no doubt can raise the organic matter content of the soil, it is not clear to what extent it can improve the physical properties of paddy soil. The application of azolla, water hyacinth, and rice straw to paddy soils decreases the modulus of rupture and bulk density and increases total porosity and microaggregate content (Table 3). However, the change of porosity is only an increase in capillary porosity, which intensities the water retention ability of soil. As seen from the changes in noncapillary porosity, the aeration in soil can even become worse. It seems that soils with more moisture but less gas content will weaken the effect of organic matter on improving soil physical properties.

**Table 2. Effect of cropping system on organic matter content of paddy soils in South China.**[a]

| Location | Cropping system | Organic matter (%) |
|---|---|---|
| Hubei | Continuous rice | 2.03 – 2.15 |
| | Rice - dryland crops | 1.85 – 1.94 |
| Zhejiang | Continuous rice | 3.11 – 5.21 |
| | Rice - cotton | 2.01 – 2.87 |
| Taihu Lake Region | Rice - rice - wheat | 2.74 ± 0.94 |
| | Rice - wheat | 2.45 ± 1.04 |
| Shanghai suburbs | Rice - rice - wheat | 2.14 ± 0.19 |
| | Rice - wheat | 1.58 ± 0.14 |

[a] Sources: Institute of Soil Science, Academia Sinica (1961); Xu et al (1980); Xi (1981).

**Table 3. Effects of organic manures on the physical properties of clayey paddy soils.**[a]

| Treatment | Modulus of rupture (kg/cm$^2$) | Micro-aggregates[b] (%) | Bulk density (g/cm$^3$) | Total porosity (%) | Noncapillary porosity (%) |
|---|---|---|---|---|---|
| Azolla | 27.9 | – | 1.11 | 58.0 | 4.5 |
| Check | 31.4 | – | 1.23 | 53.5 | 4.4 |
| Water hyacinth | 26.0 | 77.9 | 1.20 | 54.9 | 6.8 |
| Check | 30.7 | 76.9 | 1.25 | 52.8 | 7.0 |
| Rice straw | 26.0 | 79.1 | 1.14 | 56.8 | 6.1 |
| Check | 31.6 | 76.4 | 1.18 | 55.6 | 8.8 |

[a] Source: Yao (1976, unpublished). [b] 0.01-1 mm.

Most research on paddy soil structures has centered on the properties and changes of microstructures and their effects on fertility. It is commonly believed that microstructures in paddy soil are directly related to the amount of organic matter, particle composition, colloidal properties, water regime, etc. (Institute of Soil Science, Academia Sinica 1961; Yi 1963; Yao et al 1978). Statistical data in Table4 show that under approximately similar soil textures and well-drained conditions, soil organic matter content is closely correlated with microstructures, bulk density, and porosity, indicating that under a good water regime, soil organic matter plays an active part in the improvement of physical properties of paddy soil. On the other hand, with a poor water regime, it is impossible to improve soil physical properties and increase soil fertility by raising the content of soil organic matter.

A higher organic matter content in paddy soil with poor water regime has nothing to do with fertility level. The height of the water table in paddy soil significantly affects the organic matter content: organic matter increases with the rising of the water table. For example, when the water table was below 0.6 m, the organic matter content was 2.67%; when it gradually rose to 0.4-0.6,0.3-0.4, and less than 0.3 m, the organic matter increased to 3.54%, 3.92%, and 4.72%. respectively. Nevertheless, with the lowering of the water table, the paddy yield and fertility level increased from 2-3 t/ha to 6-8 t/ha (Institute of Soil Science, Academia Sinica 1961). Obviously the fertility level of paddy soil to a great extent is restricted by the soil water regime. Therefore, the effect of soil organic matter on the improvement of physical

**Table 4. Correlations between organic matter content and some physical properties of permeable paddy soils in Taihu Lake Region, China.**[a]

| *X* | *Y* | Regression equation | *r*[b] | *n* |
|---|---|---|---|---|
| Organic matter (%) | Microaggregates (%)[c] | $Y = 14.616 + 4.345\ X$ | 0.771** | 14 |
| | Volume weight in water (g/ml) | $Y = 0.726 - 0.059\ X$ | – 0.851** | 14 |
| | Bulk density (g/cm$^3$) | $Y = 1.526 - 0.182\ X$ | – 0.853** | 6 |
| | Porosity (%) | $Y = 43.234 + 6.606\ X$ | 0.838** | 6 |

[a] Calculated from Institute of Soil Science, Academia Sinica (1978); Yao (1965, unpublished). [b] All P <0.01%. [c] 0.05-1 mm.

properties of paddy soil is conditional. For low-yield clayey soils and those located in low-lying land, only the amelioration of the poor water regime can bring the organic matter into full play.

Chinese farmers have long known that the mechanical properties of paddy soil may be roughly reflected by soil hardness. Different degrees of soil hardness are required for different stages of rice cultivation. At the earlier stage of plant growth, the soil is preferably both puddly and soft, while it should be compact and hard at later stages to ensure high yield. Soil hardness also indicates the fertility of paddy soil (Chen et al 1961; Wan and Cheng 1962; Cheng 1962,1965). When a soil is puddly and soft, there are comparatively wide spaces between soil particles, there is a low percentage of solid phase, and both bulk density and hardness are low, a situation favorable to the growing of plant roots and the absorption of nutrients. But when a soil is compact and hard, the opposite occurs. Pot experiments have showed that puddly and soft soil was favorable to the growth of rice at its tillering stage; when the soil was compact and hard, the results turned to the contrary (Cheng 1965).

The hardness of rice soil may be regulated by appropriate water management and proper farming measures. Submergence and cultivation make the soil puddly and soft; drainage makes it compact and hard. In fact, periodic drainage during the plant–growing period plays a remarkable role in regulating soil hardness (Cheng et al 1979). After drainage, the soil becomes shrunken and compact, and its hardness increases. After submergence, hardness declines because of the expansion of solum and the hydration of soil particles, which lose their cohesion capability. However, under similar soil water regimes, the amount of organic matter may also affect soil hardness. Generally, soils with higher organic matter content have lower hardness, as evidenced by the results in Tables 3 and 4. Also, changes in hardness of paddy soil are influenced mainly by the soil water regime under field conditions.

## EFFECTS OF DRAINAGE ON PROPERTIES OF PADDY SOIL

During rice planting, the soil is under submerged conditions and capable of providing the plants with nutrients. Nevertheless, because of submergence, the pore spaces are filled with water and the $O_2$ content of the soil is greatly decreased. At the same time, because of biological activities in the soil, there is a considerable accumulation of $CO_2$, $H_2S$, organic acids, and reduced Fe, Mn, etc., all of which are disadvantageous and sometimes even toxic to rice growth. To get rid of these undesirable factors, the most effective measure is periodic drainage. There are two ways to drain paddy soils: percolation and evaporation plus transpiration. Percolation depends principally on soil characteristics; evaporation plus transpiration, on temperature and the growth stage of rice.

The infiltration of irrigation water into paddy soil helps to carry dissolved $O_2$ and available nutrients into the soil and to remove part of the toxic substances. A loss of water and nutrients may occur when the percolation rate is too high, as is the case with sandy soils. But when the percolation rate is too low, there will be a lack of $O_2$ and an inability to get rid of toxic substances; this is the case with heavy paddy soils having a higher content of organic matter. Nakagawa of Japan (in Ezaki 1976) suggested that the optimum percolation rate is 15-25 mm/day; Dastane of India (in

Pande 1976) suggested 1-5 mm/day. In China, Chen and Li (1981) suggested 7-20 mm/day after summarizing the results from a comprehensive investigation in Jiangsu, Zhejiang, Shanghai, and Guangdong. The differences in these recommended percolation rates may be attributed to the differences in soil conditions and farming techniques.

Of vital importance to over-damp and clayey soils is readjusting the percolation rate. Adopting mole or tile drainage can speed up the percolation rate. For most clayey paddy soils, periodic drainage during rice planting not only increases the rate by 2-3 times, up to the optimum level, but also lowers the water table to 30-40 cm, which is favorable to soil aeration (Table 5).

Although irrigation introduces a large quantity of water into a rice field, the soil pores are still not entirely filled with water. Since the soil absorbs water, which results in the swelling of the plow layer, the bulk density of paddy soil under submerged conditions is about 1.0 g/cm$^3$. After draining, the soil water content decreases gradually to a point near the field capacity, while the soil bulk density increases gradually to about 1.2 g/cm$^3$ (Cheng and Zhao 1963, Motomura et al 1976). The amount of dissolved $O_2$ in soil solution is directly proportional to the partial pressure of $O_2$ in soil air. Under submerged conditions, the gaseous phase accounted for 1-5%, but 8 days after draining it had reached over 10%. The oxidation-reduction potential of paddy soil, which is controlled mainly by the soil $O_2$ status, increased from negative values before draining to over 500 mv after draining.

The amount of $O_2$ in soil air increased immediately from 5% before draining to 18% after draining and then dropped to about 8%; in the flooded check plot it remained about 5%. The amount of $CO_2$ increased from about 8 to 12% and then decreased to below 6% in the drained plot. An excess of $CO_2$ in the soil is unfavorable to plant roots and microorganisms. Thus, the drainage of paddy soil to renew soil air and prevent the accumulation of $CO_2$ is of great significance. The drainage of paddy soil may also lead to the increase of dissolved $O_2$ in the soil solution. A field study showed that the dissolved $O_2$ in the percolated water in the drained plot increased

**Table 5. Effect of drainage on percolation rate and water table in paddy soils.** [a]

| Location | Treatment | Percolation rate (mm/day) | Water table (cm) |
|---|---|---|---|
| Changshu, | Flooding | 6.7 | – |
| Jiangsu | Drained | 16.0 | – |
| Kunshan, | Natural drainage | – | 29 – 30 |
| Jiangsu | Tile drainage | – | 41 – 48 |
| Shanghai | Flooding | 3 – 4 | 14 – 21 |
| suburbs | Drained | 9 – 15 | 38 – 45 |
| Putian, | Flooding | 6 | 60 |
| Fujian | Drained | 9 – 15 | 80 – 85 |
| Zhongshan, | Flooding | – | 19 – 29 |
| Guangdong | Drained | – | 22 – 46 |

[a] Sources: Changshu Group of Institute of Soil Science, Academia Sinica (1959); Huang (1982, unpublished); Yang et al (1979); Fujian Agricultural College (1976); Tongle Experiment Unit, Institute of Soils and Fertilizers, Agricultural Academy of Guangdong Province (1977, unpublished).

from 0.65 mg/liter before draining to 1.69 mg/liter after draining, while that in the check plot remained at 0.6-0.8 mg/liter. All these findings fully indicate that the drainage of paddy soil greatly improves the aeration conditions of the soil and is favorable for rice growth.

Different yields may result from drainage of different durations and at different stages of rice growth. The results of experiments and farmers' practical experience suggest that low yields will result from an overly long period of drainage during rice growth, including the seedling, tillering, panicle differentiation, and milk ripe stages. In general, periodic drainage between the end of the tillering stage and the panicle differentiation stage will lead to an increase in yield, since at that time the plant is in a transition period between the vegetative and reproductive stages. From then on, drainage enables the rice roots to extend more deeply and the stems to grow more strongly, resulting in big ears and eventually higher yield. It should be pointed out, however, that periodic drainage must be carried out in line with soil conditions and the growth status of the rice plants. The field should be drained if the soil is puddly and the growth excessive. This should also be the case with paddy soils in the lowlands, which are clayey, puddly, and fertile. On the other hand, it is not necessary to drain paddy soils in the highlands, which are sandy, compact, and infertile, and all that has to be done is at most to let the water layer on the field surface dry and to irrigate in time (Institute of Soil Science, Academia Sinica 1961; Cheng and Zhao 1963; Hseung et al 1980; Xiao 1981). Drainage should always be done before rice harvest in order to be ready for harvest as well as to prepare the soil for the next crop.

## EFFECTS OF DRAINAGE ON RICE GROWTH

Since drainage of paddy fields can improve soil physical properties, particularly soil aeration, there is necessarily an effect on rice growth. The color changes in a root system are a significant reflection of root activity: white roots are most active, yellow roots moderately active, and black roots inactive. Experimental results in Jiangsu and Guangdong showed that after periodic drainage, the proportion of white roots increased by 5-22%, while that of black roots decreased by 5-24%, with only a minor change in the yellow roots. Table 6 shows that, at different rice growing stages, the proportion of white roots is commonly higher in paddy fields under tile drainage than in submerged conditions. On the average, roots are longer in drained fields than

**Table 6. Effects of drainage on root growth of rice.**[a]

| Treatment | Root color | Roots (%) at | | | Mean root length (cm) |
|---|---|---|---|---|---|
| | | Tillering stage | Heading stage | Milky ripening stage | |
| Flooding | White | 17 | 8 | 0 | 36 |
| | Yellow | 64 | 72 | 76 | |
| | Black | 19 | 20 | 24 | |
| Tile drainage | White | 22 | 17 | 19 | 42 |
| | Yellow | 64 | 70 | 81 | |
| | Black | 14 | 13 | 0 | |

[a] Source: Huang (1982, unpublished).

in submerged ones. They are thus capable of increased nutrient uptake.

The intensity of root activity of the rice plant can be measured by its respiration rate (Changshu Group of Institute of Soil Science, Academia Sinica 1959). On the second day after draining, the respiratory intensity, measured by $O_2$ consumption, was 20.82 and 18.83 µl/g per hour in a drained field and a submerged field, respectively; on the seventh day after draining, it had increased to 29.00 and 25.25 µl/g per hour, respectively. This indicates that after field drainage the respiratory intensity of a root system increases with the duration of drainage, being about 15% higher than that in a submerged field. Yang et al (1978) applied $^{32}P$ to determine the activity of root systems. Under tile drainage conditions, root activity was over 60% higher than under submerged conditions. Field drainage thus helps promote root activity, which will inevitably be reflected in the aerial part of the rice plant.

After periodic drainage of a paddy field, the rice plant leaves change color from bluish green or dark green to yellowish green or light green. This color change is related to the amount of nutrients the plants have taken up, especially to the amount of N. Although the N content in the leaves in a drained field is lower than that in submerged field, drainage may bring about more sturdy stems, increase the thickness of their mechanical tissues, and make the amount and diameter of pores between cells smaller and the cells more densely arranged (Institute of Soil Science, Academia Sinica 1961).

The weight of dry matter in a plant is a good indicator of its growth rate. Table 7 shows that the growth rate and dry weight of a single plant stem or single tiller were lower under periodic drainage conditions than under submerged conditions, indicating that field drainage had a temporarily restricting effect on the growth of the aerial part of the rice plant. During the middle growth stage, though, the plant stems grow sturdily as a result of drainage. Therefore, from the viewpoint of the whole rice-growing process, the role of periodic drainage in paddy fields is significant and remarkable.

An increase in rice yield can be expected as long as proper drainage is adopted in accordance with the local soil and rice growth conditions. A large number of experiments conducted over many years in Jiangsu, Zhejiang, Shanghai, Fujian, and Guangdong, have shown that field drainage, if properly handled, will bring about an increase in yield varying from 2 to 27%, most probably 10-20%.

**Table 7. Effect of drainage on dry weight of rice plants.**[a]

| | Dry weight of rice drained after | | | |
|---|---|---|---|---|
| Treatment | 1 day | 3 days | 8 days | 9 days |
| | | *1959* (g/tiller) | | |
| Flooding | – | 1.47 (100%) | 1.97 (134%) | – |
| Drained | – | 1.34 (100%) | 1.65 (123%) | – |
| | | *1963 (g/plant)* | | |
| Flooding | 5.64 (100%) | – | – | 7.75 (137%) |
| Drained | 8.82 (100%) | – | – | 9.21 (104%) |

[a] Sources: Changshu Group of Institute of Soil Science, Academia Sinica (1959); Cheng and Zhao (1963).

## INSTALLATION OF DRAINAGE SYSTEMS FOR PADDY SOILS

For installation of drainage facilities for paddy soils, consideration should be taken not only of the requirements of rice cultivation but also of the needs of crops subsequent to rice. The best method found in many field experiments in South China over the past 20 years is tile drainage, followed by mole drainage, and finally open ditches and surface drainage. Experiments in Jiangsu and Guangdong have shown that the preferable depths of mole drains range from 0.6 to 0.8 m, with an interspace of 4-5 m and 2-4 m for loamy soil and clayey soil, respectively, while the depths of tile should be 1.0, 1.0-1.2, and 1.1-1.2 m for sandy loam soil, loamy soil, and clayey soil, respectively, with an interspace of 20, 15, and 6-10 m, respectively.

## REFERENCES CITED

Agricultural Bureau of Wuxi County, Jiangsu Province, and Dongting Experiment Unit, Institute of Soil Science, Academia Sinica. 1976. Water management of paddy field for high yield of early rice [in Chinese]. Turang 5-6:255-260.

Brady, N. C. 1981. Soil factors that influence rice production. Pages 1-19 *in* Institute of Soil Science, Academia Sinica. Proceedings of Symposium on paddy soil. Science Press, Beijing, Springer-Verlag, Berlin, Heidelberg, New York.

Changshu Farm Land Hydraulic Station, Jiangsu Province. 1979. Effect of the mole drainage on the melioration of soil waterlogging and increase in yield [ms., in Chinese].

Changshu Group of Institute of Soil Science, Academia Sinica. 1959. Effects of water management on soil characteristics and its significance [in Chinese]. Acta Pedol. Sin. 7:203-217.

Chen, J. F., Y. S. Cheng, and Z. Y. Liu. 1961. Preliminary report of theory and technique of Chen Yong-kang's high yield of rice [in Chinese]. Turang 8:6-16.

Chen, J. F., and S. Y. Li. 1981. Some characteristics of high fertility paddy soils. Pages 20-30 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, Springer-Verlag, Berlin, Heidelberg, New York.

Cheng, Y. S. 1962. The high yield experience of Chen Yong-kang for tillage techniques of rice cultivation [in Chinese]. Turang Tongbao 4:53-56.

Cheng, Y. S., and G. H. Zhao. 1963. A preliminary study on the effect of periodical drainage of paddy soils [in Chinese, Russian summary]. Acta Pedol. Sin. 11:275-285.

Cheng, Y. S. 1965. Effect of hardness of paddy soils on plant growth during tillering stage of rice [in Chinese]. Acta Pedol. Sin. 13:463-464.

Cheng, Y. S., C. Y. Lin, Y. Z. Yang, and M. X. Xu. 1979. The hardness of paddy soil during rice growth and its influence effects [in Chinese, English summary]. Acta Pedol. Sin. 16:70-74.

Cheng, Y. S. 1981. Drainage of paddy soils in Taihu Lake Region. Pages 517-523 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, Springer-Verlag Berlin, Heidelberg, New York.

Editorial Committee of Almanac of China's Agriculture. 1981. Almanac of China's Agriculture. 1980 [in Chinese]. Agriculture Press, Beijing. 508 p.

Ezaki, K. 1976. Drainage of paddy field in Japan. Pages 273-282 *in* Tropical Agriculture Research Series No. 9. Symposium on water management in rice field. Proceedings of a symposium on tropical agriculture researches, August 1975, Japan.

Fujian Agricultural College. 1976. Effect of periodical drainage of paddy field on the regulation of soil fertility and the yield of rice [in Chinese]. Turang 5-6:285-289.

Hseung, Y., Q. Xu, X. L. Yao, and Z. L. Zhu. 1980. Effect of cropping system on the fertility of paddy soil [in Chinese, English summary]. Acta Pedol. Sin. 17:101-119.

Huang, W. Q. 1982. Some problems of rice irrigation and tile drainage in paddyfield [ms., in Chinese].

Institute of Soil Science, Academia Sinica. 1961. The environmental conditions of soils for high yield of rice [in Chinese]. Science Press, Beijing. 476 p.

Institute of Soil Science, Academia Sinica, Nanjing. 1978. Soils of China [in Chinese]. Science Press, Beijing. 729 p.

Motomura, S., A. Seirayosakol, and W. Cholitkul. 1976. The changes in some physical and chemical properties of paddy soils under water management. Pages 101-115 *in* Tropical Agriculture Research Series No. 9. Symposium on water management in rice field. Proceedings of a symposium on tropical agriculture researches, August 1975, Japan.

Pande, H. K. 1976. Water management practices and rice cultivation in India. Pages 231-249 *in* Tropical Agriculture Research Series No. 9. Symposium on water management in rice field. Proceedings of a symposium on tropical agriculture researches, August 1975, Japan.

Tongle Experiment Unit, Institute of Soils and Fertilizers. Agricultural Academy of Guangdong Province. 1977. Effects of the mole drainage on the melioration of soil physical properties and increase in rice yield [ms., in Chinese].

Wan, C. B., and Y. S. Cheng. 1962. Analysis of Chen Yong-kang’s experience of cultivation practice, fertilization and water-control based on the soil conditions [in Chinese]. Jiangsu Nongxuebao No. 3, 36-41.

Wickham, T. H., and V. P. Singh. 1978. Water movement through wet soils. Pages 337-358 *in* International Rice Research Institute. Soils and rice. Los Baños, Laguna, Philippines.

Xi, Z. B. 1981. On the tendency of organic matter accumulation in paddy soil under triple cropping system in suburbs of Shanghai. Pages 502-508 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, Springer-Verlag, Berlin, Heidelberg, New York.

Xiao, Z. H. 1981, Principal types of low yield paddy soil in China. Pages 151-159 *in* Institute of Soil Science, Academia Sinica. Proceedings of symposium on paddy soil. Science Press, Beijing, Springer-Verlag, Berlin, Heidelberg, New York.

Xu, Q., Y. C. Lu, Y. C. Liu, and H. G. Zhu. 1980. The paddy soil of Tai-hu Region in China [in Chinese, English summary]. Shanghai Scientific and Technical Publishers, Shanghai, China. 98 p.

Yang, C. L., C. C. Chu, and S. C. Chiang. 1978. The drainage problem of the soils in the suburbs of Shanghai [in Chinese, English summary]. Acta Pedol. Sin. 15:95-100.

Yang, J. L., J. C. Zhu, and S. Z. Jiang. 1979. Effect of tile drainage in paddy field on the yield of rice [in Chinese]. Turang 1:10-15.

Yao, X. L., W. S. Zhao, D. F. Yu, and X. Y. Xu. 1978. Preliminary investigation of structural characteristics of fertile paddy soils [in Chinese, English summary]. Acta Pedol. Sin. 15:1-12.

Yi, P. X. 1963. A preliminary investigation on the characteristics of structure of paddy soils [in Chinese, Russian summary]. Acta Pedol. Sin. 11:306-311.

## DISCUSSION

ISMUNADJI: You stated that drainage could improve crop growth and increase yield. I would like to know when to drain, for how long, and how many times during the growing period of the rice plant.

*CHENG:* Results of investigations indicate that periodical drainage between the end of the tillering stage and the panicle differentiation stage of rice growth will lead to an increase in the yield of rice. In general, periodical drainage of the rice field must be carried out if the soil is puddled and the growth is excessive.

NEUE: Is it possible that one explanation for your positive effects of drainage might be related to excessive N after tillering in the field high in organic matter content? Otherwise the big losses of nutrients mentioned by Dr. Ponnamperuma might give yield declines instead of yield increases.

*CHENG:* That’s true. Thank you very much.

ZHU (comment): In evaluating the advantages and the disadvantages of drainage conditions and percolation rates of paddy soils, the cropping system (such as continuous rice, or rice-dryland crop rotation) as well as the soil types and organic manure amendment should all be taken into consideration. In the southern part of China, in my experience, high yielding paddy soils are characterized mostly by a moderate percolation rate and good drainage conditions, which are not only favorable for achieving a high yield of rice but are also even more helpful for the healthy growth of dryland crops.

PONNAMPERUMA (comment): You recommended percolation at the rate of 7-20 mm/day. Percolation at 20 mm/day implies leaching the soil with 2 m water/season. Apart from the waste of water, 2 m water will remove from the soil about 20 kg each of N and K and about 20 kg P/ha per season. The benefits of percolation — removal of toxic reduction products — can be achieved by drying out the soil temporarily by evapotranspiration. Our experience is that Zn application improves rice yields on poorly drained soils.

# ORGANIC MATTER AND PLANT GROWTH

# BENEFICIAL EFFECTS OF ORGANIC MATTER ON RICE GROWTH AND YIELD IN JAPAN

Kikuo Kumazawa

The results of experiments on the effects of the application of organic matter, especially compost, on rice plants in Japan are reviewed. The effect of compost is evaluated by its contents of nutrients, including N, P, K, and Si. The effect of compost is sometimes hindered by the application of chemical N fertilizers. Conditions that influence the rate of decomposition of organic matter in soil determine the effectiveness of compost. For instance, compost has little effect on poorly drained, gley, or humic paddy soil. The immobilization and mineralization of N in soil can be regulated by the addition of organic matter to improve the N absorption process of the rice plant and attain higher yields. The addition of compost accelerates the development of active rice roots that carry out nutrient absorption and thereby promote leaf activity. The long-term application of compost to the soil increases fertility, as indicated by the increase of C, N, and other nutrient elements in the soil; the increase of water-stable aggregates and cation exchange capacity (CEC); and the increase of biological N-fixing activity.

Long-term experiments at 14 Prefectural Agricultural Experiment Stations showed that the addition of compost to rice soils increased yields in plots that received no chemical N fertilizer (Yamashita 1964). Incremental rice yield increases per ton of added compost ranged from 20 to 400 kg/ha. Compost had little effect on yields in plots that had received chemical N fertilizer.

The effect of compost on rice yield varied among soil types. It increased yields on welldrained soils and did not on poorly drained, strong gley, and peat soils, on which soil reduction was accelerated by organic matter. Sometimes rice roots were severely damaged because of some inhibitors such as $H_2S$ or organic acids. Most of the effect of organic matter seemed to result from the effect of N, derived from the decomposition of the organic matter in soils.

Yamane (1974) also analyzed four rice yield experiments over periods of 24 to 31 years. He, too, concluded that most of the effect of compost or farmyard manure was attributable to the effect of N. No other effects, including the supply of trace elements, were evident.

---

Faculty of Agriculture, the University of Tokyo, Bunkyo-ku, Tokyo 113, Japan.

The experiments were carried out in normal fields of agricultural experiment stations that were not treated with any advanced technology such as water management, which accelerates the decomposition of organic matter and maintains rice root activity.

In rice fields supplied with a large amount of compost, however, rice yields were extraordinary. In fields that received large amounts of chemical fertilizers (170-240 kg N/ha) in addition to 15-21 t compost/ha, annual yields averaged 9 t/ha. The use of compost in these fields seemed indispensable to the high yields, which could not be achieved with chemical fertilizers alone.

The results indicate that the addition of organic matter may not always be necessary to obtain normal yields, but may be crucial to obtaining or maintaining high yields. Good water management may give the soils on which the high yields were obtained the ability to decompose such large amounts of compost in a rice crop season.

The general role of organic matter application to paddy fields is summarized in Table 1. The significance of the individual roles will be considered case by case, including climate, soil character, and amount and kind of fertilizer. Some important effects of compost will be considered in detail.

## NUTRITIONAL EFFECT OF ORGANIC MATTER

Organic matter contains many kinds of plant nutrients, both macroelements and microelements. The rice plant receives part of its nutrients from irrigation water and soil minerals, but remaining nutrients must be supplied by artificial sources such as chemical fertilizers and compost. Yamasaki (1966) compared the addition and loss of nutrients between fields with normal yields and high yields, and determined the amounts of nutrients that should be supplied to obtain 1 t brown rice at different yield levels (Table 2). In both fields, the same amounts of nutrients were absorbed to produce the same amount of rice.

Other sources of mineral nutrients for rice plants are irrigation water and soil clay minerals. Rice needs, besides N, P, and K, a relatively large amount of silica, which irrigation water supplies in only limited amounts, about 262 kg/ha; rice removes 860 kg silica/ ha in normal yields and 2,050 kg silica/ha in high yields.

In general, the most important role of compost for rice production is to supply N

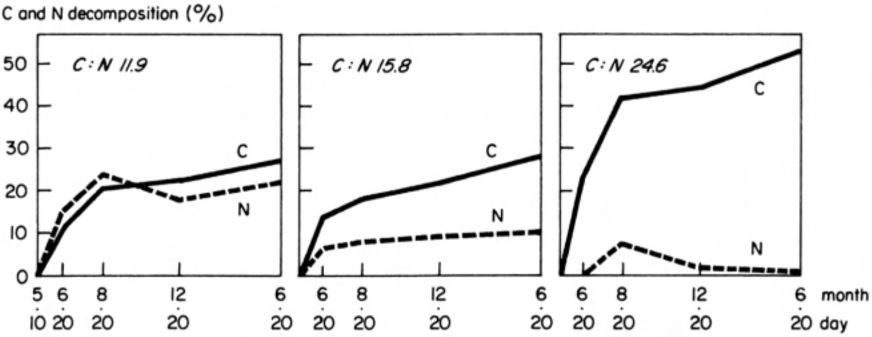
**Table 1. Effects of compost (Egawa 1964, Honya 1964).**

| Role | Effect |
|---|---|
| Nutritional | Readily available P, K; slow N release; available Si, Ca, Mg, etc. |
| Physiological chelate | Fulvic acid for Fe, AI, etc. |
| Growth promoter | Amino acids, vitamins, plant hormones, RNA, phenolic substances, humic acid, etc. |
| Fertility | Porosity, drainage, water holding capacity, ease of tilling, increase of N, cation exchange capacity, etc. |

**Table 2. Nutrients removed by rice (Yamasaki 1966).**[a]

| | | Nutrients (kg/ha) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | N | $P_2O_5$ | $K_2O$ | CaO | MgO | MnO | $SiO_2$ |
| Applied nutrients | (A) | 75 | 75 | 94 | – | – | – | – |
| | (B) | 201 | 143 | 215 | 743 | 229 | 5 | 1553 |
| Absorbed nutrients | (A) | 91 | 46 | 142 | 32 | 20 | 4 | 855 |
| | (B) | 195 | 100 | 333 | 64 | – | 10 | 2048 |
| Nutrients/t brown rice | (A) | 21 | 11 | 33 | 7 | 5 | 1 | 200 |
| | (B) | 19 | 10 | 33 | 6 | – | 1 | 200 |

[a] A = normal fields of Experimental Station; yield = 4.3 t/ha. B = high yield field; yield = 10 t/ha.



**1.** Decomposition process of composts of different C-N ratios (Maeda et al 1978).

and to regulate the immobilization and mineralization of N in the soil. The ratio of C to N (C:N) of organic matter influences the immobilization of inorganic N and the mineralization of organic N. Maeda and Shiga (1978) studied the relation between the decomposition process and the C:N of compost. Nitrogen was released from low C:N compost at the same rate as C when the C:N was 11.9, but at succeedingly higher C:N, C decomposition increased and N decomposition decreased (Fig. 1).

Yamamuro (1981) measured the distribution of $^{15}$N-labeled ammonium fertilizer applied with different amounts of compost. As the amount of compost increased, the ratio of the N absorption in rice decreased, and residual N in the soil increased (Table 3).

Residual soil N increases with the supply of compost and is available to the rice crop in subsequent years. After long-term application of compost, soil N reaches a constant level according to the amount of compost supplied, temperature, soil character, water regime, and other cultivation practices that regulate the decomposition of soil organic matter. Usually rice absorbs the N of chemical fertilizer supplied basally until 30 days after transplanting (DT). Then it absorbs the N released from soil (Wada et al 1971). Shiga et al (1971) also reported that in high yielding fields, rice absorbed only soil N after panicle initiation.

Organic matter can be used to regulate the N supply to the rice plant — as a

**Table 3. Percentage distribution of the $^{15}$N of applied ammonium in paddy soil 14, 42, and 69 days after application (Yamamuro 1981).**

| Compost application (t/ha) | | $^{15}$N distribution (%) | | |
|---|---|---|---|---|
| | | 14 days | 42 days | 69 days |
| 0 | Soil | 27.5 | 15.9 | 19.3 |
| | Rice | 30.7 | 42.2 | 40.8 |
| | Denitrification | 41.8 | 41.9 | 40.0 |
| 10 | Soil | 36.8 | 21.0 | 23.9 |
| | Rice | 23.1 | 40.7 | 40.6 |
| | Denitrification | 40.2 | 38.3 | 35.6 |
| 20 | Soil | 33.8 | 20.0 | 23.0 |
| | Rice | 23.3 | 37.4 | 34.9 |
| | Denitrification | 42.9 | 42.6 | 42.1 |
| 30 | Soil | 27.8 | 22.1 | 26.1 |
| | Rice | 25.6 | 35.2 | 33.7 |
| | Denitrification | 46.7 | 42.6 | 40.2 |

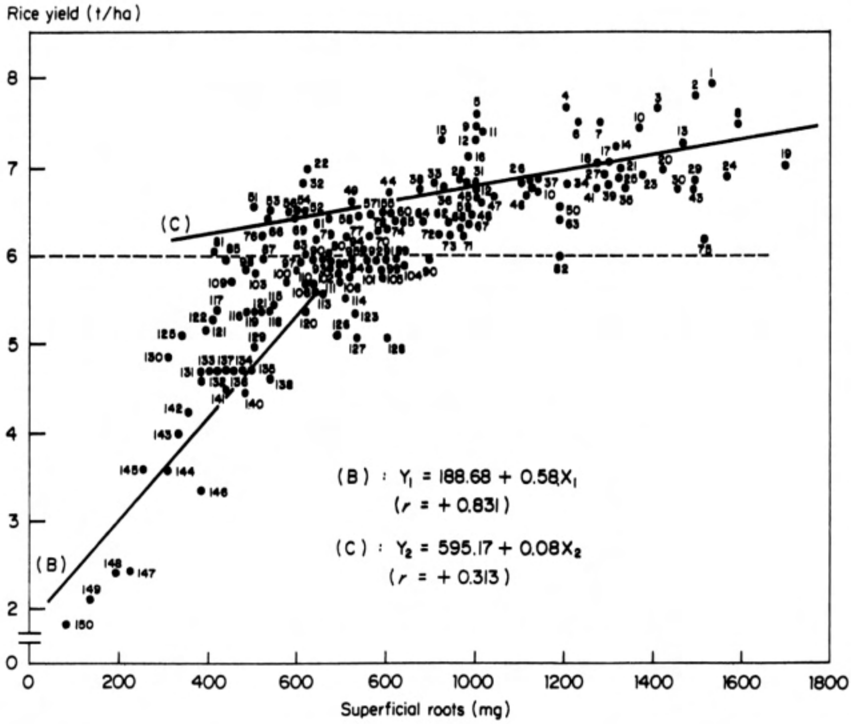
repressor in the early growth stages and as a N generator in later growth stages. To obtain high rice yields, the proper use of chemical fertilizers as a basal application and as a topdressing is necessary in addition to compost application.

## PHYSIOLOGICAL EFFECTS OF COMPOST

Kawata et a1 (1976) showed that there was a close relation between compost application and the development of the rice root system. Long-term applications of compost to rice fields (45 years at Aomori, 55 years at Fukushima) showed that compost accelerated the development of superficial roots of rice. Superficial roots are those that appear after panicle initiation; they are distributed mainly in the top 5 cm of the soil. At Aomori, rice plants developed 61 primary roots/plant in the plot that received compost and only 44/plant in the plot that did not (Kawata et al 1976). At Fukushima, plants in the compost-treated plot developed an average of 69 primary roots/plant and in control fields 46.5 roots/plant. Thick secondary roots were longer in plants grown in the compost-treated fields as well. The densities of secondary roots on primary roots and of tertiary roots on secondary roots were higher than those of the control. In the compost-treated plot, a fifth lateral root developed (Kawata et al 1976). As a result, rice roots in the compost-treated plots had larger growing points and more root surface area for nutrient absorption.

Kawata et al (1978) reported a high correlation between the development of superficial roots and rice yield up to 6 t/ha (Fig. 2). Late topdressing of N fertilizer can increase the number of superficial roots and yield up to the 6 t/ha threshold (Kawata et al 1977); beyond that, it increased the number of superficial roots, but not yield. They thought that the supply of compost accelerates thedevelopment of active roots deep into the soil and helps maintain their activity until late growth stages.

Kamata and Okada (1976) reported a similar effect of compost on root development at the Akita Prefectural Agricultural Experiment Station. There were

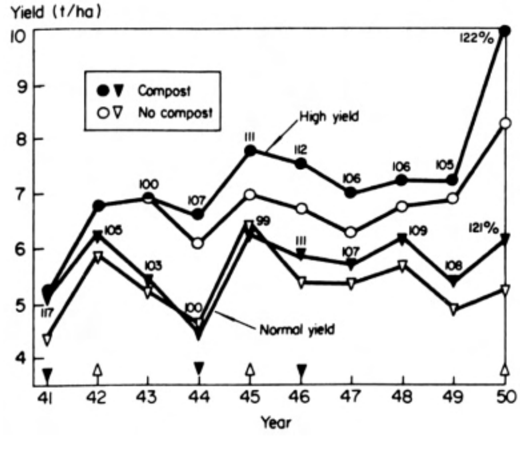


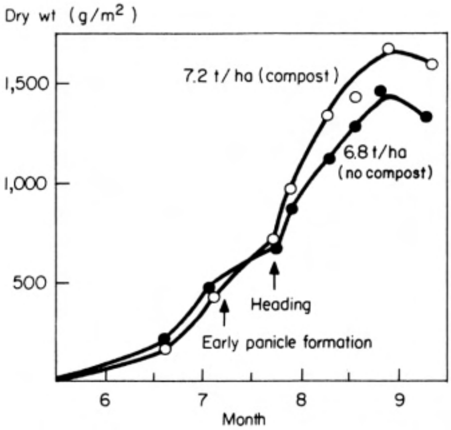
**2.** Relationship between the development of superficial roots and rice yield (Kawata et al 1978).

differences of 1.5-2.0 t/ha between high yielding and normal yielding fields, but the percentage increase in yield from the application of compost was almost the same, 8% (Fig. 3).

The process of dry matter production was different between composted and

**3.** Long-term effects of compost on rice yield (Kamata et al 1976). Index of compost to noncompost = 100.



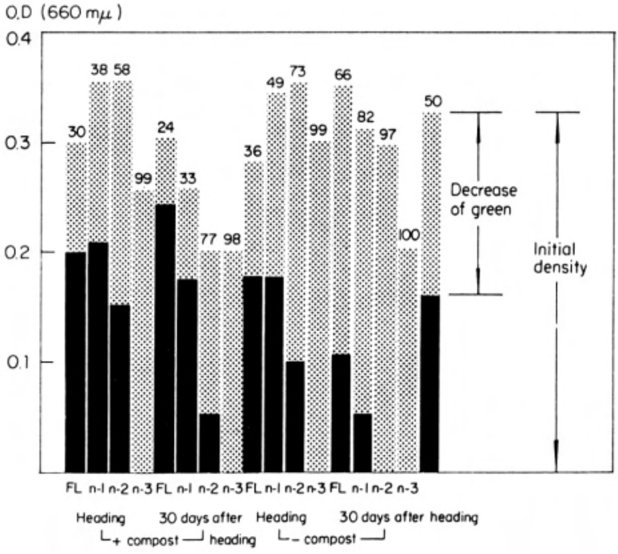


**4.** Dry weight production in composted and noncomposted fields (Kamata et al 1976).

noncomposted plots, as shown in Figure 4. Dry matter production at the early growth stages was nearly the same in treated and in control plots. After heading, dry matter of the compost-treated plot increased more rapidly. Total dry matter production was 7.2 t/ha in the treated plot and 6.8 t/ha in the control.

The degradation velocity of leaf chlorophyll after leaf abscission is shown in Figure 5. The decomposition of leaf chlorophyll was slower in the compost-treated plot than in the control plot, although the initial leaf colors were almost the same in both plots. The leaves of rice plants in the compost-treated plot might have transported more cytokinin from the apical points of the roots.

Many experiments have been carried out to elucidate the effects of organic matter on roots in the soil by using artificially extracted humic substances. Aso et al (1971) studied the effect of nitrohumic acid on the growth and activity of rice seedling roots.



**5.** Effect of compost on the degradation of chlorophyll (Kamata et al 1976).

**Table 4. Effect of alkali-treated peat on growth and number of root hairs in crown roots of rice seedling (Aso et al 1979).**

| Alkali-treated peat (ppm) | Root length (cm) | Top length (cm) | Roots (no./plant) | Dry wt (mg/15 plants) | Root hairs (no./1.0 mm) |
|---|---|---|---|---|---|
| 0 (control) | 4.9 (100) | 3.4 (100) | 5.3 (100) | 17.1 (100) | 15 (100) |
| 10 | 6.2 (127) | 3.4 (100) | 5.2 (98) | 19.8 (116) | 20 (116) |
| 50 | 6.0 (122) | 3.6 (106) | 4.4 (83) | 31.2 (182) | 25 (167) |
| 100 | 6.9 (141) | 3.6 (106) | 5.6 (106) | 31.7 (185) | 33 (220) |

They reported that 0.005-0.08% sodium nitrohumate increased root elongation by 136-195% and increased the activity to oxidize a -naphthylamine. Akashi et al (1975) obtained almost identical results using magnesium nitrohumate.

Aso et al (1979) also demonstrated that humic substances obtained from volcanic ash soil and alkali-treated peat promoted root-hair formation. Root length, top length, dry weight, and the number of root hairs per 1.0 mm increased with increased concentration of alkali-treated peat (Table 4).

Moriyama (1982) reported that $^3$H-labeled nitrohumic acid (molecular weight $1.75 \times 10^4$) was absorbed, by rice roots. It is possible that the roots absorb these humic substances by endocytosis, as was reported in the absorption of protein by rice roots by Nishizawa et al (1978).

When 20 ppm of alkali-treated peat was added to a water culture solution, respiration in the roots of seedlings and the absorption of N, P, K, Ca, and Mg increased (Moriyama 1982). From these results it was concluded that the humic substances promoted root hair formation and root elongation, thereby accelerating nutrient uptake. Yoshida (1981) found that the cytokinin content, especially trans-zeatin, increased with the addition of humic substances (Table 5). He estimated that the increase in cytokinin activity induced increased protein and RNA synthesis.

Recently Nakayama et al (1980a) showed that ethylene production in submerged conditions occurred mainly through the decomposition of organic matter or through the addition of compost and that ethylene promoted the elongation of the new roots at 0.1 ppm and increased the number of new roots at 10 ppm (Nakayama et al 1980b). Nakayama et al (1980c) also showed that the elongation of the seminal roots and coleoptiles of rice seedlings, which was observed constantly for 12-16 weeks after submergence, was stimulated by ethylene evolved from submerged soil.

**Table 5. Effect of humic substances on the cytokinin content of leaf blades of rice seedlings (Yoshida 1981).**

| Treatment | Free cytokinin content (µg/100 g fresh wt) | | | |
|---|---|---|---|---|
| | Trans-zeatin | Trans-zeatin riboside | Cis-zeatin riboside | Total |
| High humins[a] | 2.33 | 13.58 | trace | 15.91 |
| Control | 0.66 | 13.20 | trace | 13.86 |
| Difference | 1.67 | 0.38 | | 2.05 |

[a] Alkali-treated humic substances.

## ORGANIC MATTER AND SOIL FERTILITY

Soil organic matter is a good reservoir of available N. An increase of organic matter content by continuous application of compost resulted in the enhanced mineralization and immobilization of N (Maeda et al 1978). Table 6 shows the indexes of the nutrients in the soil after the long-term (11-33 years) application of compost in eight prefectural agricultural experiment stations. The content of total N was higher in the composted soils than in the corresponding noncomposted soils.

Under identical climatic, soil, and cultivation conditions, the rates of accumulation and decomposition of N compounds in the soil are thought to become almost equal. A high-yield field can supply N from compost and maintain a high level of soil organic N. In other words, the high-yield field should have the capacity to decompose a great amount of organic matter during rice cultivation, depending on good soil, irrigation, and drainage conditions. Good drainage practice properly carried out can also serve to keep the rice roots healthy without any damage due to the reduction products that are sometimes produced when an excess of organic matter is present.

The P content increased with the application of compost to most soils (Table 6). Komoto et al (1979) found compost application increased rice yields by about 10% in high and medium P applications, and 27% in no-P applications. But the effect of P fertilizer application was not clear in the composted fields, and it was concluded that rice yields were correlated with N absorption, which was stimulated by compost application. The K in compost is water soluble and is absorbed as readily as K in chemical fertilizers. The increase of K content was remarkable in composted soils (Table 6). The available Si (as the acetate buffer soluble $SiO_2$) in the soil increased as well in most of the composted soils.

Yamashita (1967) studied the effects of long-term compost application on the nature of soil organic matter and on the chemical and physical properties of paddy soils; there was an increase in humus from 0.8 to 3.0%, an increase in water-stable aggregates, a slight rise in pH from 0.2 to 0.4, and an increase in CEC from 1 to 7 meq, mainly attributed to the increase of organic matter. All these changes in soil characteristics are important to agricultural practices such as tillage, fertilization, utilization of cold tolerance, and taking advantage of high temperatures and strong light conditions for the auto-regulated supply of nutrients.

Nakada (1981) recently analyzed statistically the data of long-term field

**Table 6. Increase. of nutrients by long-term application of compost (calculated from Yamashita 1967).[a]**

| Nutrient | Index[b] | |
|---|---|---|
| | Mean | Min – max |
| N | 168 | (118 – 258) |
| Total P | 135 | ( 97 – 224) |
| Exchangeable K | 213 | ( 95 – 437) |
| Available Si | 114 | ( 70 – 175) |

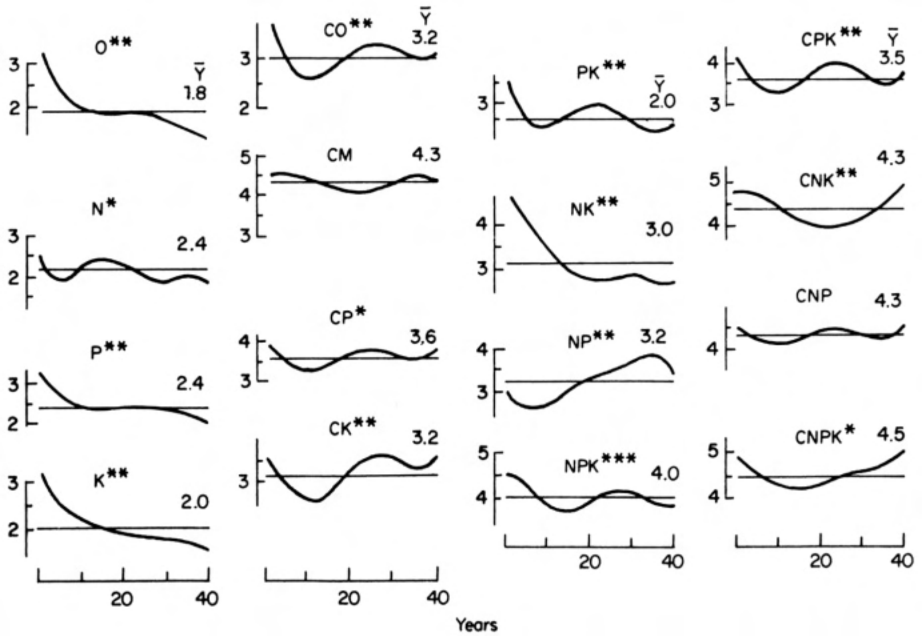
[a]Means of 8 agricultural experiment stations. [b]Control = 100.

experiments (since 1933) which combined three major elements with compost in a double cropping system of rice and wheat.

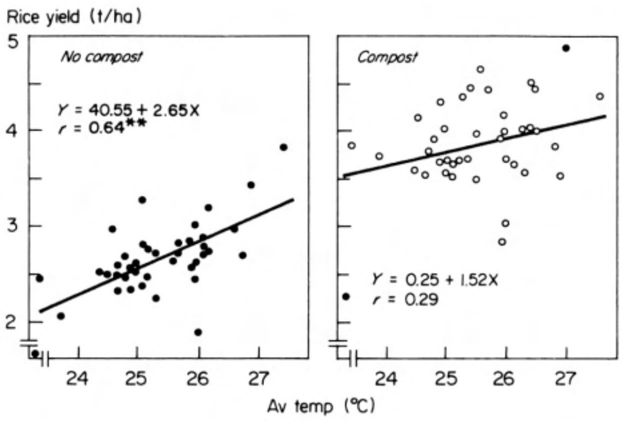
In the plots where compost (21 t/ ha per year) was used continuously, the plow layer became 1–4 cm deeper than in the plots without compost, and its specific gravity decreased because porosity increased. Concerning properties related to fertility, compost application increased the T-C, T-N, and CEC of the soil. The N dressing as $(NH_4)_2SO_4$ did not raise the T-N, and it decreased the pH by about 0.5-1.0. The amount of C in the soil increased by 300-500 kg/ha per year with compost treatment.

In the polynomial regression formula expressing the yield of the composted plots, quadratic and quartics terms are significant. Figure 6 shows the estimated curves of the yields of individual treated plots. The substantial yield has not decreased in these plots in the past 40 years, but the yields of noncomposted plots tend to decrease. By analysis of variance on the rice grain yield, the inherent effect resulting from compost application corresponds to one-half, and the effect of N to one-third of the whole deviation (Nakada 1981).

It was also suggested that compost application prevented the rice yield from decreasing at its vegetative and ripening stage in low-temperature years (Fig. 7). This phenomenon was consistent with other results (Kamata et al 1976). Nakada (1981) also analyzed P, K, Si, Mg, Ca, S, Fe, Mn, Cu, Ni, V, etc., and showed that compost treatment increased the amount of all elements, especially Ni, Mn, Zn, Cu, and Mg, but inorganic N application decreased them and P application increased P, Al, Sr, and Fe in the surface soil.



**6.** Polynomial regression curves of rice yields (t/ha) (Nakada 1981). C = compost; * = 0.05%; ** = 0.01%.



**7.** Relationship between rice yield and temperature at vegetative growth stage (NPK plot) (Nakada 1981).

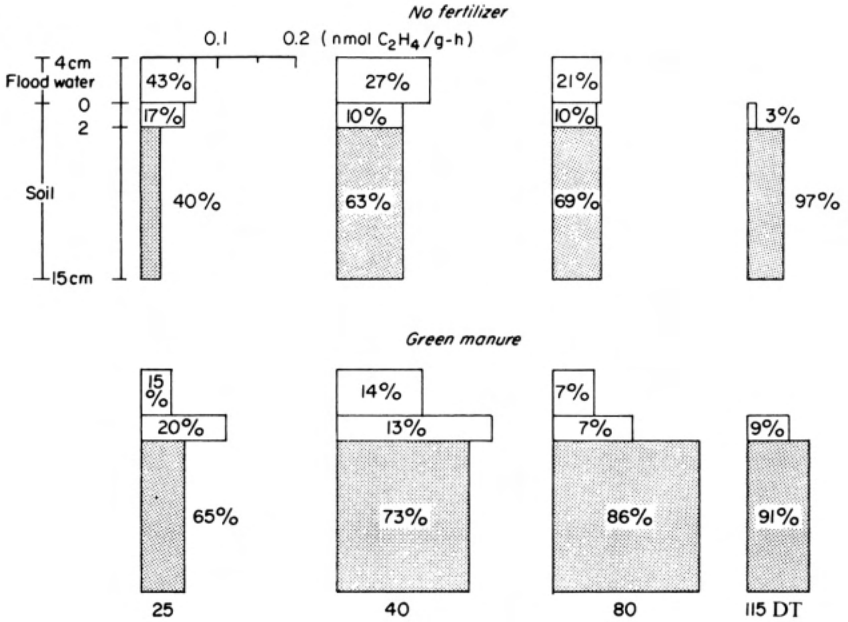
Wada et al (1978) studied N fixation in long-term experimental plots with different fertilizer treatments and showed that the application of organic matter such as organic manure and green manure enhanced N fixation activity by increasing the content of easily decomposable soil organic substances (Fig. 8).

## CONCLUSION

The significance of organic matter application must be considered first from the viewpoint of economics, including the cost of production and application of the organic matter, the price of chemical fertilizers, and the marginal effect of increased yields. Sometimes it is possible to maintain a high yield for as long as 10 years using only chemical fertilizers, but soil fertility gradually decreases and the yield becomes relatively lower and unstable, depending on the soil and climatic conditions. Compost cannot have the desired effect of increasing yield under conditions that prevent its decomposition such as poorly drained, gley, or peat soils. In such soils the addition of organic matter sometimes leads to rapid soil reduction and the production of substances inhibiting rice roots; then the effect of compost becomes negative. Even in such soils, rice plants need some of the nutrients effectively supplied with organic matter such as Si, and the application of silicate fertilizers can often produce a good effect (Imaizumi and Yoshida 1954).

Generally speaking, the addition of organic matter is useful in maintaining or increasing the organic substances or nitrogenous compounds in soil, which are decomposed slowly but steadily. The period from the application of organic matter to the liberation of N is dependent on the C:N of the materials. The inorganic N supplied with organic matter can be immobilized, become organic N, and be mineralized slowly.

High yielding rice needs a supply of N until the late growing stages, but the N applied basally is absorbed only during the vegetative growth stage; after panicle formation, N released from soil N is absorbed by the rice plants. Then the maintenance of a N reservoir that can supply its N in the late growing stages becomes important for high yield. Using the multisplitting application method of N



**8.** Nitrogen-fixing activity at different site, in soils in Konosu field (Wada et al 1978). DT = days after transplanting

fertilization, it becomes possible to get good yields, but to get stable high yields the application of compost becomes necessary (Shiga et al 1977).

The addition of compost accelerates the development of the rice root system. which elongates both at the surface and in deep soil and produces many branches and a large active surface. The active roots can absorb the nutrients from the whole layer of soil, transport them to the shoot. and keep the leaves active. Cytokinin produced at the growing point of roots probably also plays an important role in keeping the leaves active.

Artificial humic substances can replace organic matter by stimulating root elongation, root hair formation, and nutrient absorption. The long-term application of compost steadily increases C, N, P, K, and Si. The chemical, physical, and biological nature of the soil is improved by the addition of organic matter. And water-stable aggregate formation, CEC, and biological N fixation activity are increased. Soil can be nourished with the addition of organic matter and kept at a high level of nutrients, especially N, from which the proper amount of nutrients can be drawn by the use of good soil and water management.

Organic matter should be fertilizer in its true meaning — to increase soil fertility. The only difference between chemical fertilizer and organic matter is that the nutrients contained in chemical fertilizer are used rapidly but incompletely, and the nutrients supplied with organic matter are used slowly and stored a long time in the soil. Organic matter and its decomposition products promote root development. Active roots protect the leaves from early senescence, probably by the translocation of phytohormones.

## REFERENCES CITED

Akashi, K., I. Hasegawa, H. Kojima, and J. Yazaki. 1975. Studies on the physiologically active substances for plant roots (Part II). Effects of nitrohumic acid on rice seedlings [in Japanese]. J. Sci. Soil Manure Jpn. 46: 175-179.

Aso, S., and H. Moriyama. 1979. The effect of humic substances on root hair formation and nucleic acid content of rice seedling. Paper presented at VII International Symposium Humus et Plants.

Aso, E., and T. Yamaguchi. 1971. Promotive action of nitrohumic acid on the elongation and physiological activity of crop plant root [in Japanese]. J. Sci. Soil Manure Jpn. 42:291-294.

Egawa, T. 1964. Discussions on the effect of compost in the researches of soil and fertilizer [in Japanese]. J. Agric. Sci. 19:l-15.

Honya, K. 1964. Rice straw compost and soil fertility [in Japanese]. J. Agric. Sci. 31:485-489.

Imaizumi, K., and S. Yoshida. 1954. Edaphological studies on silicon supplying power of paddy fields [in Japanese, English summary]. Bull. Natl. Inst. Agric. Sci. B8:261-304.

Kamata, K., and K. Okada. 1976. Effect of compost on the rice cultivation [in Japanese]. Agric. Hortic. 51:867-871.

Kawata, S., and H. Soejima. 1976. The effect of farm compost application to the paddy field on the formation of superficial roots of rice in [Japanese, English summary]. Proc. Crop Sci. Jpn. 45:99-116.

Kawata, S., M. Soejima, and R. Tabuki. 1977. Effect of top dressing of nitrogen fertilizer on the formation of superficial roots of rice plants [in Japanese, English summary]. Proc. Crop Sci. Jpn. 46:254-260.

Kawata, S., M. Soejima, and K. Yamazaki. 1978. The superficial roots of rice plants [in Japanese, English summary]. Proc. Crop Sci. Jpn. 47:617-628.

Komoto, Y., T. Sakon, T. Fujiwara, M. Nakayasu, K. Miyaji, and S. Furui. 1979. Yearly effects of a continuous application of compost on the growth and yield of rice in southwestern Japan in relation to phosphate application [in Japanese]. J. Sci. Soil Manure Jpn. 50:347-352.

Maeda, K., and H. Shiga. 1978. Year-long decomposition processes of various organic materials in a lowland field [in Japanese]. J. Sci. Soil Manure Jpn. 49:455-460.

Moriyama, H. 1982. Studies on the physiological effects of humic substances [in Japanese, English, summary]. PhD thesis.

Nakada, H. 1980. Mathematical statistics analysis of the influence of long term application of three nutrients and compost on lowland productivity [in Japanese, English summary]. Shiga Agric. Exp. Stn. Spec. Bull. No. 13.

Nakayama, M., and Y. Ota. 1980a. Physiological action of ethylene in crop plants. V. Effect of water and compost on the ethylene production from soil [in Japanese, English summary]. Proc. Crop Sci. Jpn. 49:359-365.

Nakayama, M., and Y. Ota. 1980b. Physiological action of ethylene in crop plants. VI. Effect of hydrocarbons especially ethylene on the root growth of soybean and rice seedlings [in Japanese, English summary]. Proc. Crop Sci. Jpn. 49:366-372.

Nakayama, M., and Y. Ota. 1980c. Physiological action of ethylene in crop plants. VII. Role of ethylene in the soil atmosphere in the seedling growth of soybean and rice [in Japanese, English summary]. Proc. Crop Sci. Jpn. 49:575-581.

Nishizawa, N., and S. Mori, 1978. Endocytosis (heterophagy) in plant cells: involvement of ER and ER-derived vesicles. Plant Cell Physiol. 19:717-730.

Ohta, M. 1964. Studies on the use of slags as fertilizer [in Japanese, English summary] Kazama-shobo, Tokyo.

Shiga, H., A. Kakimoto, Y. Doi, H. Awasaki, M. Miyake, S. Sekiya, and T. Kataoka. 1971. Environment and characteristics of rice plants in high-yielding paddy fields in Hokkaido [in Japanese, English summary]. Res. Bull. Hokkaido Natl. Agric. Exp. Stn. 99:30-40.

Shiga, H., N. Miyazaki, and S. Sekiya. 1977. Time of fertilizer application in relation to the nutrient requirement of rice plants at successive growth stages. Pages 223-229 *in* Proceedings of the International Seminar on Soil Environment and Fertility Management in Intensive Agriculture.

Yamamuro, S. 1981. Immobilization, denitrification and absorption by rice plants of applied nitrogen in paddy fields [in Japanese]. J. Sci. Soil Manure Jpn. 52:141-148.

Yamane, I. 1974. Re-examination of long term experiments on compost [in Japanese]. Agric. Hort. 49:848-852.

Yamasaki, T. 1966. Micro and macro nutrients: Diagnosis and treatment for soils and crops [in Japanese]. J. Agric. Sci. 19:6-11.

Yamashita, K. 1967. The influence of the prolonged application of farmyard manure on the nature of soil organic matter and chemical and physical properties of paddy rice soils [in Japanese, English summary]. Bull. Kyushu Agric. Exp. Stn. 13:113-156.

Yoshida, R. 1981. Physiological effects of humic substances on rice plant. Proc. Crop Sci. Jpn. 50: (Extra issue 2):187-188.

Wada, H., S. Panichsakpatana, M. Kimura, and Y. Takai. 1978. Nitrogen fixation in paddy soils. I. Factors affecting $N_2$ fixation. Soil Sci. Plant Nutr. 24:357-365.

## DISCUSSION

FLAIG: You have demonstrated a positive effect of compost in the case of unfavorable growth conditions (e.g., increase of rice yield at higher temperature in presence of compost). Did you also observe higher resistance against disease?

*KUMAZAWA:* No, there is no indication of higher resistance against disease by the application of compost.

GAUR: You have indicated some growth-promoting effects of compost on rice. Have bio-assay tests been conducted for the presence of auxins, gibberellins, cytokinins, etc. in compost?

*KUMAZAWA:* Dr. Moriyama assayed the plant hormones in compost and found small amounts of cytokinin-like substances. However, 1 think the application of compost initially promotes root growth; then the roots can produce and supply more cytokinin.

SINGH: Did you find a relationship between the soil Eh and formation of nodal roots at the soil surface?

*KUMAZAWA:* No.

SINGH: Were the effects of compost on root growth due to better nutrition or improved soil physical conditions?

*KUMAZAWA:* Long-term application of compost can improve soil chemical and physical properties. However, the direct stimulative effect on root growth is due to the decomposition products of compost including phenols, hormones, and soluble humic substances.

AGBOOLA: YOU said compost alone increases soil N. Can this statement be justified in light of our present knowledge of compost? Have you considered the effects of compost on both the physical and chemical properties of the experimental soils?

*KUMAZAWA:* It is clear that the application of compost can reclaim the soil physical and chemical properties.

HESSE: What was your compost made from and how was it made? Have you any analysis? Was the same kind of compost used by all the different investigation mentioned?

*KUMAZAWA:* Usually compost was made from rice straw. rice straw + N fertilizer, or rice straw + animal excreta. The chemical components of compost vary widely because of their sources.

# CHEMICALS THAT PROMOTE ROOT GROWTH

R. L. Wain

A brief account is given of the complex of hormones and hormone inhibitors that operate in controlling plant growth and development. Recent findings on the hormonal control of root growth are described and an account is given of a group of synthetic chemicals (*di*-halogen substituted 4-hydroxybenzoic acids) which, under certain conditions, can markedly increase root growth. Studies with these compounds using seedlings growing in culture solution with their nodes exposed to light, and with plants growing in compacted soils, are described.

Research on the hormonal control of plant growth has led to impressive developments since Kogl et al (1934) first demonstrated the growth-promoting properties of indole-3-acetic acid (IAA). This discovery led to intensive studies on this auxin and its synthetic analogues, some of which are widely used in agriculture.

Three main groups of plant growth hormones — the auxins, gibberellins, and cytokinins — are now recognized. The discovery of the gibberellins arose from observations by Kurasawa (1926) in Taiwan. Like the auxins, the gibberellins promote cell enlargement and thereby increase the size of the plant. The other fundamental process that determines growth is cell division, by which new cells are produced. The hormones that influence this process in plants are known as cytokinins. The naturally occurring cytokinins, e.g., zeatin (Letham and Miller 1964), are derivatives of adenine (6-aminopurine), but synthetic cytokinins that are not adenine derivatives are now known. One of these compounds, 6-benzyloxypurine, can induce morphological differentiation as well as cell division in sterile tissue culture tests, thereby leading to the production of whole plants (Wilcox and Wain 1976).

---

Chemical Laboratory, University of Kent, Canterbury, Kent, England.

In addition to the above three types of hormone, all of which are concerned with the promotion of growth, two hormone inhibitors have been identified in plants. One of them, abscisic acid [3-methyl-5-(1-hydroxy-4-oxo-2,6,6-trimethylcyclohex-2-en-y)*cis-trans*-penta-2,4-dienoic acid], was found in cotton fruits by Okhuma et a1 (1965). Abscisic acid has since been found in a wide range of plant species, and physiological studies have shown that it can inhibit the activity of auxins, gibberellins, and cytokinins. For this reason, it is a potent seed-germination inhibitor as well as an inhibitor of plant growth. Abscisic acid also defends plants against the effects of physiological stress such as those imposed by drought or waterlogging of the soil (Wright and Hiron 1969, Hiron and Wright 1973).

Xanthoxin, discovered in the author's laboratory, is the other endogenous growth-hormone inhibitor. It appears in plants when certain xanthophyll pigments, present in leaves, are exposed to light. Like abscisic acid, it inhibits the activity of auxins, gibberellins, and cytokinins and represses seed germination and extension growth in plants. The formation of xanthoxin from xanthophyll epoxides exposed to light offers, for the first time, an explanation of why plants grow taller in the dark. The structure of xanthoxin has been established as *2-cis-4 trans*-5-(1,2-epoxy-4-hydroxy-2,6,6-trimethyl-l~yclohexyl)-3-methylpentadienal (Taylor and Burden 1972).

In addition to the above hormones and hormone inhibitors, which operate together in plant growth, another compound exerts profound physiological effects on plants. This is the simple, unsaturated gaseous hydrocarbon ethylene. It is evolved by certain plants, especially by ripening fruits, and can promote abscission of both leaves and fruit. A particularly important property of ethylene in relation to the present account is the effect it exerts at low concentrations on plant roots, causing growth inhibition (Larque-Saavedra et a1 I975), stunting, and deformed growth (Cornforth and Stevens 1973, Lieberman and Kunishi 1970).

## HORMONES AND ROOT GROWTH

It is now generally recognized that the growth of roots is controlled mainly by the combined action of IAA moving down from the shoot and by abscisic acid produced in the cells of the root cap (Pilet 1979, Ney and Pilet 1980, Rivier and Pilet 1981).

The application of IAA to roots, however, strongly inhibits growth, except at very low concentrations ( $10^{-6}$ $M$ or less), in which case root growth and the production of root hairs are promoted. It is possible that soil organic matter provides these low beneficial concentrations of IAA by microbial biosynthesis and from the enzymic breakdown of tryptophane present in decomposing plant residues. A wide range of bacteria, actinomycetes, and fungi isolated from soil have been shown to produce IAA when grown on a medium containing tryptophane (Roberts and Roberts 1939), and Brian (1957) showed that most of the fungi he examined could do the same. However, soil microorganisms can readily degrade IAA, so the soil content at any time will represent an equilibrium between biosynthesis and breakdown.

Whitehead (1963), working in the author's laboratory, detected auxin activity equivalent to an IAA concentration of $1.5 \times 10^{-7}$ $M$ in a calcareous soil under permanent pasture and a concentration of about $1.5 \times 10^{-8}$ $M$ in a clay soil under arable cultivation; both soils were sampled to a depth of 18 cm.

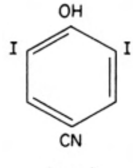
It would appear, then, that production of auxin should be included among the beneficial effects on crop growth which arise from the presence of organic matter in soils.

## EFFECT OF LIGHT OS ROOT GROWTH

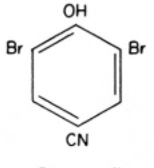
White light inhibits the rate of root elongation in many plant species (Torrey 1952; Pilet and Went 1956; Burstrom 1960; Wilkins et al 1974a,b; Ohno and Fujiwara 1967). It has been demonstrated in the author's laboratory that the root cap of *Zea mays* seedlings is solely responsible for the perception of light and that it responds to this stimulus by producing growth inhibitors (Wilkins et al 1974a, Wilkins and Wain 1974). There is evidence that abscisic acid is a growth inhibitor produced in response to light (Wilkins and Wain 1974, Tietz 1974). Because the light-exposed roots of maize seedlings contain the xanthophyll pigment violaxanthin (Wilkins et al 1974a), the effect of light could be to convert violaxanthin into xanthoxin, which is known to be transformed into abscisic acid within certain plant tissues (Taylor and Burden 1972).

## PROMOTION OF ROOT GROWTH WITH 3,5-DIIODO-4-HYDROXYBENZOIC ACID

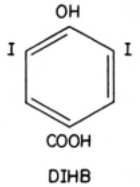
The discovery by the author (Wain 1963) of the selective herbicidal activity of 3,5-diiodo-4-hydroxybenzonitrile (ioxynil) and its dibromo analogue (bromoxynil) led to a number of other developments (Wain et al 1968, Wain 1977), one of which arose from a study of 3,5-diiodo-4-hydroxybenzoic acid (DIHB), a product obtained by the hydrolysis of ioxynil.



Ioxynil



Bromoxynil



DIHB

In studies on the translocation of DIHB, seedlings of cress (*Lepidium sativum* L.) were grown with their roots immersed in a solution containing inorganic nutrients and small amounts of DIHB. The chemical caused a marked stimulation of root growth; treated roots grew up to three times as long as control roots. The dibromo- and dichloro-analogues of DIHB were less effective (Table 1, Fig. 1).

Stimulation was similar with other plant species, including rice (*Oryza sativa*, variety "Jao Lenang 11"). In the rice experiments, the optimum concentration of DIHB ($5 \times 10^{-6} M$) caused the roots to grow to about twice as long as control roots (Interakosit 1967). Further experiments showed that DIHB treatment did not affect the number of cells per root, but increased cell lengths appreciably (Wain et al 1968). DIHB, however, did not increase the growth rate in excised roots (Interakosit 1967).

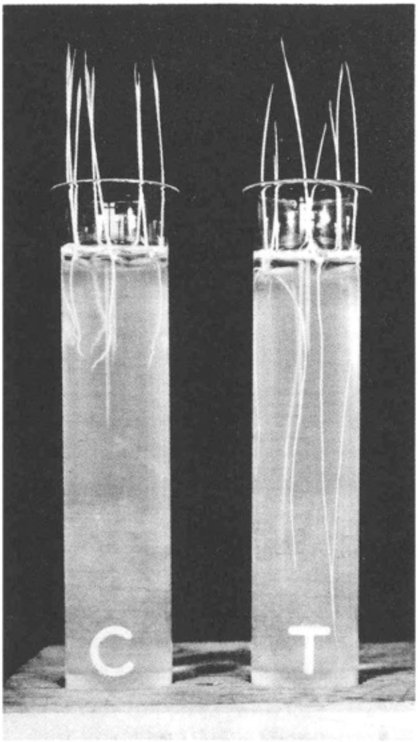
**Table 1. Stimulation of root growth[a] of cress seedlings by DIHB and related compounds.**

| Compound | Concentration ($M$) | | | | |
|---|---|---|---|---|---|
| | $5 \times 10^{-7}$ | $10^{-6}$ | $5 \times 10^{-6}$ | $10^{-5}$ | $5 \times 10^{-5}$ |
| 3,5-diiodo-4-hydroxy benzoic acid (DIHB) | 143* | 175** | 285** | 331*** | 211*** |
| 3,5-dibromo-4-hydroxy benzoic acid | 110 | 120 | 210*** | 234*** | 261*** |
| 3,5-dichloro-4-hydroxy benzoic acid | 102 | 120 | 160 | 176** | 218*** |

[a] All results expressed as a percentage of control root lengths. * = significant at the 5% level; ** = significant at the 1% level; *** = significant at the 0.1% level.

Increases in root length resulting from chemical treatment of cucumber seedlings had been previously reported by Minarik et al (1951), but all the compounds used by these workers were less active than DIHB.

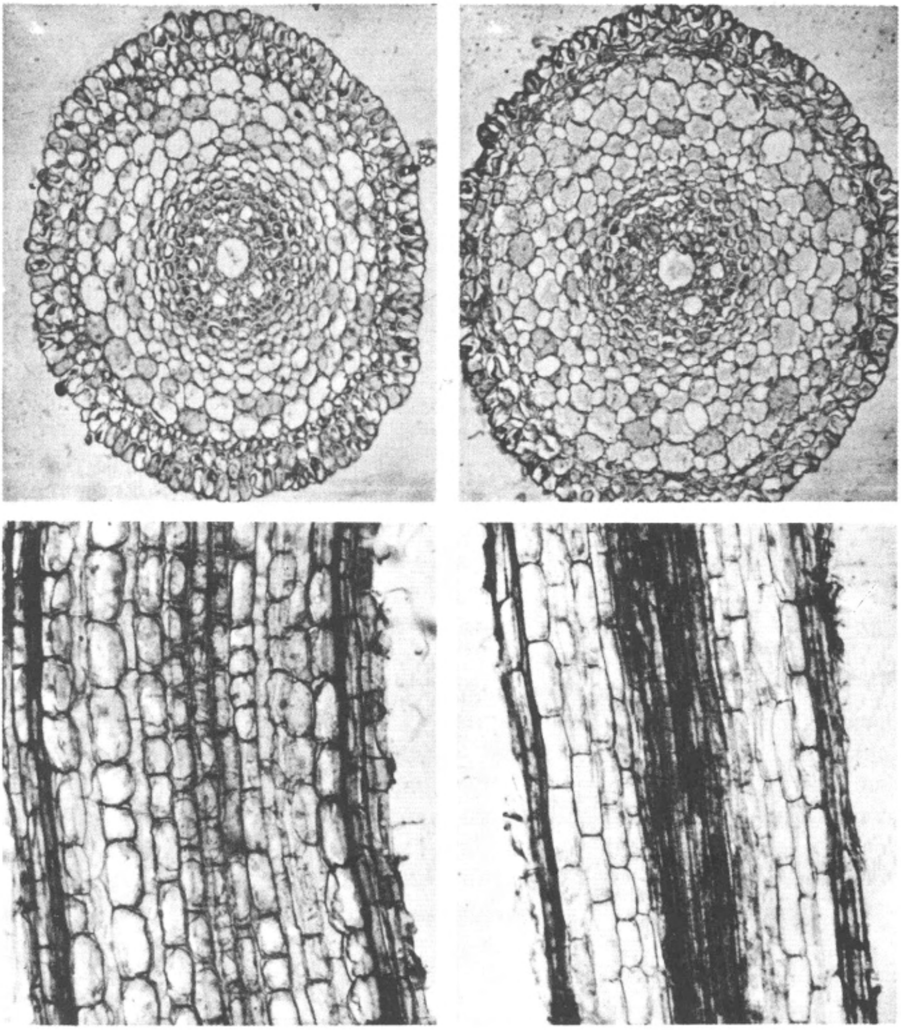
Further experiments with cress seedlings showed that the DIHB treatment did not stimulate root growth in seedlings grown with their roots in the dark (Wain et al 1968). Treatment with DIHB removed the inhibition by light of the growth of control roots so root growth was not stimulated when seedlings growing in well-aerated soil were treated with the chemical.



**1.** Stimulation of barley seedling root growth with 3,5-diiodo-4-hydroxybenzoic acid (as sodium salt) at $10^{-5}$ $M$ in the culture solution. Control plant *on left.*

In addition to white light, other constraints might operate in the growth of plant roots. Soil compaction can often reduce crop yields by causing poor development of root systems (Taylor 1971, Zimmerman and Kardos 1961). Laboratory tests have shown that progressive increases in mechanical resistance of the growth medium cause reduced root elongation (Zimmerman and Kardos 1961, Gooderham and Fisher 1975), stunting and thickening of root systems (Goss and Drew 1972), and reduced shoot growth (Taylor 1971).

Thus, both white light and compacted soil can induce stunting and thickening of root systems, and since DIHB can counteract the light effect, a study was carried out



**2.** Increase in cell length of rice seedling roots after treatment with 3,5-diiodo-4-hydroxybenzoic acid (DIHB); control transverse and longitudinal sections at left, treated sections at right.

to determine whether it can improve root development in compacted soils (Wilkins et al 1976, 1977).

In experiments with pea seedlings the addition of $10^{-4}$ *M* solution of DIHB, followed by compaction, caused roots to grow to overall lengths 19% greater, than those of corresponding roots in the untreated compacted soil; the addition of $10^{-6}$ *M* DIHB solution caused a 31% increase in root length. Similar DIHB treatments applied to loose soil produced no beneficial effects. In seedlings grown in compacted soil treated with DIHB at rates ranging from $10^{-4}$ *M* to $10^{-6}$ *M* small increases in shoot length and seedling dry weight occurred. In seedlings grown in loose soil, however, the chemical had no such effect.

This demonstration that DIHB can reduce root growth inhibition induced by both compacted soil and exposure to white light indicates that the two responses might have similar control mechanisms. In the author's laboratory DIHB has been shown to counteract the effects of light on root elongation by reducing ethylene-induced growth inhibition (Larque-Saavedra et al 1975, Robert et al 1975). As earlier mentioned, ethylene can also cause bending and swelling of roots, distortions similar to those observed in roots of seedlings growing in compacted soils (Goss and Drew 1972).

Anaerobic conditions that prevail in some compacted soils can stimulate the production of ethylene by soil microflora (Smith et al 1973, Eavis 1972). Furthermore, mechanical resistance can also induce the endogenous production of ethylene by roots and shoots (Kays et al 1974, Goeschl et al 1966). Thus, it is possible that the activity of DIHB arises from a lowering of the level of ethylene in the root or within the root environment. However, the capacity of DIHB to counteract ethylene effects on root growth does not appear to arise from a chemical interaction between DIHB and ethylene (Burden, pers. comm.), and DIHB may well act by reducing the biosynthetic capacity of the root tissues or soil microorganisms to produce ethylene. Research now in progress should further elucidate the mode of action of DIHB in promoting root growth. It has been established that the ioxynil analogues 3,5-dibromo- and 3,5-dichloro-4-hydroxybenzoic acid can also improve root growth in compacted soils (Wilkins et a1 1978), though its activity in this respect is less than that of DIHB (Fig. 2). Further field experiments with all these hydroxybenzoic acids are being undertaken. It is of interest here to note that Saini (1979) has reported beneficial results on root growth and crop yields of alfalfa of treatment of compacted soils with DIHB. The mean root length of the alfalfa plants was 51.2 cm (control 33.2 cm) and the mean dry weight of shoots was 5.59 g (control 3.09 g). Whatever the mechanism by which these hydroxybenzoic acids affect root growth, the finding of enhanced seedling performance resulting from their use in adverse soil conditions could open up important new possibilities in practical agriculture of using chemicals to combat the effects of soil compaction on plant growth.

## REFERENCES CITED

Brian, P. W. 1957. The effects of some microbial metabolic products on plant growth. Symp. Soc. Exp. Biol. No. 11:166-182.

Burstrom, H. 1960. Influence of iron and gibberellic acid on the light sensitivity of roots. Physiol. Plant 13:597-615.

Cornforth, I. S., and R. J. Stevens. 1973. Ethylene and the germination and early growth of barley. Plant Soil 38:581-587.

Eavis, B. W. 1972. Soil physical conditions affecting seedling root growth: I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in sandy loam soil. Plant Soil 36:613-622.

Goeschl, J. D., L. Rappaport, and H. K. Pratt. 1966. Ethylene as a factor regulating the growth of pea epicotyls subjected to physical stress. Plant Physiol. 41:877-884.

Gooderham, P. T., and H. M. Fischer. 1975. Experiments to determine the effect of induced soil compaction on soil physical conditions, seedling root growth and crop yield. Min. Agric. Tech. Bull. (U.K.) 29:469-482.

Goss, M. J., and M, C. Drew. 1972. Effect of mechanical resistance on root growth of seedlings. Pages 35-42 *in* Agric. Res. Coun. (U.K.). Lectombe Lab. Ann. Rep. for 1971.

Hiron, R. W. P., and S. T. C. Wright. 1973. The role of endogenous abscisic acid in the response of plants to stress. J. Exp. Bot. 24:769-781.

Interakosit, P. 1967. Studies on plant growth-regulating substances. Ph D thesis. University of London.

Kays, S. J., C. W. Nicklow, and D. H. Simons. 1974. Ethylene in relation to the response of roots to physical impedence. Plant Soil 40:565-571.

Kogl, F., A. J. Haagen-Smith, and H. Erxleben. 1934. Uber ein neues auxin (“Heteroauxin”) aus Harn. Hoppe-Seyl Z. 228:90-103.

Kurasawa, E. 1926. Experimental studies on the secretion of *Fusarium heterosporum* on rice plants. Trans. Nat. Hist. Soc., Formosa 16:213-214.

Larque-Saavedra, A., H. Wilkins, and R. L. Wain. 1975. Promotion of cress root elongation in white light by 3,5-diiodo-4-hydroxybenzoic acid. Planta (Berl.) 126:269-272.

Letham, D. S. and C. O. Miller. 1964. Identity of kinetin-like factors from *Zea mays.* Plant Cell Physiol. 6:355-359.

Lieberman, M., and A. T. Kunishi. 1.970. Thoughts on the role of ethylene in plant growth and development Pages 549-560 *in* D. J. Carr, ed. Plant growth substances, 1970. Springer-Verlag, Berlin. 1972.

Minarik, C. E., D. Ready, A. G. Norman, F. E. Thompson, and J. F. Owings. 1951. New growth-regulating compounds II. Substituted benzoic acids. Bot. Gaz. 113:135-147.

Ney, D., and P. E. Pilet. 1980. Importance of the Caryopsis in root growth and georeaction. Physiol. Plant 50:166-168.

Ohno, Y., and A. Fujiwara. 1967. Photoinhibition of elongation growth of roots in rice seedlings. Plant Cell Physiol. 8:141-150.

Okhuma, K., F. T. Addicott, O. E. Smith, and W. E. Thiessen. 1965. The structure of abscism 11. Tetrahedron Letters 29:2529-35.

Pilet, P. E. 1979. Hormonal control of root georeaction: some light effects. Pages 450-461 *in* F. Skoog, ed. Plant growth substances, 1979. Springer-Verlag, Berlin. 1980.

Pilet, P. E., and F. W. Went. 1956. Control of growth of *Lens culinaris* by temperature and light. Am. J. Bot. 43:190-198.

Rivier, L., and P. E. Pilet. 1981. Abscisic acid levels in the root tips of seven *Zea mays* varieties. Phytochemistry 20:17-19.

Robert, M. L., H. F. Taylor, and R. L. Wain. 1975. Ethylene production by cress roots and excised cress root segments and its inhibition by 3, 5-diiodo-4-hydroxybenzoic acid. Planta (Berl.) 126:273-284.

Roberts, J. L., and E. Roberts. 1939. Auxin production by soil microorganisms. Soil Sci. 48:135-139.

Smith, K. A., R. J. Dowdell, K. C. Hall, and R. Crees. 1973. Effect of cultivation on the content of oxygen and ethylene in soil. Pages 35-36 *in* Agric. Res. Counc. (U.K.). Letcombe Lab. Ann. Rep.

Saini, G. R. 1979. Root elongation and plant growth in a basal till compact soil treated with 3,5-diido-4-hydroxybenzoic acid and gibberellic acid. Agron. J. 71:1067-1070.

Taylor, H. F., and R. S. Burden. 1972. Xanthoxin, a recently discovered plant growth inhibitor. Proc. Roy. Soc. London Ser. B. 180:317-346.

Taylor, H. M. 1971. Root elongation rates of cotton and peanuts as a function of soil strength and water content. Monogr. Am. Soc. Agric. Engineers:292-305.

Tietz, A. 1974. The effect of light on growth and abscisic acid content of pea roots. Biochem. Physiol. Pflanz. 165(4):387-392.

Torrey, J. G. 1952. Effects of light on elongation and branching in pea roots. Plant Physiol. Lancaster 27:591-602

Wain, R. L. 1963. 3,5-Dihalogeno-4-hydroxybenzonitriles: New herbicides with molluscicidal activity. Nature 200:28.

Wain, R. L. 1977. Crop protection. Some developments and future prospects. Pages 224-235 *in* Rept, Long Ashton Research Station, University of Bristol.

Wain, R. L., P. Interakosit, and H. F. Taylor. 1968. Meded. Rijksfac. Landbouwwet. Gent. 33:1341-1346.

Wain, R. L., H. F. Taylor, P. Interakosit, and T. G. D. Shannon. 1968. Halogen derivatives of 4-hydroxybenzoic acid as root growth stimulants and the importance of light in this response. Nature 217:870-871.

Whitehead, D. C. 1963. Some aspects of the influence of organic matter on soil fertility. Soils Fert. 26:217-223.

Wilcox, E. J., and R. L. Wain. 1976. Studies on plant growth regulating substances XLIV. The cytokinin activity of 6-benzyloxy purine. Ann. Appl. Biol. 84:403-407.

Wilkins, H., and R. L. Wain. 1974. The root cap and control of root elongation in *Zea mays* L. Seedlings exposed to white light. Planta 121:1-8.

Wilkins, H., A. Larque-Saavedra, and R. L. Wain. 1974a. Studies on plant growth regulating substances. XXXVII. The effect of light and hormone inhibitors on plant growth. Ann. Appl. Biol. 78:169-177.

Wilkins, H., A. Larque-Saavedra, and R. L. Wain. 1974b. Control of *Zea* root elongation by light and the action of 3,5-diiodo-4-hydroxybenzoic acid. Nature 248:449-450.

Wilkins, H., S. M. Wilkins, and R. L. Wain. 1977. Studies on plant growth-regulating substances XLVIII. The effects of 3,5-diiodo-4-hydroxybenzoic acid on seedling growth in compact and loose soils. Ann. Appl. Biol. 87:415-422.

Wilkins, S. M., H. Wilkins, and R. L. Wain. 1976. Chemical treatment of soil alleviates effects of soil compaction on pea seedling growth. Nature 259:392-394.

Wilkins, S. M, H. Wilkins, and R. L. Wain. 1978. Studies on plant growth regulating substances LI. The effects of 3,5-dibromo- and 3,5-dichloro-4-hydroxybenzoic acids on seedling growth in compact and loose soils. Ann. Appl. Biol. 89:265-269.

Wright, S. T. C., and R. W. P. Hiron. 1969. (+)-Abscisic acid, the growth inhibitor induced in detached wheat leaves by a period of wilting. Nature 224:719.

Zimmerman, R. P., and L. T. Kardos. 1961. Effect of bulk density on root growth. Soil Sci. 91:280-288.

## DISCUSSION

HUNDAL: We know that crop species and varieties within a species differ in their rooting depth. From your studies on rooting in compact soil, is there a possibility of identifying a plant root parameter that controls rooting ability and then using that parameter to screen crops and species with good rooting ability in unfavorable soil conditions such as hard pans, etc.?

*WAIN:* Your suggestion that rice species that root deeply might contain more “root promoter” than those species that have shallow rooting ability is interesting, but so far, no one has attempted to identify such a promoter in rice plants.

HUNDAL: In your studies on the effects of chemicals on increased rooting in compact soil, what is the mechanism most affected by the chemicals that increase rooting depth? Is it increased root pressure or something else?

*WAIN:* In our experiments, the improved root growth in compacted soil arises from the effect of one chemical in reducing the amount of $C_2H_4$ produced by the root and by microbial activity in the compacted soil. There is no information on whether the chemical causes the root pressure to increase.

ROGER (comment): In your paper you indicated the possibility of treating seeds or seedlings with low concentrations of some “natural” products that may contribute a powerful and cheap source of growth-promoting substances. Besides increasing N fertility, algae have been said to benefit rice plants by growth-promoting substances. Evidence for hormonal effects comes primarily from treatment of rice seedlings with algae cultures and their extracts. The different effects reported after presoaking the seed or the seedling were: enhancement of germination, faster seedling growth, early recovery of transplanted seedlings, prolonged period of tillering, rhizogenous effect, stimulation of vegetative growth of the plant, increase in weight, and increase in protein content of the grain. The nature of the substance responsible for this — whether hormone, vitamin, amino-acid, or other — is not known. This growth-promotingeffect was observed with N-fixing green algae. (P. A. Roger and S. A. Kulasooriya 1980. *Blue green algae and rice.* IRRI pub.)

AGBOOLA: At the University of Ibadan, we have used a retarding growth hormone on the $OS_6$ cultivar of rice, We observed that the time of application of the hormone plays a vital role. The yield is affected adversely, as the hormone affects the physiological age of the plant. May I know whether you have any explanation for this? Furthermore, I would like to know if you have ever looked at the effects of these chemicals on the food chain and whether you can increase the physiological age and yield of plants with some of these organic substances.

*WAIN:* By growth-regarding hormone I suppose you mean a synthetic growth-retarding chemical such as CCC. CCC is not active as a retardant on all plant species. The adverse effect on yields which you observed could have arisen from using too high a concentration. There are no reliable data on increasing the physiological age by treating plants with these physiologcally active chemicals. Effects on food chains have not been investigated.

WATANABE: Iodine is very toxic to wetland rice only at 10 $\mu M$ 1. Rice growth is inhibited because iodine would be released from DIHB, so I suspect DIHB would be harmful. Iodine is reduced in flooded conditions and becomes toxic. Did you test DIHB on wetland rice?

*WAIN:* Yes, if iodide ion is released from DIHB, it could be toxic to rice plants, expecially if the iodide is converted to iodine under the influence of a peroxidase enzyme. However, DIHB is not the only chemical in this group; the analogue 3, 5-dibromo-4-hydroxybenzoic acid also possesses this property, though it is not so active as DIHB.

SINGH: In your opinion how does mechanical resistance induce $C_2H_4$ production in roots? Is the site of $C_2H_4$ production the root tip?

*WAIN:* It is not known how mechanical resistance induces the production of $C_2H_4$. Of course, the $C_2H_4$ biosynthesis within living cells should be considered (endogenous $C_2H_4$), and we have evidence that the production of $C_2H_4$ in this way can be inhibited by the compound DIHB. It is unlikely that the site of $C_2H_4$ biosynthesis is solely the root tip.

FLAIG: In the past, food yields were increased by mineral fertilization, soil conditioning, plant breeding, and protection. The world food situation demands that yields be further increased. This could possibly be done by using other plant varieties for food, other production systems, and substances physiologically active against unfavorable growth conditions (e.g., cycocel in the case of wheat) such as those formed during decomposition of dead plant material. It might be that synthetic substances will be too expensive for farmers. How do you judge the situation?

*WAIN:* I fully agree with the views you have expressed. The possible advantages of using physiologically active compounds for promoting the growth of plants need to be more fully explored. Their effects on root growth have received little attention. I agree with you that some of the highly potent synthetic compounds ought to be examined for their effects in promoting the growth of rice. Also, further studies should be made on the active chemicals that can arise during the decomposition of dead plant material. Some synthetic compounds are active when applied at very low concentrations, and the treatments might not be too expensive for the farmers.

# POSSIBLE ADVERSE EFFECTS OF DECOMPOSING CROP RESIDUES ON PLANT GROWTH

R. Q. Cannell and J. M. Lynch

The adverse effects on crops growing in the proximity of decaying crop residues occur predominantly under anaerobic soil conditions. So, some consideration is given to the development and effect of restricted oxygen supply on plant growth, which precedes the formation of organic substances from microbial activity. The occurrence of aliphatic acids, phenolic acids, $C_2H_4$, $CO_2$, and $H_2S$ in soils is discussed, but the main concern is their effects on plant growth. Although they are less toxic than aromatic acids, aliphatic acids seem likely to be more important because they occur in greater concentrations and are derived mainly from cellulose and water-soluble carbohydrates, which decompose before lignin. Exogenous $C_2H_4$ can augment endogenous $C_2H_4$ and can modify growth, but as a natural growth regulator, it does not kill plants, and many of the effects are adaptive responses to anaerobic conditions. Carbon dioxide seems unlikely to be important, but $H_2S$, a general cell poison, can be toxic. It is difficult to be certain how important these substances are in practice, as toxic concentrations are usually transient, and compensatory growth can often occur. In rice with prolonged flooding, injurious concentrations of $H_2S$ may persist; however, management can alleviate the effects.

Adverse effects of substances from decomposing crop residues have been long considered as causes of poor growth and yield, not only of rice, but of many crops (Collison and Conn 1925, Patrick et al 1963, McCalla and Haskins 1964). Microorganisms can produce a large range of substances potentially toxic to plant roots (Lynch 1976), but most of these rarely accumulate in aerobic soil because they are metabolized rapidly by other microorganisms. In anaerobic soils, however, where fermentative biochemical pathways can be more common and catabolism is restricted or modified, the metabolites may reach phytotoxic concentrations. In rice soils rich in organic matter, symptoms associated with poor root systems often have been attributed to the presence of growth-inhibiting substances in the soils under extremely reduced conditions (Takijima 1963). Because rice is often grown in submerged soils, poor growth of the rice plant has often been related to the chemical

---

Agricultural Research Council, Letcombe Laboratory, Wantage, OX12 9JT, United Kingdom.

processes taking place in submerged soils. Possible causes of physiological diseases associated with such conditions have been grouped by Tanaka and Yoshida (1970):

- deficiency of nutrient elements: N, P, K, Fe, Mn, Zn, Si, etc.
- toxicity of elements: Fe, Mn, B, Al, etc.
- high salt injury: Na salts, etc.
- toxicity of substances accumulated in the soil under reduced conditions: sulfide, organic acids, $CO_2$, etc.

The last group is the subject of this paper. The main purpose here is to consider their adverse effects on plant growth.

Incorporation of crop residues can have adverse effects on subsequent crops other than rice if anaerobic conditions develop. Recently the worldwide development and adoption of simplified and conservation tillage systems have created new problems with residues (Cannell 1981). These tillage systems involve leaving the residues on the soil surface or only shallowly incorporating them. When seed drills operate in such conditions, especially on heavy-textured soils, seed and residues can be placed in close contact. Wet conditions that lead to anaerobic decomposition of the residues can adversely affect seedling growth. Such problems have been reported from Australia (Kimber 1967), the United Kingdom (Lynch 1977), and the United States (Elliott et al 1978) for crops other than wetland rice.

Because the formation of phytotoxic substances from degrading organic matter occurs under anaerobic soil conditions (at least in localized zones), waterlogging is often a prerequisite for any associated problems. Rice, because of the presence of aerenchymatous tissue, is well adapted to waterlogged conditions after submerged shoots reach the water surface (Arikado 1955), but most other crop species are not. For species other than wetland rice, part of the syndrome also may be due to the more direct effects of low oxygen on plant growth and development. Therefore, it is relevant to consider some of the factors affecting the rate of development of anaerobic conditions.

## DEVELOPMENT OF ANAEROBIC CONDITIONS IN SOIL

Anaerobic conditions develop in the soil when roots and soil organisms use $O_2$ for respiration faster than it can enter the soil by diffusion through air-filled pores (Currie 1970). Waterlogging or submergence of the soil is a prerequisite, because of

**Table 1. Effect of soil organic matter content on the rate of depletion of soil oxygen in waterlogged mixtures of sandy loam topsoil at 10°C.**[a]

| Topsoil (%) | Organic matter (%) | Days at 10°C before oxygen flux decreased |
|---|---|---|
| 100 | 2.2 | 1.5 |
| 75 | 1.8 | 2.5 |
| 50 | 1.2 | 7 |
| 25 | 0.6 | 15 |
| 0 | 0.2 | >21 |

[a] Source: P. S. Blackwell, Agricultural Research Council Letcombe Laboratory, Wantage, U. K. (unpublished).

**Table 2. Concentration of dissolved oxygen, oxygen flux density, and redox potential in a clay soil with low and high populations of winter wheat after 21 days of waterlogging at 4°C.** [a]

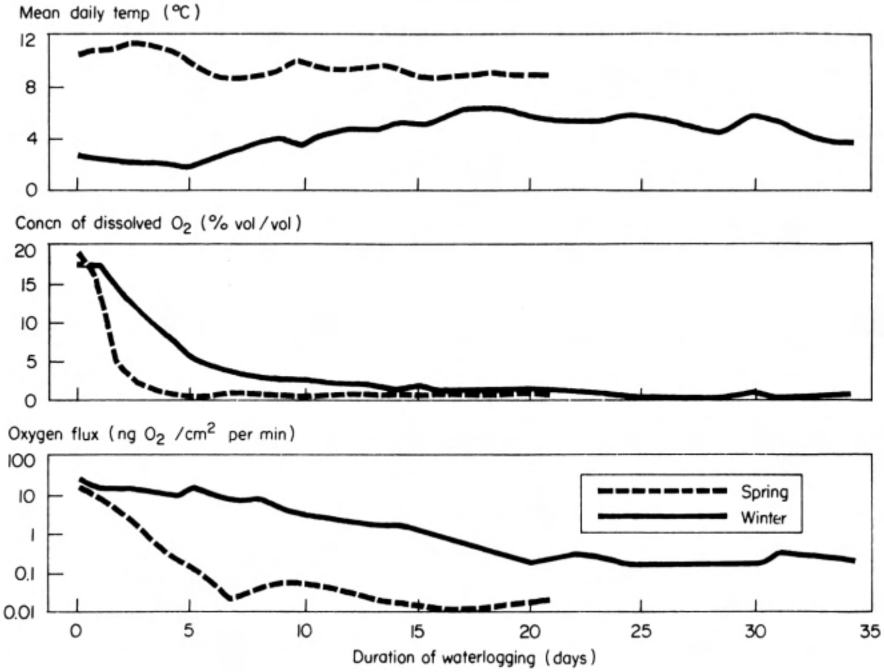
| Plant population | Dissolved $O_2$ (%, vol/vol) | Oxygen flux (ng/cm$^2$ per min) | Redox potential (mV) |
|---|---|---|---|
| < 300/m$^2$ | 0.24 | 1.05 | 130 |
| > 300/m$^2$ | 0.28 | 0.02 | −80 |

[a] Source: P. S. Blackwell, Agricultural Research Council Letcombe Laboratory, Wantage, U. K. (unpublished).

the slow rate of $O_2$ diffusion through water (about 10,000 times slower than in air). Furthermore, diffusion of gases, such as $CO_2$, out of the soil will be impeded by excess $H_2O$, and these can then accumulate.

The rate of utilization of $O_2$ by respiration can be large in comparison with the amount contained in the volume of soil that roots usually occupy, and anaerobic conditions can develop quite rapidly. The rate of $O_2$ consumption depends on the biological activity of the soil, as indicated by the concentration of organic matter in the soil (Table 1) and by the number of roots (plants) in the soil (Table 2). However, the rate of decline in $O_2$ is greatly influenced by soil temperature. For example, it is more rapid in the spring than in the winter in Britain (Fig. 1). In tropical areas the onset of anaerobiosis will be much more rapid.

Crop species vary in their sensitivity to waterlogging (Cannel1 and Jackson 1981).



**1.** Effect of soil temperature on the rate of decline of oxygen in a waterlogged clay soil in Britain (Blackwell and Ayling 1981).

The period of greatest sensitivity is after seeds have germinated but before the shoots have emerged, with the possibility of some $O_2$ transfer from the air to the roots via the shoot. Rice seeds can germinate under anaerobic conditions, but growth of the coleoptile, true leaves, and roots becomes abnormal (Kordan 1972). Less adapted species can be more adversely affected, and even in temperate zones more than 2 days' waterlogging at this stage can depress populations of peas *Pisum sativum* L. (Belford and Thomson 1980); more than 4 days will depress populations of wheat (Fig. 2; Cannell and Belford 1982) and barley (Cannell et al 1981). This growth stage can coincide with the period of most rapid breakdown of organic matter when phytotoxic substances may form, and it is at this stage that the combination of stresses is likely to be most damaging.

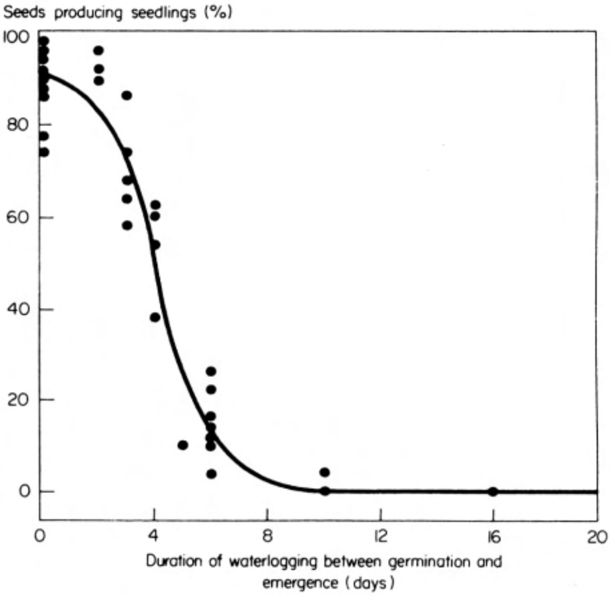
Where residues are incorporated, anaerobic decomposition is more likely to occur. But when they are left on the surface (at least when the soil is not waterlogged), degradation is slower, predominantly aerobic, and there is less potential to produce phytotoxic effects (Fig. 3).

Sometimes there is no clearly established causal link between the observed effects and the substance in the soil environment to which the effects are attributed. Sometimes this is due to the difficulties of measuring the particular substance, but in some investigations only a limited number of substances have been measured.

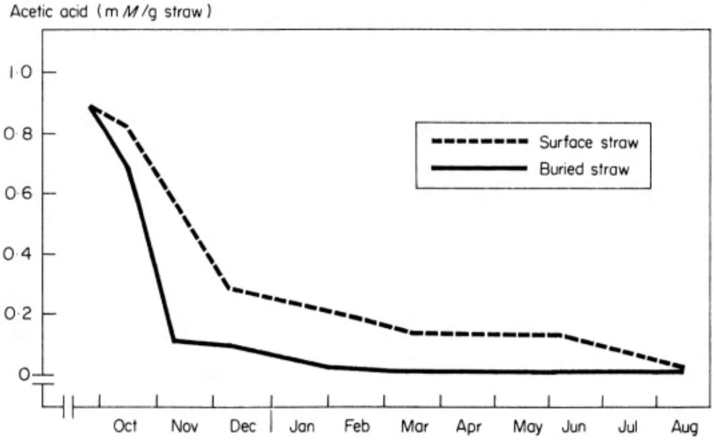
## ALIPHATIC ACIDS

### Effects on rice

The toxic effects of aliphatic acids on rice growth have been widely studied. Most investigations have been short-term ones on young plants. Nevertheless, in several



**2.** The effect of waterlogging winter wheat between germination and emergence on the number of emerged seedlings (Cannell and Belford 1982).



**3.** Decline in the potential of straw to produce acetic acid when on the soil surface or buried in a clay soil (Harper and Lynch 1981).

instances, quite low concentrations have killed plants. For example, Takijima (1964) reported that rice seedlings died within 3 weeks when grown in culture solution containing 6 mM acetic acid, and Rao and Mikkelsen (1977c) found that 14-day-old seedlings died within 2-3 days when grown in solutions with 10 mM concentrations of acetic, propionic, or butyric acids. In other studies, however, although the size of plants was greatly reduced, they still survived after growing for 20 days in culture solutions containing 40 mM acetic and butyric acid (Tanaka and Navasero 1967).

The injury caused by monobasic aliphatic acids depends on the type of acid present and its concentration. The inhibitory effects on rice seedlings generally increase with increasing molecular weight, increasing in the order formic, acetic, propionic, and butyric (Takijima 1964, Chandrasekaran and Yoshida 1973, Rao and Mikkelsen 1977a). An example of the effects on plant growth is given in Table 3.

The severity of the effect of the acids on the plant depends on the pH of the rooting medium; it is greatest at low pH (Table 4), and sometimes not evident in plants grown in neutral media (Rao and Mikkelsen 1977a). The inhibition of root elongation with a decrease in pH at the same acid concentration shows that the increased concentration of undissociated acids at lower pH causes the greater inhibition, rather than the acetate ion.

**Table 3. Relative effect of adding 1.0 mM solutions of different aliphatic acids on the weight of whole rice plants grown in soil.**[a]

| Acid | Plant wt (% of control) |
|---|---|
| Formic | 64 |
| Acetic | 44 |
| Propionic | 29 |
| Butyric | 38 |

[a] Source: Chandrasekaran and Yoshida (1973). Fourteen-day-old plants were transplanted and grown for 22 days.

**Table 4. Relative effect of nutrient solution containing 10 mM acetic or butyric acids at different pH values on the weight of whole rice plants.**[a]

| pH | Plant wt (% of control) | |
|---|---|---|
| 4 | 29 | 16 |
| 6 | 70 | 75 |
| 8 | 67 | 70 |

[a]Source: Tanaka and Navasero (1967). Twenty-day-old plants were grown for 20 days.

The minimum concentration that significantly affects the weight of the whole plant is low; 1 mM concentrations of acetic, propionic, and butyric acids in culture solution have slightly depressed total plant weight (Takijima 1964, Rao and Mikkelsen 1977a,c). Root elongation of rice is most sensitive to the presence of small concentrations of acetic, propionic, and butyric acids (Rao and Mikkelsen 1977a,c). At 1 mM and pH 3, root length after 7 days was only 40-50% of the control. Although roots elongated for some time at 5 mM concentration, some of the root tips died (also noted by Takijima 1964). Initiation of new roots still continued, so that root weight was less affected than root length (Table 5). At 19 mM, root elongation and initiation were severely inhibited, especially at low pH. According to Takijima (1964), butyric acid inhibited root initiation and elongation at concentrations between 0.1 mM and 2 mM.

Uptake of inorganic nutrients by rice can be restricted in the presence of organic acids, but the reports in the literature are not consistent. Concentrations of acetic acid greater than 1 mM have restricted the concentration and uptake of P and K (Takijima 1964, Rao and Mikkelsen 1977c). Tanaka and Navasero (1967) found, however, that acetic acid up to 40 mM did not affect the concentration of K in rice. Propionic and butyric acids have also affected uptake of K (Tanaka and Navasero 1967, Rao and Mikkelsen 1977c), with 1 mM butyric acid sometimes restricting the concentration and uptake of P and K (Takijima 1964). Acetic acid (greater than 10 mM) has also restricted uptake of Si (Takijima 1964) and of Mn (Tanaka and Navasero 1967). Deficiency symptoms may not be evident in short-term experiments (Rao and Mikkelsen 1977c).

Shoot growth of rice is much less affected by aliphatic acids than root growth, especially elongation (Takijima 1964; Rao and Mikkelsen 1977a,c; see Table 5). Nevertheless, even at low concentrations (1 mM), seedlings have withered and leaf

**Table 5. Effect of acetic acid on the growth of roots and shoots of rice seedlings (expressed as percent of control).**[a]

| | Acetic acid concn (mM) | | |
|---|---|---|---|
| | 1 | 5 | 10 |
| Maximum root length | 81 | 69 | 56 |
| Root weight | 85 | 78 | 65 |
| Shoot weight | 81 | 79 | 78 |

[a]Source: Rao and Mikkelsen (1977a). Sprouted seeds were grown for 7 days.

tips have become bronzed in culture solution experiments of only a few days.

The practical relevance of the results of these short-term experiments is uncertain. In the field, the concentration of phytotoxins (if present) will vary during the growth period of the crop; it is probably greatest in the early stages of flooding (Takai and Kamura 1966), and may also vary spatially within the root environment. The proportion of the root system that could be affected is likely to vary in time and space.

The rice crop can show considerable compensatory growth from adverse effects on early growth after chopped rice straw has been plowed into the soil. For example, where either 0 or 15 t of straw/ ha had been incorporated, the tiller numbers at the peak value and at booting, and the straw and grain yields at harvest were 66%, 71%, 83%, and 99% of the untreated values (Gotoh and Onikura 1971). The authors, who measured organic acids in the soil, considered the effects of the organic acids from the decomposing straw minor, and held that the effects on poorer vegetative growth were more likely to have been due to immobilization of N by the microorganisms degrading the straw.

## Effects on other species

In wet autumns in the United Kingdom, establishment of wheat and oats by direct drilling (zero tillage) through straw residues from the preceding crop can result in poor plant establishment and lower crop yields (Cannell et al 1982). Similar problems have occurred with conservation tillage systems in the Pacific Northwest and Midwest of the United States (Elliott et al 1978) and in the Soviet Union (Mishustin 1972). Straw, particularly when it is wet, can impede the drill mechanism, keeping the topsoil wetter (Ellis et al 1977). The decomposition of straw residues in close contact with developing seedlings under anaerobic soil conditions can result in the production of toxic substances that are harmful to developing seedlings. Laboratory studies with mixed populations of soil microorganisms in liquid culture showed that phytotoxic concentrations of acetic acid rapidly accumulated from the anaerobic fermentation of wheat straw (Lynch 1977). Although propionic, butyric, and hydrocinnamic acids also formed, the concentrations were not phytotoxic. Acetic acid significantly restricted the extension of barley roots in concentrations of 15 mM at pH 6.5 and around 7 mM at pH 3.5. Residues from several species have all provided substrates for the formation of acetic acid in excess of these concentrations, and have inhibited the extension of barley roots (Table 6). Temperate cereals in nutrient culture may be a little less sensitive to the organic acids than rice growing in soil, but the activity of the acids again increases with increased C chain length (Lynch 1980). The effect at low pH is greater because the acid is associated, and therefore soluble in the lipid components of the root membrane. In the field, only localized regions of the root system would be exposed to the organic acids. Recent observations (Gussin and Lynch 1982) have shown that treating a single root tip with a small concentration (5 mM) of acetic acid stimulated root and shoot growth. Treating more than one root with greater concentrations of the acid sometimes caused inhibition rather than stimulation. Treating 2-cm lengths along the root axis distal to the root-tip region (2 cm long) inhibited root and shoot growth more than did the corresponding root-tip treatment. Treatments of tips and 2-cm lengths

**Table 6. Accumulation of acetic acid after 6 days from slurries of a chalk loam soil containing residues of different species, and their effect on the root extension of barley seedlings.** [a]

| Residue | Acetic acid concn (mM) | Root extension (% of control) |
|---|---|---|
| Rhizomes | | |
| *Agropyron repens* (couch or quack grass) | 12.6 | 73 |
| Straw | | |
| *Hordeum vulgare* (barley) | 14.4 | 43 |
| *Triticum aestivum* (wheat) | 16.1 | 41 |
| *Avena sativa* (oats) | 18.1 | 42 |
| *Brassica napus* (rape) | 24.7 | 37 |
| LSD (P = 0.05) | | 4 |

[a] Source: Lynch (1978).

resulted in some compensatory growth in the untreated roots. In the field, therefore, roots will be sensitive only to small concentrations of the acid if much of the root system becomes exposed.

Another aspect that may be important is the possible synergistic effect among volatile fatty acids. Wallace and Whitehand (1980) examined this effect for wheat. Concentrations of acetic, propionic, and butyric acids alone at concentrations near the believed threshold for root inhibition had little effect, but in combination caused large effects (Table 7).

For organic acids to be formed, ample substrate in the form of plant residues must be present. High concentrations can be formed in the residue, but they do not diffuse very far into the soil. The concentration of acid decreases by one half about 1.5 cm from the straw surface (Lynch et a1 1980b). The establishing crop roots must come into close contact with decomposing residues.

Studies on homogeneous slurries of soil in a chemostat showed that the formation of organic acids from plant residues is primarily linked to redox potential, the critical $E_h$ being about zero (Lynch and Gunn 1978)—a conclusion expected from the work of Ponnamperuma (1972). The process is also associated with falling pH and the solubilization of Fe and Mn. Indeed, in some situations these ions might reach toxic levels.

**Table 7. Interaction between acetic, propionic, and butyric acids on root growth of wheat seedlings.**[a]

| | Mean root length after 7 days (mm) |
|---|---|
| Control | 60 |
| Acetic acid (3.2 mM) | 64 |
| Propionic acid (0.41 mM) | 59 |
| Butyric acid (0.38 mM) | 57 |
| Acetic + propionic acids | 42 |
| Acetic + butyric acids | 37 |
| Propionic +butyric acids | 39 |
| Acetic + propionic + butyric acids | 30 |

[a] Source: Wallace and Whitehand (1980).

When cereals are direct-drilled into straw in wet soil, it has not yet been possible to indicate to what extent the observed effects are due to the establishment of fewer seedlings (possibly caused by drilling and phytotoxic problems) and to what extent they are due to smaller and less vigorous seedlings (possibly caused by phytotoxins or limited supply of N, or both). One field trial, however, demonstrated that straw, while not affecting the percentage of seeds producing plants, inhibited tillering and, at harvest, the weight of straw, grain yield, and number of ears per meter of row (Lynch et al 1980a).

As with rice, there is not yet unequivocal evidence on the importance of phytotoxic effects of aliphatic acids in this syndrome. Furthermore, as with rice, compensatory crop growth of wheat and barley seedlings can considerably offset the restricted early growth. The extent of possible compensatory growth in winter wheat is illustrated in an experiment where waterlogging occurred after germination, but before coleoptiles emerged above the soil. The plant population was limited to 12% of the control, yet following compensatory growth later in the growing season, yield reached 82% of the control (Cannell et al 1980).

Extracts from anaerobically decomposing shoots of a range of grass species have been found to be toxic to other grasses and to clover (Gussin and Lynch 1981). The phytotoxicity seemed most likely due to acetic acid (as the concentration of other acids was less). As has been observed with rice, the phytotoxicity diminished with time. The residues from different species differed in phytotoxicity: *Festuca rubra, Alopecurus pratensis,* and *Agrostis stolonifera* were the most toxic.

## PHENOLIC ACIDS

Phenolic acids have been implicated in phytotoxic problems in mulch tillage systems (McCalla and Norstadt 1974). Using acid and alkali extractants on residues of maize, wheat, sorghum, and oats, Guenzi and McCalla (1966a) obtained ferulic, *p*-coumaric, syringic, vanillic, and *p*-hydroxybenzoic acids. Of these, only *p*-coumaric was obtained in concentrations (0.2-90 mM) that could be phytotoxic to wheat seedlings (Table 8). Similar concentrations were not found, however, in soils (Guenzi and McCalla 1966b). In culture solution experiments, *p*-hydroxybenzoic acid, at concentrations greater than 7-70 µM, suppressed the growth of wheat, maize, and soybean seedlings, whereas sugarcane was unaffected by 180 µM, but its roots were affected by 360 µM of the acid (Wang et al 1967a). When tested by Guenzi and McCalla (1966a), *p*-hydrobenzoic acid at the lowest concentration, 9 µM, had similar effects to *p*-coumaric acid (Table 8). With rice seedlings in solution culture, Chandramohan et al (1973) found that 0.1 M cinnamic acid depressed shoot growth. As with aliphatic acids, synergistic inhibitory effects between phenolic acids may also occur. Rasmussen and Emhellig (1977) reported such effects by *p*-coumaric and ferulic acids on sorghum.

In spite of the sometimes large effects of small concentrations of phenolic acids on plant growth, the practical relevance of some results must be questioned, because acid extraction procedures usually have been used. However, Chou and Lin (1976) found *p*-hydroxybenzoic, *p*-coumaric, vanillic, ferulic, and *o*-hydroxyphenylacetic acids in aqueous extracts from rice residues decomposing in waterlogged soil. The

**Table 8. Effect of *p*-coumaric acid on growth of wheat seedlings.**[a]

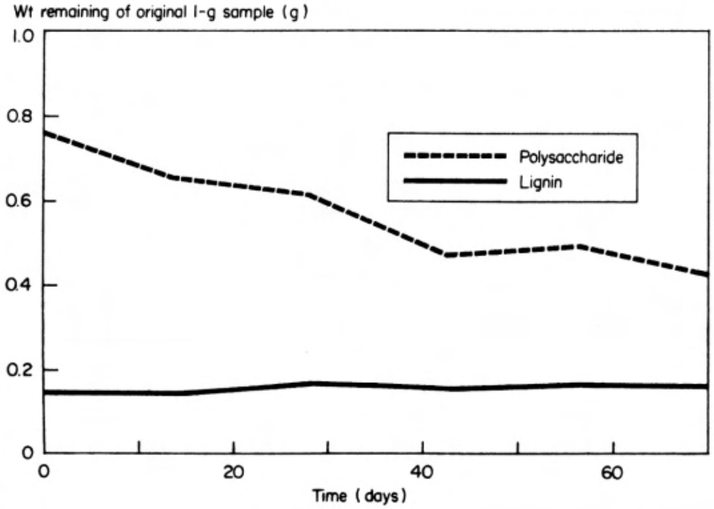
| Concn of *p*-coumaric acid (mM) | Wt (% of control) | |
|---|---|---|
| | Roots | Shoots |
| 4 | 87 | 73 |
| 8 | 75 | 75 |
| 15 | 50 | 52 |
| 30 | 41 | 48 |

[a] Source: Guenzi and McCalla (1966a).

radicle growth of rice and lettuce and root initiation of mungbean were inhibited by *o*-hydroxyphenylacetic acid in low concentrations.

A further consideration that contributes to the doubt about the ecological importance of phenolic acids is that in the breakdown of crop residues, one might expect short-chain fatty acids to be produced first from cellulose breakdown, with phenolic acid production occurring later from lignin. In wheat straw, cellulose breakdown occurs readily, but lignin is much more resistant (Fig. 4). This is an important point, because many of the reported adverse effects of residues occur within a relatively short time after the residues have been incorporated and the following crop has been seeded. Furthermore, in warmer soil, breakdown will be more rapid, the $Q_{10}$ for acetic acid formation from anaerobically decomposing straw being 2.9 (Lynch and Gunn 1978).

Comparatively few investigators have confirmed the relative toxicity of aliphatic and aromatic acids. Wang et al (1967b) found that residues of sugarcane leaf and *Crotolaria juncea* gave concentrations of volatile fatty acids (mainly acetic), nonvolatile aliphatic acids (mainly tartaric), and phenolic acids up to 2 µM, 80 µM,



**4.** The rate of breakdown of cellulose and lignin in wheat straw in a clay soil. The mean soil temperature at 10 cm depth was 11°C during the experiment (Harper and Lynch 1981).

and 20 μM per 100 g soil, respectively. The volatile fatty acids were more phytotoxic than the nonvolatile aliphatic acids between 0.5 and 1 mM. Other work has indicated that, although aromatic acids could be present when straw decomposes anaerobically in soil, they are less important than aliphatic acids because they are destroyed more easily in the soil (Mishustin et al 1966). Prill et al (1949), in examining the sensitivity of the roots of wheat seedlings, found that some of the aromatic acids were as toxic as coumarin, but the lower fatty acids were less inhibitory (Table 9).

## ETHYLENE

Work in our laboratory first showed that $C_2H_4$ could accumulate in phytotoxic concentrations in wet soils (Smith and Russell 1969), and its origin appeared to be microbiological (Smith and Restall 1971, Lynch 1972). The source of substrates in soil is the decomposing plant residues (Lynch and Harper 1980). In England in the spring and early summer, $C_2H_4$ can reach concentrations of 1-10 μl/liter in the soil atmosphere from heavy soils (Smith and Dowdell 1974). Such concentrations caused a marked reduction in the elongation of roots of barley, maize, rice, rye, and wheat in aerated solutions (Crossett and Campbell 1975, Drew et al 1979, Smith and Robertson 1971, Smith and Russell 1969), but rapid elongation resumed when $C_2H_4$ was no longer added to the root environment (Smith and Russell 1969). Elongation of adventitious roots of maize in solution culture bubbled with 0, 0.1, 1.0, and 5.0 μl/liter of $C_2H_4$ in air gave root extension rates of 35, 26, 11, and 8 mm/day, respectively (Drew et al 1981). Dryland rice behaved somewhat differently in that concentrations of $C_2H_4$ ranging from 0.1 to 1.0 μl/liter slightly stimulated root extension (Smith and Russell 1969; Fig. 5c).

In maize, exogenous $C_2H_4$ in the root environment (5 ml/liter in air) markedly reduced shoot growth (Jackson et al 1981), but in barley 10 µl/liter had little effect (Crossett and Campbell 1975). In legumes, root nodulation and N fixation in existing nodules is inhibited by concentrations of $C_2H_4$ as low as 0.4 µl/liter (Goodlass and Smith 1979, Grobelaar et al 1971).

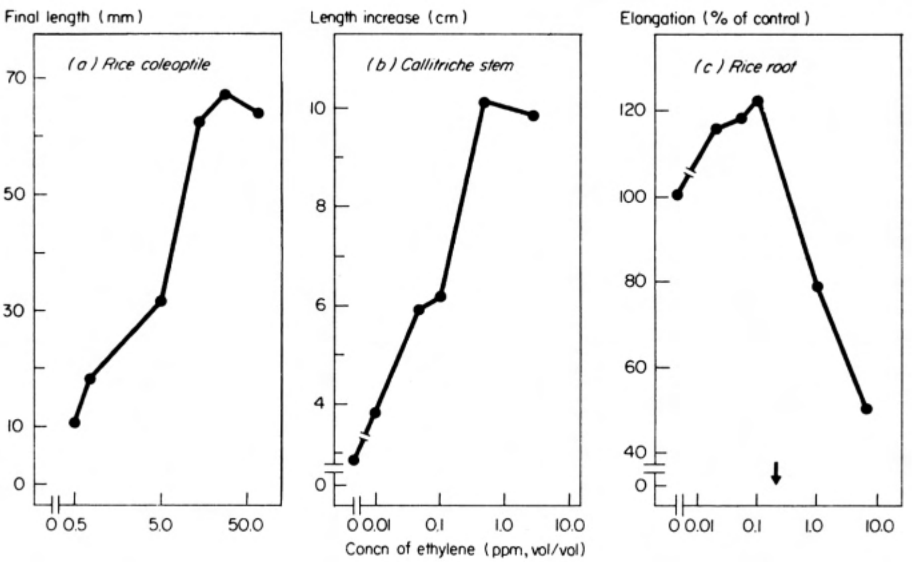
Ethylene rarely, if ever, brings about cell death, because it is a natural growth regulator rather than a toxin, and as such is involved in numerous mechanisms that enable plants to tolerate or adapt to submergence (Cannel1 and Jackson 1981).

After roots become surrounded by water, the loss of $C_2H_4$ from the submerged

**Table 9. Concentrations of organic acids and related compounds required to inhibit the growth of the roots of wheat seedlings by 50%.**[a]

| 0.01 mM | 0.05 mM | 0.25 mM | 1.25 mM | 6.25 mM | >6.25 mM |
|---|---|---|---|---|---|
| Coumarin<br>2-Furanacrylic<br>Hydrocinnamic<br>Melilotic<br>Phenylpropiolic<br>Salicylic<br>Tetrahydropiperic | Anthracylic<br>Benzoic<br>Capric<br>*trans*-Cinnamic<br>Piperic<br>Propionic | Butyric<br>Caproic<br>Crotonic<br>Formic | Acetic<br>Adipic<br>l-Malic | Citric<br>Malonic<br>d-Tartaric | Fumaric<br>Hydrocinnamide<br>Succinic |

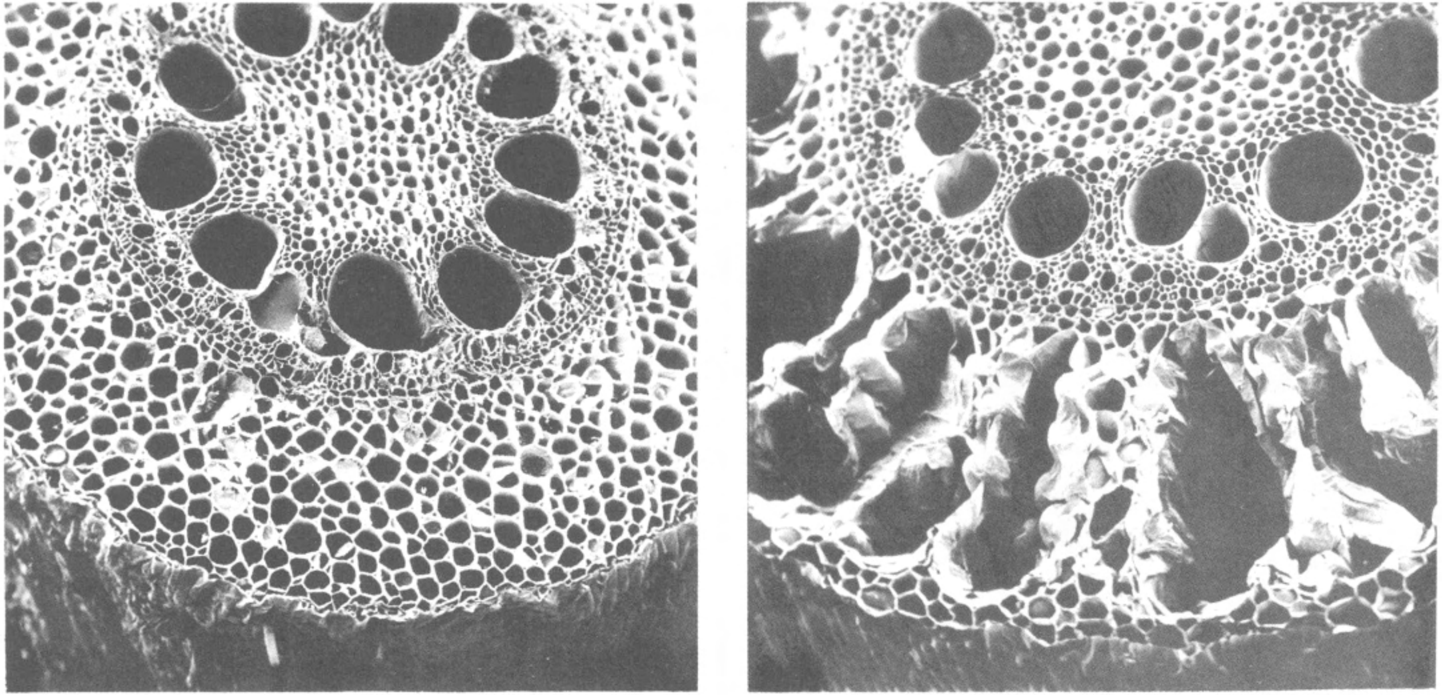
[a]Source: Prill et al (1949).



**5.** Promotion of elongation by ethylene: a) in coleoptiles of rice seedlings (Ku et al 1970); b) in the stems of the aquatic plant *Callitriche platycarpa* (Musgrave et al 1972); and c) in roots of rice seedlings (Konings and Jackson 1979). Arrow indicates expected increase in ethylene concentration when roots are submerged.

parts is restricted. A layer of water only 0.5 mm thick over the roots of white mustard *Sinapis alba* L. is sufficient to trap growth-inhibiting concentrations of $C_2H_4$ (Konings and Jackson 1979). Thus the endogenous $C_2H_4$ concentration may increase during submergence. Ethylene biosynthesis in submerged organs, however, requires $O_2$ and in roots is severely curtailed when the concentration of $O_2$ in the soil water falls to about 2% or less (Jackson et a1 1978). Extra $C_2H_4$ can be produced in the shoots of waterlogged plants in response to $O_2$ deprivation around the roots (Bradford and Dilley 1978), and may encourage adventitious rooting. In maize, tomato, and sunflower, additional $C_2H_4$ in the root environment has given this effect (Drew et a1 1979, Jackson and Campbell 1975, Kawase 1974). In maize, at least, $C_2H_4$ stimulates the formation of aerenchyma (interconnected air spaces) within roots (Drew et a1 1979, 1981), which could improve internal aeration of the plant (Fig. 6). Air can diffuse through aerenchymatous roots of flood-tolerant species for considerable distances (Armstrong 1979). And excess $O_2$ moving out of the root into the anaerobic soil may oxidize substances in the rhizosphere and inhibit the formation of toxins (Armstrong 1964). Internal aeration may be less effective in older plants, possibly because of blockage or collapse of the conducting channels (Arikado 1955, Yamasaki and Saeki 1976), but the ability to absorb and translocate nutrients may be little affected by cortical degeneration (Drew et a1 1980).

In rice, $C_2H_4$ generated within the tissues and trapped by water films may accelerate stem extension by affecting elongation of the mesocotyl (Suge 1971) and the coleoptile (Ku et a1 1970), ensuring that submerged shoots quickly reach the surface of the water (Fig. 5a). Ethylene is also involved in the mechanism of



**6.** Scanning electron micrographs of transverse sections of adventitious maize roots: left, control grown in well-aerated solution; right, root receiving 5 μl/liter ethylene in air, showing large cortical air spaces (aerenchyma). Sections were prepared from the zone 0.6 cm along the length of the root (Drewet al 1979).

regulation of internode elongation in floating rice (Metraux and Kende 1982). Enhanced internode elongation occurred after submergence if plants were at least 21 days old. This elongation was associated with increased $C_2H_4$ concentrations in the flooded plants. When nonsubmerged plants were treated with $C_2H_4$, internode elongation also occurred at a threshold concentration of 0.1 µl/ liter. Although the mesocotyl of japonica types of rice elongates in response to $C_2H_4$, little effect is seen in indica types unless seeds are given a heat pretreatment (Suge 1972). The effect of $C_2H_4$ on stem elongation is also seen in other aquatic plants such as *Callitriche platycarpa* Kutz (Musgrave et al 1972; Fig. 5b).

## CARBON DIOXIDE

Concentrations of $CO_2$ as high as 17.5% can occur in waterlogged soils (Vine et al 1942, Jackson 1979), but they have little negative effect on growth (Leonard and Pinckard 1946, Jackson 1979), and may even stimulate growth (Talbot and Street 1968). In rice, $CO_2$ can enhance the elongation of mesocotyls and coleoptiles (Suge 1971), and the effect is greater in the presence of $C_2H_4$ (Ku et al 1970). In extreme $O_2$-deficient conditions, $CO_2$ may adversely affect the growth of some species (Williamson and Splinter 1968, Geisler 1967); however, reports of high concentrations of $CO_2$ injuring plants may be due more to the effects of excluding $O_2$ by the gassing procedure, or to having unrealistically high $CO_2$ concentrations such as in experiments on rice by Rao and Mikkelsen (1977b). Even for species less adopted to waterlogging, $CO_2$ has only small effects, compared with the absence of $O_2$ from the root environment (Trought and Drew 1980). Nitrogen fixation by root nodules on legumes has been inhibited by 3% $CO_2$ (Grobbelaar et al 1971).

## HYDROGEN SULFIDE

Hydrogen sulfide is a general cell poison, inhibiting enzymes and the uptake of nutrients. Nevertheless, a still unresolved problem in rice production is the damage caused by $H_2S$. Takijima (1963) considered that free $H_2S$ found in the well-drained degraded rice field caused root damage to plants in midsummer, but Yoshida (1981) was of the view that $H_2S$ toxicity in rice in flooded soils was not clear-cut. Straighthead disease in rice in the USA has been attributed to $S^{2-}$ toxicity (Allam et al 1972). The physiological condition associated with $H_2S$ toxicity, called Akiochi (meaning autumn-decline), described by Tanaka and Yoshida (1970), was once widespread in Japan, affecting at least 20% of the rice area (Takijima 1963).

The symptoms associated with Akiochi — *Helminthosporium* leaf spots; deficiencies of K, Mg, and Si; and $H_2S$ toxicity (Tanaka and Yoshida 1970) — complicate interpretation, since cause and effect are not always clear. The method of measuring $H_2S$ in soil has also contributed to the uncertainty about its importance. This is well discussed by Yoshida (1981). In laboratory determinations, $H_2S$ values of up to 5 ppm have been found, while in field tests in Japan and Korea they were up to 1.5 ppm, and in Louisiana they were as low as $5 \times 10^{-5}$ to 0.064 ppm.

In nutrient solutions containing $H_2S$, leaves wilt depending on the concentration and duration of treatment. Mitsui (1960) reported that leaves wilted at a concentration of 0.07 ppm after about 4 days. Shorter treatments can inhibit nutrient uptake, in the order $P_2O_5$ < $K_2O$ < $SiO_2$ < $NH_4$-N < MnO < $H_2O$ < MgO < CaO. Hydrogen sulfide also retards translocation of carbohydrates, N, and P from the basal part of the shoot to the growing organs (Yoshida 1981).

Hydrogen sulfide may also contribute to Fe toxicity in rice, because the production of the gas and FeS in flooded soils under highly reduced conditions lessens the oxidizing power of rice roots (Tanaka et al 1968).

The degraded soils on which Akiochi occurs are sandy, have low pH, and are low in Fe and exchangeable cations (Tanaka and Yoshida 1970). These authors consider that various remedial measures, including avoiding use of fertilizers containing sulfate. adding Fe rich soil and furnace slag, and draining fields in midsummer to oxidize the soil, have largely overcome Akiochi. Cultivars also differ in sensitivity; japonica types are more resistant than indica (Vamos and Koves 1973). Varietal resistance to Akiochi (Baba 1955) may be attributable to the rate at which $O_2$ can be transmitted through the aerenchymatous tissue of the plant into the rhizosphere; Joshi et al (1975) reported that varietal resistance to straighthead is correlated with this characteristic.

Ford (1973) reported that the toxicity threshold for $H_2S$ is also low for citrus roots, 2.8 ppm for 5 days. Sulfate-reducing bacteria can use lactic and citric acids from root exudates as their substrate.

## GENERAL CONSIDERATIONS

It is evident that small concentrations of aliphatic acids, aromatic acids, $C_2H_4$, and $H_2S$ can modify plant growth. Organic acids can retard root elongation restrict nutrient uptake, and reduce shoot weight. Laboratory studies enable the toxicity of the different acids to be ranked, but the most important consideration is the likelihood of toxic concentrations occurring in practice. For this condition to be realized, the acids must be shown to be present in the form (usually water-soluble) and in the concentrations that are biologically active. Acid or alkali extraction procedures, however, have often been used. Although aromatic acids are more toxic than aliphatic acids, they are probably produced from lignin, whereas aliphatic acids are derived mainly from cellulose, which decays earlier. Of the aliphatic acids, acetic acid is less toxic than acids with higher molecular weight at a particular concentration, but because acetic acid usually occurs in higher concentrations, it is likely to be of much greater agricultural significance.

A further consideration in assessing the relevance of work on toxic substances is that, in practice, several substances may occur together. As Wallace and Whitehead (1980) have shown for aliphatic acids, there may be synergistic effects, so that lower concentrations of individual substances may be important. On the other hand, the occurrence of toxic concentrations of organic acids may be quite transient. Although they can retard the growth of seedlings, death has rarely been reported in laboratory studies. Death might result, however, from a secondary soil stress. Dryland and wetland cereal crops have a great ability for compensatory growth; the extent of this ability has been often demonstrated, for example, in rice (Gotoh and Onikura 1971) and in wheat (Cannell et al 1980). For these species, limited seedling growth may not be important. Where seedlings are restricted and further exposure to a toxin occurs, such as to $H_2S$ that is produced under prolonged anaerobic conditions with low redox potential, then growth inhibition and yield depression are expected. Appropriate management such as the use of N fertilizer and adequate percolation and drainage may enable adverse effects of toxins to be offset or avoided, even for rice. However, there has been insufficient work on this subject (Yoshida 1981).

Poor crop establishment and subsequent growth and yield in the presence of decaying organic matter might result from low $O_2$ partial pressures or the effect of microbial toxic metabolites or pathogens. The alleviation of $O_2$ stress on rice emergence has been achieved by pelleting seeds with formulations containing calcium peroxide, which release $O_2$ slowly (Ota and Nakayama 1971). In the laboratory and greenhouse, the formulation has also proved effective with temperate cereals. It has the added advantages of neutralizing toxic organic acids and acting as an antifungal compound (Lynch et al 1981). Further trials have substantiated the preliminary observations, but field trials have not always been successful. Clearly the formulation has potential, and research aimed at producing consistent responses in the field should be of high priority.

## REFERENCES CITED

Allam, A. L., G. Pitts, and J. P. Hollis. 1972. Sulfide determinations in submerged soils with an ion-selective electrode. Soil Sci. 114:456-467.

Arikado, H. 1955. Studies on the development of the ventilating system in relation to the tolerance against excess-moisture injury in various crop plants. VI. Proc. Crop Sci. Soc. Jpn. 24:53-58.

Armstrong, W. 1964. Oxygen diffusion from the roots of some British bog plants. Nature 204: 801-802.

Armstrong, W. 1979. Aeration in higher plants. Adv. Botan. Res. 7:225-332.

Baba, I. 1955. Varietal differences of the rice plant in relation to the resisting capacity to root rot diseases, induced by hydrogen sulfide, and a convenient method to test them. Proc. Crop Sci. Soc. Jpn. 23:167-168.

Belford, R. K., and R. J. Thomson. 1980. Effect of waterlogging before seedling emergence on growth and yield of peas. Pages 27-28 *in* Agricultural Research Council Letcombe Laboratory Annual Report 1979.

Blackwell, P. S., and S. M. Ayling. 1981. Changes in aeration following transient waterlogging of sandy loam and clay soils cropped with winter cereals. Pages 35-38 *in* Agricultural Research Council Letcombe Laboratory Annual Report 1980.

Bradford, K. J., and D. R. Dilley. 1978. Effect of root anaerobiosis on ethylene production, epinasty and growth of tomato plants. Plant Physiol. 61:506-509.

Cannell, R. Q. 1981. Potentials and problems of simplified cultivation and conservation tillage. Outl. Agric. 10:379-384.

Cannell, R. Q., and R. K. Belford. 1982. Crop growth after transient waterlogging. Proceedings 4th Nat. Drainage Conference American Society Agriculture Engineers, St. Joseph, Michigan. (in press)

Cannell, R. Q., R. K. Belford, K. Gales, C. W. Dennis, and R. D. Prew. 1980. Effects of waterlogging at different stages of development on the growth and yield of winter wheat. J. Sci. Food Agric. 31:117-132.

Cannell, R. Q., R. K. Belford, and R. J. Thomson. 1981. Effect of waterlogging at different stages of development on the growth and yield of winter barley. Pages 33-34 *in* Agricultural Research Council Letcombe Laboratory Annual Report 1980.

Cannell, R. Q., F. B. Ellis, D. G. Christian, and B. T. Barnes. 1982. Long-term comparisons of direct drilling, shallow tillage and ploughing on clay and silt loam soils, with particular reference to straw disposal. Pages 85-90 *in* Proceedings 9th Conference International Soil Tillage Research Organization, Osijek, Yugoslavia.

Cannell, R. Q.,and M. B. Jackson. 1981. Alleviating aeration stresses. Pages 141-192 in G. F. Arkin and H, M. Taylor, eds. Modifying the root environment to reduce crop stress. Am. Soc. Agric. Eng. Monogr. 4.

Chandramohan, D., D. Purushothaman, and R. Kothandaraman. 1973. Soil phenolics and plant growth inhibition. Plant Soil 39:303-308.

Chandrasekaran, S., and T. Yoshida. 1973. Effect of organic acid transformations in submerged soils on growth of the rice plant. Soil Sci. Plant Nutr. 19:39-45.

Chou, C. H., and H. S. Lin. 1976. Auto-intoxication mechanism of *Oryza sativa.* I. Phytotoxic effects of decomposing rice residues in soil. J. Chem. Ecol. 2:353-367.

Collison, R. C., and H. J. Conn. 1925. The effect of straw on plant growth. New York (Geneva) Agricultural Experiment Station Tech. Bull. 114.

Crossett, R. N., and D. J. Campbell. 1975. The effects of ethylene in the root environment upon the development of barley. Plant Soil 42:453-464.

Currie, J. A. 1970. Movement of gases in soil respiration. *In* Sorption and transport processes in soil. Soc. Chem. Ind. Monogr. 37:152-171.

Drew, M. C., A. Chamel, J-P. Garrec, and A. Fourcy. 1980. Cortical air spaces (aerenchyma) in roots of corn subjected to oxygen stress. Plant Physiol. 65:506-511.

Drew, M. C., M. B. Jackson, and S. C. Giffard. 1979. Ethylene-promoted adventitious rooting and development of cortical air spaces (aerenchyma) in roots may be adaptive responses to flooding in *Zea mays* L. Planta 147:83-88.

Drew, M. C., M. B. Jackson, S. C. Giffard, and R. Campbell. 1981. Inhibition by silver ions of gas space (aerenchyma) formation in adventitious roots of *Zea mays* L. subjected to exogenous ethylene or to oxygen deficiency. Planta 153:217-224.

Elliott, L. F., T. M. McCalla, and A. Waiss. 1978. Phytotoxicity associated with residue management. Pages 131-146 *in* W. R. Oschwald, ed. Crop Residue Management Systems. American Society Agronomy, Madison.

Ellis, F. B., J. T. Douglas, and D. G. Christian. 1977. A preliminary study of theeffect of straw burning on soil physical conditions. Page 49 *in* Agricultural Research Council Letcombe Laboratory Annual Report 1976.

Ford, H. W. 1973. Levels of hydrogen sulfide toxic to citrus roots. J. Am. Soc. Hort. Sci. 98:66-68.

Geisler, G. 1967. Interactive effects of carbon dioxide and oxygen in soil on root and tip growth of barley and peas. Plant Physiol. 42:305-307.

Goodlass, G., and K. A. Smith. 1979. Effect of ethylene on root extension and nodulation of pea ( *Pisum sativum* L.) and white clover ( *Trifolium repens* L.). Plant Soil 51:387-395.

Gotoh, S., and Y. Onikura. 1971. Organic acids in a flooded soil receiving added rice straw and their effect on the growth of rice. Soil Sci. Plant Nutr. 17: 1-8.

Grobbelaar, N. B., B. Clarke, and M. C. Hough. 1971. The nodulation and nitrogen fixation of isolated roots of *Phaseolus vulgaris.* III. The effect of carbon dioxide and ethylene. Plant Soil Spec. Vol: 215-221.

Guenzi, W. D., and T. M. McCalla. 1966a. Phenolic acids in oats, wheat, sorghum, and corn residues and their phytotoxicity. Agron. J. 58:303-304.

Guenzi, W. D., and T. M. McCalla. 1966b. Phytotoxic substances extracted from soil. Soil Sci. Soc. Am. Proc. 30:214-216.

Gussin, E. J., and J. M. Lynch. 1981. Microbial fermentation of grass residues to organic acids as a factor in the establishment of new grass swards. New Phytol. 89:449-457.

Gussin, E. J., and J. M. Lynch. 1982. Effect of local concentrations of acetic acid around barley roots on seedling growth. New Phytologist (in press).

Harper, S. H. T., and J. M. Lynch. 1981. The kinetics of straw decomposition in relation to its potential to produce the phytotoxin acetic acid. J. Soil Sci. 32:627-637.

Jackson, M. B. 1979. Rapid injury to peas by soil waterlogging. J. Sci. Food Agric. 30:143-152.

Jackson, M. B., and D. J. Campbell. 1975. Ethylene and waterlogging effects in tomato. Ann. Appl. Biol. 81:102-105.

Jackson, M. B., M. C. Drew, and S. C. Giffard. 1981. Effects of applying ethylene to the root system of *Zea mays* on growth and nutrient concentration in relation to flooding tolerance. Physiol. Plant 52:23-28.

Jackson, M. B., K. Gales, and D. J. Campbell. 1978. Effect of waterlogged soil conditions on the production of ethylene and on water relationships in tomato plants. J. Exp. Bot. 29:183-193.

Joshi, M. M., I. K. A. Ibrahim, and J. P. Hollis. 1975. Hydrogen sulfide: effects on the physiology of rice plants and relation to straighthead disease. Phytopathology 65:1165-1170.

Kawase, M. 1974. Role of ethylene in induction of flooding damage in sunflower. Physiol. Plant. 31:29-38.

Kimber, R. W. L. 1967. Phytotoxicity from plant residues. I. The influence of rotted wheat straw on seedling growth. Aust. J. Agric. Res. 18:361-374.

Konings, H., and M. B. Jackson. 1979. A relationship between rates of ethylene production by roots and the promoting or inhibiting effects of exogenous ethylene and water on root elongation. Zeitsch. fur Pflanzenphysiol. 92:385-397.

Kordan, H. A. 1972. Rice seedlings germinated in water with normal and impeded environmental gas exchange. J. Appl. Ecol. 9:527-533.

Ku, H. S., H. Suge, L. Rappaport, and H. K. Pratt. 1970. Stimulation of rice coleoptile growth by ethylene. Planta 90:333-339.

Leonard, O. A., and J. A. Pinckard. 1946. Effect of various oxygen and carbon dioxide concentrations on cotton root development. Plant Physiol. 2:18-36.

Lynch, J. M. 1972. Identification of substrates and isolation of microorganisms responsible for ethylene production in the soil. Nature (Lond.) 240:45-46.

Lynch, J. M. 1976. Products of soil micro-organisms in relation to plant growth. CRC Crit. Rev. Microbiol. 5:67-107.

Lynch, J. M. 1977. Phytotoxicity of acetic acid produced in the anaerobic decomposition of wheat straw. J. Appl. Bact. 42:81-87.

Lynch, J. M. 1978. Production and phytotoxicity of acetic acid in anaerobic soils containing plant residues. Soil Biol. Biochem. 10:131-135.

Lynch, J. M. 1980. Effects of organic acids on the germination of seeds and growth of seedlings. Plant Cell Environ. 3:255-259.

Lynch, J. M., F. B. Ellis, S. H. T. Harper, and D. G. Christian. 1980a. The effect of straw on the establishment and growth of winter cereals. Agric. Environ. 5:321-328.

Lynch, J. M., and K. B. Gunn. 1978. The use of the chemostat to study the decomposition of wheat straw in soil slurries. J. Soil Sci. 29:551-556.

Lynch, J. M., K. B. Gunn, and L. M. Panting. 1980b. On the concentration of acetic acid in straw and soil. Plant Soil 56:93-98.

Lynch, J. M., and S. H. T. Harper. 1980. Role of substrates and anoxia in the accumulation of soil ethylene. Soil Biol. Biochem. 12:363-367.

Lynch, J. M., S. H. T. Harper, and M. Sladdin. 1981. Alleviation by a formulation containing calcium peroxide and lime, of microbial inhibition of cereal seedling establishment. Curr. Microbiol. 5:27-30.

McCalla, T. M., and F. A. Haskins. 1964. Phytotoxic substances from soil microorganism, and crop residues. Bacteriol. Rev. 28:181-207.

McCalla, T. M., and F. A. Norstadt. 1974. Toxicity problems in mulch tillage. Agric. Environ. 1:153-174.

Metraux, J. P., and H. Kende. 1982. On the role of ethylene in the growth response of floating rice to submergence. Eleventh International Conference on Plant Growth Substances, Abstr. 737, Aberystwyth.

Mishustin, E. N. 1972. Potential and effective soil fertility as related to plant remains. Symp. Biol. Hung. 11:25-39.

Mishustin, E. N., N. S. Erofeev, and K. A. Timiryasev. 1966. Nature of the toxic compounds accumulating during the decomposition of straw in soil. Microbiology 35:126-129.

Mitsui, S. 1960. Inorganic nutrition fertilization and soil amelioration for lowland rice. 4th ed. Yokendo Press, Tokyo. 107 p.

Musgrave, A., M. B. Jackson, and E. Ling. 1972. Callitriche stem elongation is controlled by ethylene and gibberellin. Nature New Biol. 238:93-96.

Ota, Y ., and M. Nakayama. 1971. Utilization of calcium peroxide for agriculture — as oxygen supplying material. Nogyo Oyobi Engei 46:869-872. (in Japanese)

Patrick, Z. A,, T. A. Toussoun, and W. C. Snyder. 1963. Phytotoxic substances in arable soils associated with decomposition of plant residues. Phytopathology 53:152-161.

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Prill, E. A., L. V. Barton, and M. L. Soft. 1949. Effects of some organic acids on the growth of wheat roots in solutions. Contrib. Boyce Thompson Inst. 15:429-435.

Rao, D., and D. S. Mikkelsen. 1977a. Effect of acetic, propionic, and butyric acids on young rice seedlings' growth. Agron. J. 69:923-928.

Rao, D., and D. S. Mikkelsen. 1977b. Effects of $CO_2$, $CH_4$ and $N_2$ on growth and nutrition of rice seedlings. Plant Soil 47:313-322.

Rao, D., and D. S. Mikkelsen. 1977c. Effects of acetic, propionic and butyric acids on rice seedling growth and nutrition: Plant Soil 47:323-334.

Rosmussan, J. A., and F. A. Einhellig. 1977. Synergistic inhibitory effects of *p*-coumaric and ferulic acids on germination and growth of grain sorghum. J. Chem. Ecol. 3: 197-205

Smith, K. A., and R. J. Dowdell. 1974. Field studies of the soil atmosphere. I. Relationships between ethylene, oxygen, soil moisture content, and temperature. J. Soil Sci. 25:217-230.

Smith, K. A., and S. W. F. Restall. 1971. The occurrence of ethylene in anaerobic soil. J. Soil Sci. 22:430-443.

Smith, K. A., and P. D. Robertson. 1971. Effect of ethylene on root extension of cereals. Nature 234.148-149.

Smith, K. A., and R. S. Russell. 1969. Occurrence of ethylene and its signifance in anaerobic soil. Nature 222:469-471.

Suge, H. 1971. Stimulation of oat and rice mesocotyl growth by ethylene. Plant Cell Physiol. 12:831-837.

Suge, H. 1972. Mesocotyl elongation in japonica rice: Effect of high temperature pre-treatment and ethylene. Plant Cell Physiol. 13:401-405.

Takai, Y., and T. Kamura. 1966. The mechanisms of reduction in waterlogged paddy soil. Folia Microbiol. 11:304-313.

Takijima, Y. 1963. Studies on behaviour of the growth inhibiting substances in paddy soils with special reference to the occurrence of root damage in the peaty paddy fields. Bull. Natl. Inst. Agric. Sci. Jpn., Series B, 13:117-252.

Takijima, Y. 1964. Studies on organic acids in paddy field soils with reference to their inhibitory effects on the growth of rice plants. Part 1. Growth inhibiting action of organic acids and absorption and decomposition of them by soils. Soil Sci. Plant Nutr. 10:14-21.

Talbot, B., and H. E. Street. 1968. Studies on the growth in culture of excised wheat roots. V. Influence of carbon dioxide on growth and branching. Phyiol. Plant. 21:800-805.

Tanaka, A., and S. A. Navasero. 1967. Carbon dioxide and organic acids in relation to the growth of rice. Soil Sci. Plant Nutr. 13:25-30.

Tanaka, A., R. P. Mulleriyawa, and T. Yasu. 1968. Possibility of hydrogen sulfide induced iron toxicity of the rice plant. Soil Sci. Plant Nutr. 14:1-6.

Tanaka, A., and S. Yoshida. 1970. Nutritional disorders of the rice plant in Asia. International Rice Research Institute Technology Bulletin 10. 51 p.

Trought, M. C. T., and M. C. Drew. 1980. The development of waterlogging damage in young wheat plants in anaerobic solution cultures. J. Exp. Bot. 31:1573-1585.

Vamos, R., and E. Koves. 1973. Role of the light in the prevention of the poisoning action of hydrogen sulphide in the rice plant. J. Appl. Ecol. 9:519-525.

Vine, H., H. A. Thomson, and F. Handy. 1942. Studies on aeration of cacao soils in Trinidad. Trinidad Trop. Agric. 19:215-223.

Wallace, J. M., and L. C. Whitehand. 1980. Adverse synergistic effects between acetic, propionic, butyric and valeric acids on the growth of wheat seedling roots. Soil Biol. Biochem. 12:445-446.

Wang, T. S. C., T-K. Yang, and T-T Chuang. 1967a. Soil phenolic acids as plant growth inhibitors. Soil Sci. 103:239-246.

Wang, T. S. C., S-Y. Cheng. and H. Tung. 1967b. Dynamics of soil acids. Soil Sci. 104:138-144.

Williamson, R. E., and W. E. Splinter. 1968. Effect of' gaseous composition of root environment upon root development and growth of *Nicotiana tabacum* L. Agron. J. 60:365-368.

Yamasaki, S., and T. Saeki. 1976. Oxygen supply from shoots to roots relative to the total oxygen consumption in rice shoots. Bot. Mag. Tokyo 89:309-319.

Yoshida, S. 1981. Fundamentals of rice crop science. International Rice Research Institute, Los Baños, Philippines. 269 p.

## DISCUSSION

FLAIG (comment): In non-aerated nutrient solution culture, low molecular-weight fractions of humic substances compensate for the diminution of root growth. The ratio of the different phenolic acids that can be isolated from rotten plant material differs according to the composition of the lignins.

HAYES: I have noted differing observations of the effects of rice straw amendments to rice soils. Your paper raises the probability of release of phenolic carboxylic acids from the anaerobic decomposition of the lignin fractions of straw. The phytotoxic effects of these might depend on the amounts and types of organic matter in the soil. It could be expected that soils with appreciable quantities of humic substances might strongly absorb phytotoxic aromatic acids. Thus there might be distinct differences in the extents of phytotoxicity between different soils. Do you have any observations along these lines?

*CANNELL:* Your comment seems very relevant, and emphasizes that, in ascertaining the likely effect of phenolic compounds, they should be easily extractable, probably in water. Much past work has relied on acid or alkali extractants, and it introduces doubt as to the actual release of the work. Aliphatic acids, although less toxic, occur in solution in higher concentrations, and are likely to be derived mainly from the more readily decomposable cellulose in the straw.

HUNDAL: In one of the slides showing results of straw application on rice, the use of 15 t/ha rice straw (if it was on dry weight basis) would seem to be too high under practical conditions. Would you expect the same response if the amount of straw used were within the practical limit, say up to 5 t/ha?

*CANNELL:* This was citing work by Gotoh and Onikura (see bibliography of paper). The magnitude of the effect is likely to be less with less straw. However, the purpose was to show that rice, like other small-grained cereals, can compensate for restricted early growth, so that grain yield is less affected than would have been expected at an early stage of growth. Similar effects can occur with stresses due to factors other than the presence of straw.

# EFFECTS OF ORGANIC MATTER ON RICE PRODUCTION

W. K. Oh

The management of rough organic matter for high yielding rice fields was studied. Among these materials, compost and rice straw are the major sources presently used. Well-processed organic manure is less effective in improving the soil than fresh rice straw or partially processed compost.

Rice straw is particularly effective when it is applied to oxidative. less leached infertile soil. The amount of rice straw that should be applied ranges from 3 to 6 t/ha depending on whether the soil is fertile or infertile. Application time does not critically influence the effect of rice straw on yield, but it seems best to apply straw from 2 to 6 weeks before transplanting.

The effect of rice straw can be improved by simultaneously applying lime or applying the straw on limed soil. Simultaneous application counterbalances the adverse effects the two materials have on each other and increases the buffer capacity of soil. These improvements provide better physical and chemical soil conditions for rice growth and promote soil fertility.

Organic matter is very important to improving soil productivity and has been used since agriculture began. Various organic matter, including oil cakes, fish meals, green manures, and compost, were used in the early days of farming. Oil cakes and fish meals became obsolete in modern rice production, while green manure and particularly compost became the important sources. Recently, fresh rice straw has become a popular source, particularly in wetland rice production (Oh 1978).

In the production of wetland rice in Korea, well-processed compost, partially rotten manure, and fresh rice straw are used. However, the effect of these materials on rice yield is uncertain. Park (1978) reviewed previous experimental results and observed that very often organic matter application resulted in intensive soil reduction which cancelled its positive effects, particularly in poorly drained wetland soils. He also found that the effectiveness of organic matter was not consistent in short-term experiments. Ryu et al (1971) found a negative correlation between paddy yield and organic matter content of soil, particularly in imperfectly and poorly drained fields. Even though the effects of compost or rice straw are often minimal in rice production (ORD, Honam Crops Exp. Sta., 1981), some farmers and officials believe that organic matter is indispensable. Huge amounts of compost are applied in campaigns to increase rice yields (Park and Lee 1969).

---

The City University of Seoul, Korea.

**Table 1. Analysis of selected organic materials.**

| Organic materials | Dry matter (%) | | | | | | | Source[a] |
|---|---|---|---|---|---|---|---|---|
| | N | P | K | C | Mg | Organic matter | Others | |
| Alcohol residue | 2.86 | 0.15 | 0.90 | 0.74 | 0.09 | 84.7 | | ORD, IAT 1978b |
| Malt residue | 4.76 | 0.59 | 0.02 | 0.11 | 0.60 | 88.0 | | " |
| Sauce residue | 2.71 | 0.14 | 0.22 | 0.06 | 0.14 | 32.6 | | " |
| Amino acid fermentation residue | 3.50 | 0.12 | 0.29 | 0.30 | 0.60 | 60.0 | Na:4.19 | " |
| Animal hide | 8.20 | 0.03 | 0.04 | 0.48 | 0.02 | 59.8 | Cr:0.98 | " |
| Waste pulp | 0.67 | 0.02 | 0.06 | 0.18 | 0.23 | 73.3 | | " |
| Sugar factory waste | 0.68 | 0.13 | 0.07 | 4.20 | 0.32 | 19.4 | | " |
| Sweet potato starch residue | 1.39 | 0.07 | 0.53 | 0.65 | 0.14 | 77.0 | | " |
| Rice straw | 0.63 | 0.05 | 0.70 | – | – | 78.6 | | Mizu 1930 |
| Barley straw | 0.64 | 0.13 | 0.89 | – | – | 81.3 | | " |
| Wheat straw | 0.48 | 0.10 | 0.52 | – | – | 81.1 | | " |
| Corn stalks | 0.48 | 0.17 | 1.36 | – | – | 80.2 | | " |
| Compost | 0.42 | 0.08 | 0.43 | 0.30 | 0.10 | – | | " |
| Chinese vetch | 0.75 | 0.24 | 1.71 | 1.16 | – | | | " |
| Hairy vetch | 3.80 | 0.41 | 2.70 | – | – | | | " |
| Rye[b] | 0.54 | 0.10 | 0.52 | – | – | | | " |
| Soybean oil cake | 5.90 | 4.72 | 0.04 | 1.77 | 1.07 | 24.3 | | ORD, IAT 1978b |
| Rape oil cake | 4.89 | 0.99 | – | – | – | – | | Mizu 1930 |
| Cottonseed oil cake | 5.68 | 1.15 | 1.40 | – | – | – | | " |
| Fish wastes[b] | 2.1-3.6 | 0.74-2.71 | – | 2.5-8.2 | 0.12-1.08 | – | | " |
| Fish bone meal | 4.2-7.0 | 0.48-0.57 | – | – | – | – | | " |

[a] IAT = Institute of Agricultural Technology. [b] Analysis of fresh material.

The best results are expected from applying organic matter when it provides the rice plant with a suitable environment. In this regard, various factors must be considered. In this paper, the sources of organic matter, tonnage, time of application, and management are discussed.

## SOURCES

Many organic residues and wastes have been added to agricultural lands to increase crop production. Analysis of selected organic materials (Table 1) indicates their plant nutrient contents. Fish wastes, fish bone meals (Mizu 1930), oil cakes, animal hide wastes, and some fermentation residues are very rich in plant nutrients (ORD, IAT, 1978b). The green manures are also high in plant nutrients. The plant nutrients in these organic residues and wastes become available quickly so that some are used as commercial fertilizers. However, almost none are used in rice production.

Straw and compost are popular sources of rough organic matter for rice production. Green manures — mainly rye, hairy vetch, and Chinese milk vetch — have limited use. Farmers often return fresh rice straw to their fields now. Some farmers who raise cattle use rice straw as litter, which they compost later. The characteristics of compost made from litter are not much different from compost made directly from straw or grain manures. Partially decomposed or fresh organic matter, particularly those low in N such as straw, compete with the plant for available N in the early days of decomposition, which can seriously reduce plant growth (Rao and Mikkelsen 1976, Gotoh and Onikura 1971). However, with the simultaneous addition of readily available plant nutrients, deficiencies can be corrected (Lee et a1 1975, Maas and Adamson 1972, Pritam and Broadbent 1977) and a good rice yield realized (Oh 1978, Oh and Lee 1971). Recently, the use of rice straw has caused problems with machinery operation at soil preparation time. Partially decomposed rice straw disturbs rotary cultivator operation, so a straw-chopping machine has been developed.

## EFFECT OF COMPOST AND RICE STRAW ON RICE YIELD

### Effects with and without commercial fertilizer

Fresh rice straw was rarely applied to rice fields until recently because it caused severe N shortage, reducing yields (Agricultural Experiment Station 1962). The results of a long-term experiment using no commercial fertilizers are shown in Table 2. Completely and partially processed or rotted compost greatly increased rice yield, but fresh rice straw increased yields only slightly. The yield from the partially processed compost was the greatest. However, analysis of the organic matter showed a higher plant nutrient content in the completely processed compost than in the partially processed compost (Table 3). The decomposition of rough organic matter low in plant nutrients occurs slowly when no mineral nutrients, particularly N, are added. The decomposition of the partially processed compost is probably quicker than the decomposition of fresh rice straw because of the compost’s N content and the previous decomposition, which might result in quick soil reduction. It is known that soil reduction not only improves the availability of plant nutrients, but also

**Table 2. Effects of completely processed compost, partially processed compost, and fresh rice straw on rice yield (Agricultural Experiment Station 1962).**

| Treatment | Yield (g/pot) | Index (%) |
|---|---|---|
| No compost | 89.0 | 100 |
| Completely processed compost at 11.25 t/ha | 144.6 | 163 |
| Partially processed compost equivalent to 11.25 t compost/ha[a] | 155.4 | 175 |
| Fresh rice straw applied the previous autumn at 1.88 t/ha | 96.3 | 108 |

[a] Applied before transplanting.

**Table 3. Plant nutrient percentages in completely processed compost, partially processed compost, and fresh rice straw.**

|  | Completely processed compost | Partially processed compost | Fresh rice straw |
|---|---|---|---|
| Total N | 0.861 | 0.621 | 0.443 |
| Total P | 0.196 | 0.108 | 0.100 |
| Total K | 0.705 | 0.640 | 1.076 |

**Table 4. Effect on rice yield of compost and rice straw each applied at 7.5 t/ha in combination with 80-80-80 commercial fertilizer at 2 locations (Oh 1966).**

| Location | Plow depth (cm) | Compost (t/ha) | Rice straw (t/ha) | Increase by straw over compost (%) |
|---|---|---|---|---|
| Suwon[a] | 10 | 4.86 | 5.02 | 3.3 |
|  | 20 | 4.83 | 5.12 | 6.0 |
| Iri[b] | 10 | 6.08 | 6.34 | 4.3 |
|  | 20 | 6.09 | 6.08 | 0.0 |

[a] 4-year average. [b] 2-year average.

increases N fixation (ORD, IAT, 1978a). As a result, the N shortage in a partially processed compost plot may be minimal, but the N shortage in a rice straw plot may cause severe N starvation of the rice plants, particularly in the early growth stages. Consequently, this shortage resulted in fewer panicles and low rice yields. Yields were low in pot experiments where the canopy status of rice plants was different from that in the fields (Huh and Lee 1981).

Table 4 indicates results of adding compost and rice straw in addition to chemical fertilizers in field experiments. The superiority of rice straw over compost was generally observed except at 20-cm plow depth in Iri. The serious N starvation caused by fresh rice straw is probably offset by the application of chemical fertilizers. Although N starvation still suppresses early rice growth, it improves growth in later stages (Lee and Kwon 1967). This effect of rice straw under normal farming practice produces a greater number of panicles and increases the maturity level of the grain, which is particularly important in light soils in warm climates.

## Effect of different soil conditions

Good rice yields may be expected when applying compost and rice straw on sandy, permeable soil. Soil permeability is particularly important when applying partially processed compost or fresh rice straw (Oh and Lee 1971). Figure 1 indicates the effect of fresh rice straw on yield when the straw is applied to soils differing in permeability. With poor soil permeability, rice straw caused a negative effect, probably because of a heavy accumulation of intermediate-decomposition products.

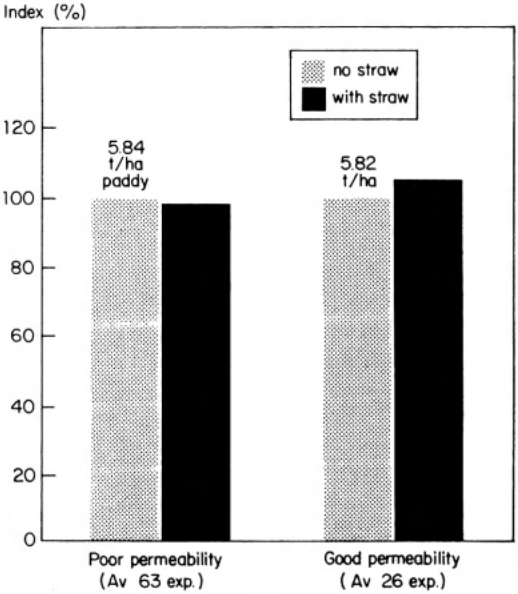
## Effect of different application rates

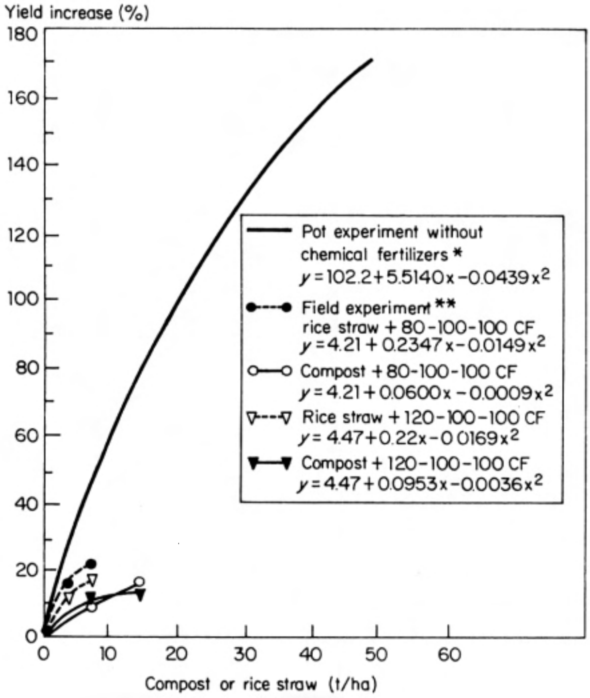
Figure 2 shows the percentage increase of rice yield resulting from application of compost or rice straw, with and without commercial fertilizers. Without commercial fertilizers, compost increased the yield percentage considerably. When compost or rice straw was applied in combination with readily available commercial fertilizers, however, percentage increase of yield decreased markedly. Furthermore, the calculated maximum percentage yields of these treatments were nearly the same. Compost had to be applied in combination with commercial fertilizer at 34 t/ha to reach a maximum percentage yield with 80-100-100 fertilizer and at 13 t/ha with 120-100-100, showing that it is indeed fertilizer. Rice straw had to be applied at 8 t/ha with 80-100-100 and at 7 t/ha with 120-100-100 (practically no difference), showing that it is a soil amendment due to the great promotion of soil productivity at the former treatment level.

Oh and Lee (1971) reported that in oxidative, less fertile soil the effect of rice straw is particularly great and the amount of rice straw required for a good yield of paddy is high.

Another 4-year experiment (ORD, IAT, 1978a) conducted on clay loam soil of medium fertility showed 8.8 and 13.8% yield increases with 3.0 and 6.0 t/ha of rice

**1.** Effect of rice straw on rice yield of two soils differing in permeability.





**2.** Percentage increase of rice yield resulting from application of compost or rice straw with simultaneous application of chemical fertilizers (CF). *10-year average 1926-36 (Agricultural Experiment Station 1962). **3-year average 1966-68 (Oh and Lee 1971).

straw application over use of chemical fertilizers alone. This indicates that rice straw should be applied at rates of about 5-6 t/ha for oxidative, infertile soil and 2-3 t/ha for fertile soil.

## Effect of time of application and pretreatment

A common practice is to spread compost and plow just before transplanting. This can save plant nutrients, particularly $NH_3$ contained in the compost. Rice straw application time varies. Some farmers spread straw over the field immediately after

**Table 5. Effect of pretreatment of rice straw with nitrogen solution on rice yield (ORD, IAT, 1978a).**

| Treatment[a] | Rice yield (t/ha) | Increase by straw |
|---|---|---|
| No pretreatment | | |
| No rice straw | 5.42 | – |
| 6.0 t straw/ha | 5.80 | 0.38 |
| 100 kg N pretreatment | | |
| No rice straw | 6.12 | – |
| 6.0 t straw/ha | 6.67 | 0.55 |

[a] Two weeks before transplanting, the rice straw with and without N pretreatment was spread over the field and followed by plowing, which was also done to the plots with no pretreatment with N. Another 60 kg of N with normal rates of P and K was applied at transplanting time to all treatments.

**Table 6. Brown rice harvested from the treatments applied with rice straw and woll as tonite, separately or in combination (Kyong-Gi Prov, ORD, unpubl.).**

| Treatment | 22-cm plowing | | 12-cm plowing | |
|---|---|---|---|---|
| | Yield (t/ha) | Index (%) | Yield (t/ha) | Index (%) |
| Control | 4.91 | 100 | 4.59 | 100 |
| Rice straw 5.0 t/ha | 5.14 | 105 | 4.98 | 108 |
| Wollastonite 5.39 t/ha | 5.19 | 106 | 5.02 | 109 |
| Rice straw + wollastonite | 5.40 | 110 | 5.23 | 112 |

harvesting; others apply it 2 weeks before transplanting, usually plowing immediately after. The plowing time varies when straw is applied after harvest. Some farmers plow immediately after spreading; others leave the straw on the field to decompose until land preparation for the next crop. Some plow some time after spreading, but well before preparation for the next crop. Research by ORD, IAT (198la), showed that rice yields are somewhat higher when the straw is applied and plowed under in spring to early summer (2-6 weeks before transplanting).

To reduce nutrient starvation of plants when fresh rice straw is applied, some pretreatments of the straw with fertilizer solutions have been tried. The effects of these treatments vary, but they are often beneficial. Table 5 shows the results of a pretreatment of 100 kg N on the straw. Yields were increased by 0.55 t/ha, compared with a 0.38-t/ha increase without the pretreatment. Although the yield difference is not great, the positive effects of pretreatment can be expected, particularly when a large amount of straw is applied to infertile soil or is applied just before transplanting.

## EFFECT OF RICE STRAW IN COMBINATION WITH LIME

Large amounts of organic matter incorporated into soil produce enough gases, acids, and various metabolites to reduce crop yield (Chandrasekaran and Yoshida 1973, Morachan et a1 1972). Calcium can often counteract these harmful substances.

### Effect on rice yield and yield components

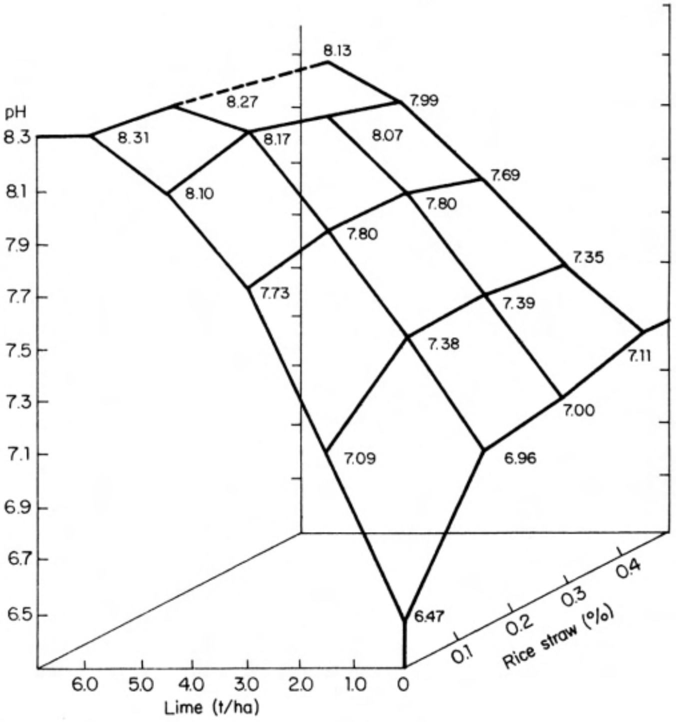
Many experiments show that compost, green manure, or rice straw produce higher yields when applied with lime than when applied without (ORD, Honam Crops Exp. Stn., 1974; ORD, IAT, 1981a). The results ofanexperiment with rice straw and wollastonite (calcium silicate) are shown in Table 6. With plowing depths of 12 and 22 cm, the combined application of the two materials produced more rice than their separate application. The yield of brown rice where lime and rice straw were applied increased because of greater numbers of panicles per hill and grains per panicle.

### Effect on soil fertility

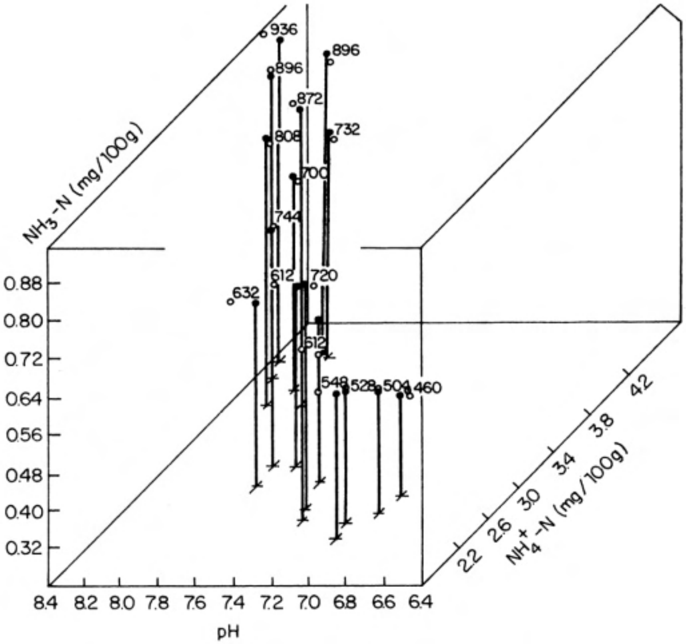
Adverse effects of organic matter and lime could be counterbalanced if both materials were used at the same time (An et a1 1973). Figure 3 shows the pH of flooded soil incubated for 19 days as affected by rice straw powder and lime. The addition of rice straw raised low soil pH and lowered high soil pH.

Rice straw decomposition produces a large amount of $CO_2$, which establishes a $CaCO_3$-$Ca^{++}$-$HCO_3$-$H_2O$ system in a limed, flooded soil, and stabilizes the pH of the soil solution in a limited but somewhat high range, which may favor rice growth. Undoubtedly, rice can grow better in a buffered soil. The application of rice straw to high-pH soils also reduces ammonia volatilization (Oh and Hwang 1982). There is also an increase of N fixation when rice straw and lime are applied (ORD, IAT, 1981c). The author found that the high pH of flooded soil enhanced $NH_3$ volatilization but increased $NH_3$ accumulation in the soil (Fig. 4). Fenn and Miyamoto (1981) reported that Ca and Mg were precipitated with the application of urea and $NH_4OH$. The amount of Ca and Mg precipitation was increased with decreasing $NH_3$ loss. They also reported that precipitation of bivalent cations enhanced the adsorption of $NH_4^+$ on soil cation exchange sites. Fenn et al (1981) reported that the precipitation of $CO_3$ by Ca suppressed $NH_3$ loss, preventing permanent $(NH_4)_2CO_3 \cdot H_2O$ formation when urea or inorganic N was added by surface application.

The reduction of loss from lime application might be one of the important merits of rice straw application to rice fields. The author conducted a laboratory experiment from which the fluctuation of total N in flooded soil can be partly understood (Table 7). With a small amount of rice straw (0.15%), total N decreased at all levels of lime because of the increased soil pH. Increased amounts of rice straw,



**3.** pH of flooded soil 19 days after flooding, as affected by lime and rice straw application (Oh, unpublished).



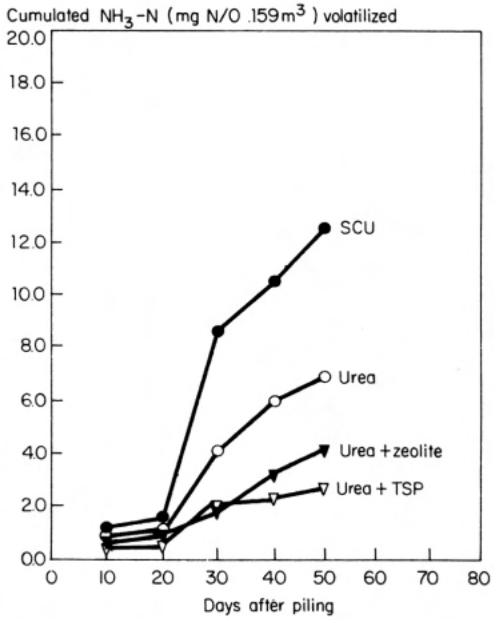
**4.** $NH_3$-N volatilization in relation to flooded soil pH and $NH_1^-$-N retained in soil (Oh, unpublished).

however, increased the total soil N content in general. Hwang (unpubl.) analyzed soil samples from a field experiment and found similar effects of rice straw on preserving total N in the limited plot.

Rice grows well vegetatively at rather low soil pH, but high rice yields are usually obtained from soil with somewhat high pH (Park and Lee 1969). High pH seems necessary for improving soil conditions for favorable rice growth. For instance, high pH reduces the amount of toxic substances in the soil, which may be serious with heavy fertilization. High soil pH appeared to be necessary in light soils that have a low adsorption capacity (Oh et al 1974).

**Table 7. Total nitrogen in soil as a result of the amount of rice straw powder and lime (Oh, unpubl.).**

| Lime (%) | Total N (mg/100 g soil) resulting from rice straw application at | | | | |
|---|---|---|---|---|---|
| | 0% | 0.15 % | 0.30 % | 0.45 % | Av |
| 0 | 161 | 158 | 162 | 169 | 163 |
| 0.15 | 148 | 135 | 139 | 153 | 144 |
| 0.30 | 127 | 135 | 144 | 142 | 137 |
| 0.45 | 135 | 134 | 139 | 136 | 136 |
| 0.60 | 132 | 127 | 126 | 138 | 131 |
| Av | 141 | 138 | 142 | 148 | |



**5.** Ammonia volatilization during processing of rice straw when urea and some additives were added. The experiment was conducted in plastic baskets of 75-1 volume. 0.7% N, 2% $P_2O_5$, 3% zeolite were added to the straw (Lee et al 1975a).

If rice straw is returned to the field with the necessary amount of lime, the soil can be kept properly buffered while the straw is broken down into humus.

For a high rice yield, soil fertility must be built up. It is common to harvest 5-6 t rice straw/ha. All or most of this straw should be returned to the soil during the first several years, except in fields with poor drainage, where the amount may be reduced to 2-3 t/ha.

## PROCESSING ORGANIC MATERIALS

Raw organic materials obtained in the off-season are usually processed. Compost is sometimes prepared for particular purposes, for instance, for poorly drained fields. The processing method may be different depending on need. For agronomic use, farmyard manure and other organic wastes, including straw and weeds, are collected and piled about 1.5 m high. While awaiting use, the plant nutrients in the raw materials change. Nitrogen content is sometimes changed drastically. Lee et al (1975) found that 50-90% of N in the raw materials is lost about 15 days after piling. They also found that the higher the amount of N in the raw material, the greater the N loss.

Nitrogen loss during the processing period is primarily due to $NH_3$ volatilization and denitrification. Various methods are being adopted to minimize these N losses. Figure 5 shows the effects of several additives that decrease the N loss during the processing period. Triple superphosphate is effective. Zeolite is also effective because it adsorbs $NH_4^+$. A common recommendation is to use superphosphate or $CaSO_4$ and earth when processing organic material for compost. Composts obtained as a byproduct of mushroom production or biogas-making are also good sources for agricultural use.

## REFERENCES CITED

Agricultural Experiment Station. 1962. Experimental data on the application of compost, in Korea [in Japanese]. Agric. Res. Bull. Suweon, Korea 12(1):1-149.

An, S. B., M. H. Lee, and W. K. Oh. 1973. The effect of slaked lime and straw on the soil pH in the flooded and upland conditions [in Korean, English summary]. Res. Rep. Off. Rural Dev. 15 (Plant Environ.): 67-71.

Chandrasekaran, S., and T. Yoshida. 1973. Effect of organic acid transformations in submerged soils on growth of the rice plant. Soil Sci. Plant Nutr. (Tokyo) 19(1):39-45.

Fenn, L. B., and S. Miyamoto. 1981. Ammonia loss and associated reactions of urea in calcareous soils. Soil Sci. Soc. Am. J. 45:537-540.

Fenn, L. B., R. M. Taylor, and J. E. Matocha. 1981. Ammonia losses from surface-applied nitrogen fertilizers as controlled by soluble calcium and magnesium: General theory. Soil Sci. Soc. Am. J. 45:777-781.

Gotoh, S., and Y. Onikura. 1971. Organic acids in a flooded soil receiving added rice straw and their effect on the growth of rice. Soil Sci. Plant Nutr. (Tokyo) 17:1-8.

Huh, B. L., and C. D. Lee. 1981. Effect of rice straw application on the tillering of paddy rice [in Korean, English summary]. J. Korean Soc. Soil Sci. Fert. 14(3):146-156.

Lee, E. U., and Y. U. Kwon. 1967. Effect of yearly application of straw and nitrogen, phosphate and potassium fertilizer on growth and yield in rice [in Korean, English summary]. J. Korean Agr. Chem. Soc. 8:51-59.

Lee, S. K., I. D. Yoo, and B. R. Huh. 1975. Effect of decomposition rate of compost materials on the change of organic and inorganic substances and growth status of Chinese cabbage [in Korean, English summary]. Res. Rep. Off. Rural Dev. 17 (Soil Fert.):67-80.

Lee, S. K., I. D. Yoo, and J. F. Parr. 1975. Decomposition of rice straw and compost in an acid sulphate soil under aerobic and anaerobic conditions. J. Korean Soc. Soil Sci. Fert. 8(4):171-176.

Maas, E. F., and R. M. Adamson. 1972. Resistance of sawdusts, peats, and bark to decomposition in the presence of soil and nutrient solution. Soil Sci. Soc. Am. Proc. 36:769-772.

Mizu, H. O. 1930. Fertilizer sciences [in Japanese]. Asakura.

Morachan, Y. B., W. C. Mordenhauer, and W. E. Larson. 1972. Effect of increasing amount of organic residues on continuous corn yield and soil physical properties. Agric. J. 64(2):199-203.

Oh, W. K., and S. K. Lee. 1971. Studies on the effect of compost and fresh rice straw on paddy yield. J. Korean Soil Sci. Soc. Fert. 4(2):177-186.

Oh, W. K., S. B. Lee, C. W. Hong, and I. K. Chong. 1974. Studies on the optimum pH, base saturation, lime requirement of soil for paddy production [in Korean, English summary]. Ministry of Science and Technology. Seoul, Korea. R-74-32.

Oh, W. K. 1978, Effect of incorporation of organic materials on paddy soils. Pages 435-449 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Oh, W. K., and K. N. Hwang. 1982. Volatilization of ammonia from a flooded soil in relation to the application of wallastonite and rice straw. J. Korean Soc. Soil Fert. 15.

ORD (Office of Rural Development), Honam Crops Experimental Station. 1974. Pages 323-333 *in* Annual report for 1973 [in Korean], IRRI, Korea.

ORD, Honam Crops Experimental Station. 1981. Pages 407-411 *in* Annual report for 1980 [in Korean]. IRRI, Korea.

ORD (Office of Rural Development), IAT (Institute of Agricultural Technology). 1978a. Important research results and future programs [in Korean]. Suweon, Korea.

ORD, IAT. 1978b. Pages 407-408 *in* Important research results and future programs [in Korean]. Suweon, Korea.

ORD, IAT. 1981a. Pages 298-353 *in* Annual report for 1980 [in Korean]. Suweon, Korea.

ORD, IAT. 1981b. Pages 349-353 *in* Annual report for 1980 [in Korean]. Suweon, Korea.

ORD, IAT. 1981c. Pages 379-390 *in* Annual report for 1980 [in Korean]. Suweon, Korea.

Park, C. S. 1978. Effect of organic material application on the growth and yield of crops in Korea [in Korean, English summary]. J. Korean Soc. Soil Fert. 11:175-194.

Park, S. H., and Y. M. Lee. 1969. Studies on the cultivation techniques of high yielding rice farming in Korea [in Korean, English summary]. Res. Rep. Off. Rural Dev. 12(1):133-146.

Pritam Sain, and F. E. Broadbent, 1977. Decomposition of rice straw in soils as affected by some management factors. J. Environ. Qual. 6(1):96-100.

Rao, D. N., and D. S. Mikkelsen. 1976. Effect of rice straw incorporation on rice growth and nutrition. Agron. J. 68(5):752-755.

Ryu, I. S., Y. S. Kim, and C. S. Park. 1971. Studies on the relationship between productivity of paddy soil, and their physical and chemical properties [in Korean, English summary]. Res. Rep. Rural Dev. 14 (Plant Environ.):1-16.

# PEAT SOILS PROBLEMS AND CROP PRODUCTION

M. Ismunadji and G. Soepardi

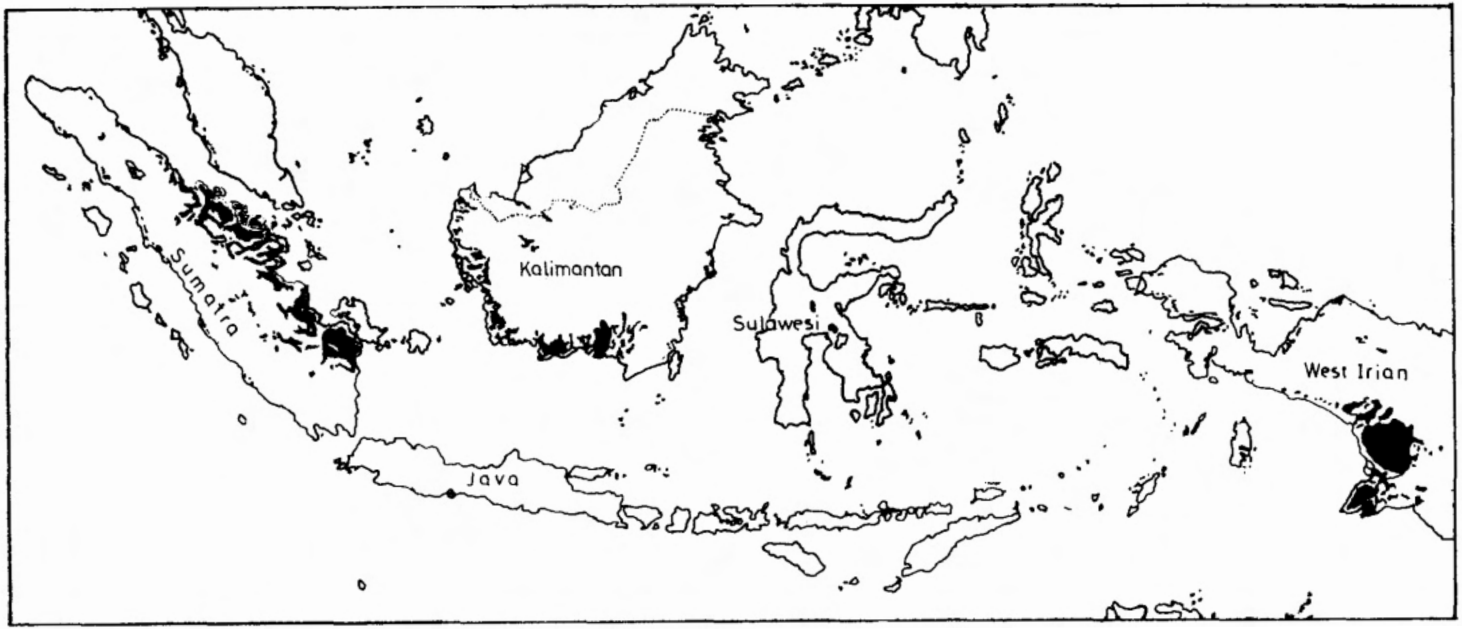
Peat areas in Southeast Asia are concentrated in Malaysia (about 2.4 million ha) and Indonesia (about 16.5 million ha), mainly in Kalimantan, Sumatra, and West Irian. Soil problems increase with increasing peat depth. In many countries various kinds of crops can be grown on peat when properly managed after reclamation. Soil fertility and crop productivity vary with location. Fertilizer requirements can be assessed by nutritional disorder symptoms, pot tests, plant and soil analyses, and field experiments. Traditional rice cultivation on peat is discussed. Some farmers have recently begun to plant rice twice a year, including one modern cultivar and one traditional cultivar. The “surjan” system has recently been introduced. It consists of dry raised beds planted with dryland crops and sunken beds planted with rice. Dominant rice diseases and pests observed on peat are given.

Peat deposits are found in many countries, but the greater part of the total peat area of the world is within the Boreal zone (around the North Pole), and the USSR has the largest peat area (Sjors 1965, Farnham and Finney 1965). Peats cover more than 200 million ha worldwide, of which about 32 million ha are in the tropics, specifically about 22 million in Asia, 3 million in Africa, and 7 million in America (Driessen 1978). Peat in Southeast Asia is concentrated mainly in Indonesia and Malaysia (Soepraptohardjo and Driessen 1976). Polak (1952) estimated the area covered with peat in Indonesia to be about 16.5 million ha, mainly on the southern coast of West Irian, the southern and western coasts of Kalimantan, and the eastern coast of Sumatra (Fig. 1). In Malaysia, peat soils cover about 1 million ha in Peninsular Malaysia and about 1.4 million ha in Sarawak (Kanapathy 1975). Peat soils are also found in Ceylon, Vietnam, the Philippines, and India (Tamhane et al 1970). Although the existence of peat formations under tropical conditions has long been recognized, tropical peats have received little detailed attention (Coulter 1950).

In Indonesia, it is estimated that less than 0.5 million ha of peat is under cultivation and the remaining 16 million ha are still undeveloped. Population

---

Central Research Institute for Food Crops (CRIFC), Jalan Merdeka 99, Bogor, Indonesia, and Faculty of Agriculture, Bogor Agricultural University, Jalan Raya Pajajaran, Bogor, Indonesia,



**1.** Peat distribution in Indonesia (Polak 1952).

pressure has been forcing the government to expand agricultural land to marginal and problem soils, including peat soils. Although many problems are encountered, experience indicates that, with proper management, peat soils can be made productive. In Japan the average production of rice per hectare on peat is actually higher than the national average (T. Motomatsu 1981, pers. comm.).

Generally speaking, problems increase with increasing peat depth. Farmers usually use peat with depths of less than 1 m for agriculture. However, the possibility of using deep peat for agriculture still exists (Bogor Agricultural University 1978, Notohadiprawiro 1979). Research to promote crop production on peat has high priority, and proper packages of technology to reclaim peat soils will have a large impact on the economy of the country.

## FORMATION AND CHARACTERISTICS

All soils contain organic matter, but relatively few contain enough to be classified as organic soils. The basic criterion for this classification is that enough organic matter be present to dominate the soil properties. Organic soils are formed when the rate of organic matter production at a certain place exceeds the rate of destruction. In the formation of organic soils, an environment that is water saturated for extended periods of time and contains low quantities of $O_2$ or is anaerobic is required (Gorham 1957). Organic soils are thus poorly drained and have a high water table for most of the year. Poor drainage causes lack of oxygen, salinity, and acidity. The existence of substances inhibiting microbiological activity is common in peat (Notohadiprawiro 1979). Peats are of little agricultural value unless reclaimed and well managed.

Kanapathy (1975) states that peat is technically defined as organic soil that is at least 0.5 m in depth, a minimum of 1 ha in extent, and with mineral matter not exceeding 70%. Polak (1952) considers only those soils that contain more than 65% organic matter down to 1 m or more (50 cm if under cultivation) to be genuine peat soils. The international criterion for organic soils is the presence of 30% organic matter in a cumulative layer of 40 cm or more (Driessen and Soepraptohardjo 1974). Shallow or moderately deep tropical peat soils are usually less poor in plant nutrients than deep peat. Nutrient deficiencies are most severe in genetically old peats, with the exception of topogenous peats, which receive nutrients from outside and cannot be included in any generalized account of the chemical properties of tropical peats (Driessen 1978).

Peat soils in Indonesia are found mainly along the coast in relatively inaccessible swamps; the area of inland peat is smaller. The sea level was approximately 60 m lower in Pleistocene times than at present. During the Holocene, the sea rose until the present level was reached. Vast marshy tracks were formed with a pallustric vegetation of water plants, reeds, and sedges. In time plant residues with varying thickness accumulated. Peat more than 15 m thick can be found along the Sumatran coast (Driessen and Soepraptohardjo 1974), and a thickness of 10 m is not uncommon. The depth of peat varies greatly, being least at the edge of the swamp and increasing toward the middle.

During the accumulation of organic matter, the vegetation changed gradually in composition until finally the marsh forest developed on groundwater peat (or topogenic peat) of varying thickness. If the rainfall is sufficiently high, very moist conditions are maintained in this peat, even if the groundwater does not reach the surface any more. Under such moist conditions rainfall alone is capable of preventing the decomposition of the forest litter, and peat accumulation continues. The surface of the peat then rises over the former groundwater level, and a body of domed peat is formed. This ombrogenic peat is poorer in quality than the underlying topogenic peat (Driessen and Soepraptohardjo 1974). Most Indonesian peats are woody ombrogeneous peats formed in swamp forest, in mixed forests with mosses and ferns, or in mangrove forests.

Organic soils are identified as the order Histosol. Three major suborders have been established. The Fibrist suborder includes organic soils in which the undecomposed fibrous organic materials are easily identified. They have high water-holding capacities. The most highly decomposed organic materials are found in organic soils belonging to the Saprist suborder. The orignal plant fibers have mostly disappeared. Their water-holding capacities are the lowest of any organic soils. The Hemist suborder includes organic soils intermediate in their properties between those of the Fibrist and Saprist. They have intermediate values for water-holding capacity (Brady 1974). Peat has an enormous water-holding capacity. When the rainy season sets in, large quantities of water are absorbed, and seepage occurs only after the organic mass has become saturated. This characteristic property of peat, which is related to the colloidal composition of the organic substance, is lost forever in cases of severe drying (irreversible dehydration of the colloids). Being permanently saturated with water, uncultivated peat is always poor in oxygen (Van Wijk 1951).

Two sources of mineral nutrients are available to peat: the atmosphere and the soil. Areas dependent exclusively on nutrients from the air are termed ombrotrophic, i.e., nourished by the rain. Sites that also receive terrestrial mineral nutrition are termed minerotrophic, indicating that nutrients are brought to the peat by water that has previously been extracted from a mineral soil (Sjors 1965). Fleisher proposed the separation of peat into fertile eutrophic, moderately fertile mesotrophic, and poor oligotrophic peat (Driessen and Soepraptohardjo 1974).

Polak (1941) proposed the following points to be considered in the classification of peat:

1. Position of peat relative to the groundwater, namely whether above or below the water table
2. Whether the peat formation occurs locally (autochthone) or not (allochthone)
3. Mineral content
4. Composition of the vegetation
5. The vegetative composition and the succession forming the peat layer.

Most acidic (pH 3-5), deep, tropical wetland peats contain less than 5% inorganic constituents. The organic fraction consists largely of hemicellulose, cellulose, lignin, humic substances, and smaller amounts of protein, wax, tannin, resin, suberin, etc. (Driessen 1978).

The chemical poverty of most coastal peats is notorious, and their physical properties are generally only marginal as well, even after reclamation. Most peats have a very low, pH (less than 4.0); a high C-N ratio; poor drainage; occasionally high Al content; and usually low contents of P, K, and Ca (Suryanto et al 1974). They have high subsidence; extremely rapid horizontal water conductivity or extremely slow vertical conductivity; high heat capacity and low thermal conductivity, which cause great temperature variations at the soil surface; poor decomposition of organic matter and high percentage of wood; low bearing capacity, which causes trees to topple after some time; rapid oxidation and decomposition of organic matter after drainage; and irreversible shrinkage, which causes adverse water retention and sensitivity to erosion (Soepraptohardjo and Driessen 1976).

Pot experiments using peat soils from West Kalimantan indicated that application of 0.5 g $CuSO_4$/pot (12.5 kg peat) yielded twice as much maize as when no Cu was added, and field experiments reconfirmed the importance of Cu in increasing maize yields (Polak and Soepraptohardjo 1951). Driessen and Suhardjo (1976) tentatively attributed defective seed formation in rice to certain organic compounds, notably lignin degradation products and their polymers; through Cu fixation, these directly or indirectly hinder essential enzyme-catalyzed carbohydrate transformations. Soil samples taken from Pontianak in West Kalimantan and Indragiri Ilir in Sumatra by Driessen and Suhardjo (1976) showed more Cu in the upper layers of the peat than at greater depth; an area that had been drained and cleared 17 years beforehand had less Cu than the virgin forest. Russell (1976) mentioned that, on some organic soils, particularly in the early years after reclamation, it was best to use Cu both as a soil dressing and a spray. Miyake (1981) stated that abnormal panicles or sterility observed in the field are caused by harmful substances produced by delayed and incomplete decomposition of organic matter. However, experiments conducted by Coulter (1950) on rice using Malaysian peat indicated that rice did not respond to the addition of trace elements, namely Cu, Zn, and Mn. The fertility of peat seems to be site specific, and many factors are involved, such as the source or quality of organic matter, rate of decomposition, water regime, etc.

In swampy areas which have been reclaimed for paddy fields for some years, the organic matter content has gradually decreased as a result of tillage and supply of fresh water, and now amounts to about 10-30%. The average percentage of readily oxidizable matter increases as the percentage of organic matter decreases. The C-N ratio decreases from roughly 25-50 in the original state to 15-20 in the cultivated soil. In temperate zones the process of shrinking and humification of organic matter takes some 20 years for a peat layer of about 3 m; in the tropics it is completed within a few years when there is adequate aeration, and a shrinkage of 0.5 m/year is not unusual (Van Wijk 1951). Factors responsible for the loss of peat are 1) burning during clearance and after harvest; 2) oxidation due to excessive drainage; 3) destruction and compaction due to hoeing and other agricultural activities; and 4) leaching (Chambers 1979).

Driessen and Suhardjo (1976) studied the inorganic fraction of six surface soils from reclaimed Indonesian peat. They showed that felling the forest caused drastic changes in the contents of most nutrients because of interrupted cycling, release of nutrients from decaying organic matter, and compaction of the drained surface soil (Table 1). Total ash, K, P, and Si decreased, while Ca and Mg increased after felling the forest.

**Table 1. Nutrients in 6 surface soils from lowland peat areas in Sumatra and Kalimantan (Driessen and Suhardjo 1976).**

| Surface soil | Nutrient content (kg/ha) | | | | | |
|---|---|---|---|---|---|---|
| | P | K | MgO | CaO | $SiO_2$ | Total ash |
| *West Kaliman tan (10-20 cm)* | | | | | | |
| Deep peat under light mixed swamp forest | 290 | 99 | 482 | 444 | 5,892 | 9,070 |
| Same; cleared 16 years ago; cropped 3 times | 99 | 106 | 647 | 1,239 | 1,670 | 6,570 |
| Same; cropped 16 times | 71 | 33 | 432 | 933 | 983 | 4,340 |
| *Riau (0-25 cm)* | | | | | | |
| Moderately deep peat under mixed swamp forest | 95 | 71 | 685 | 211 | 14,960 | 17,500 |
| Same; cleared 3 years ago; never cropped | 100 | 41 | 965 | 1,612 | 11,870 | 17,180 |
| Same; cleared 30 years ago; perennial crops | 189 | 61 | 854 | 3,050 | 4,400 | 16,000 |

Indonesian peats are sometimes underlain by cat clay, in which $FeS_2$ has been formed under anaerobic conditions. If this type of clay is exposed to the air after drainage, $O_2$ from the air will oxidize the sulfides and $H_2SO_4$ is formed. In base-deficient clay, $Al_2(SO_4)_3$ and, by hydrolysis, $Al(OH)_3$ may be formed (Van der Spek 1950).

The chemical and physical characteristics of peat from different depths vary. The acidity, CEC, carbon, C-N ratio, P, K, Ca, and exchangeable H of peat from Sumatra increased while its ash and Cu decreased with increasing peat depth, as shown in Table 2 (Bogor Agricultural University 1978). Pot experiments indicated that rice grew more poorly at increasing peat depths. The dry matter weight, number of productive tillers, and yield decreased, while panicle emptiness increased with increasing peat depth (Bogor Agricultural University 1978, Leiwakabessy and Wahyudin 1979). These results indicate that rice grown on deep peat needs strong soil amelioration and fertility management. “Minus one element” pot experiments using deeper peat, i.e., 110 cm and 120 cm, indicated that addition of nutrients improved plant growth and increased the dry matter weights of grain and straw dramatically, as shown in Table 3 (Bogor Agricultural University 1978).

Results obtained by the Soil Reseach Institute (1976) indicated that application of sufficient lime is a prerequisite for the success of crop production on acid peat. Application of 4 t lime/ha increased soybean yield from 1.0 to 1.6 t/ha in North Sumatra. In Central Kalimantan, dolomitic limestone seemed to be superior to calcitic limestone (Bogor Agricultural University 1982), very likely because the former contains Mg. Rice failed completely to grow on newly reclaimed ombrogenous inland peat overlying quartz sand in Central Kalimantan even though dolomite, macronutrients, and micronutrients had been added. However, other crops such as corn, soybean, and peats did well (Bogor Agricultural University 1982). The very low base saturation of an ombrogenous inland peat soil in Central

**Table 2. Chemical and physical characteristics of peat from South Sumatra (Bogor Agricultural University 1978).**

| Soil characteristic | Peat from a depth of | | | | |
|---|---|---|---|---|---|
| | 20 cm | 50 cm | 80 cm | 110 cm | 180 cm |
| pH $H_2O$ (1:1) | 4.6 | 4.0 | 3.3 | 3.4 | 3.4 |
| CEC (rneq) | 77.3 | 148 | 165 | 134 | 216 |
| Base saturation (%) | 37.4 | 33.0 | 20.8 | 17.0 | 24.1 |
| Carbon (%) | 26.4 | 39.9 | 50.4 | 50.0 | 53.8 |
| Total N (%) | 1.2 | 1.7 | 1.7 | 1.7 | 1.8 |
| C:N | 22 | 24 | 30 | 29 | 30 |
| P (ppm) | 31.5 | 74.6 | 80.4 | 57.0 | 95.3 |
| Exch. K (meq) | 0.78 | 0.94 | 1.22 | 0.93 | 1.32 |
| Exch. Na (meq) | 2.49 | 2.75 | 1.83 | 0.69 | 3.28 |
| Exch. Ca (meq) | 15.0 | 33.7 | 22.6 | 13.4 | 33.7 |
| Exch. Mg (meq) | 10.6 | 11.4 | 8.75 | 7.82 | 14.0 |
| Exch. Al (meq) | 4.27 | 3.19 | 2.69 | 2.10 | 2.00 |
| Exch. H (meq) | 1.24 | 1.80 | 5.16 | 5.38 | 6.19 |
| Fe ($NH_4OAc$, pH 4.8) (meq) | 4.75 | 0.05 | 0.03 | nd[a] | 0.01 |
| Cu (0.05 *N* HCI) (ppm) | 1.2 | 0.9 | trace | 0.5 | trace |
| Zn (0.05 *N* HCl) (ppm) | 4.8 | 3.8 | 3.8 | 2.3 | 4.3 |
| Ash (%) | 54.7 | 31.3 | 13.3 | 14.0 | 7.41 |

[a] Not determined.

Kalimantan resulted in retarded plant growth (Bogor Agricultural University 1982). However, increasing the base saturation percentage by addition of either mineral soil, peat ash, basic slag, or lime improved plant growth. Peat ash was superior to other materials, but burning peat would deplete this valuable agricultural resource. Peat soils in Berengbengkel (Central Kalimantan) were notorious for their low availability of micronutrients and high sorption capacity for these nutrients. Any plant grown on this kind of soil showed retarded growth and unhealthy leaf color (Bogor Agricultural University 1982). Addition of micronutrients to the soil was ineffective; however, when they were applied to the leaves at rates of 0.25 kg Cu, 0.25 kg Zn, 0.5 kg B, and 0.005 kg Mo/ha, growth and nutrient uptake improved.

**Table 3. Dry matter weight of IR26 rice as affected by "minus one element" conditions, grown on 1l0-cm and 120-cm peats (Bogor Agricultural University 1978).**

| Treatment | Dry matter weight (g/pot) [a] | | | |
|---|---|---|---|---|
| | Grain | | Straw | |
| | 110 cm peat | 120 cm peat | 110 cm peat | 120 cm peat |
| Check | 0.45 | 3.5 | 0.60 | 9.0 |
| Complete | 36.4 | 42.1 | 26.5 | 40.0 |
| –N | 23.3 | 27.6 | 16.2 | 22.1 |
| –P | 32.9 | 38.1 | 29.3 | 35.8 |
| –K | 32.3 | n.t. | 28.3 | n.t. |
| –Ca | 3.8 | 22.3 | 4.9 | 22.2 |
| –Mg | 30.0 | 25.1 | 27.7 | 25.1 |
| –Cu | 22.0 | 15.0 | 24.3 | 17.4 |
| –Mo | n.t. | 35.4 | n.t. | 31.0 |

[a] n. t. = not treated.

## MANAGEMENT

Peat occurs in poorly drained swampy areas and consists largely of plant residues that have not been completely decomposed. Organic debris or raw peat is unsuitable for agriculture, but well-decomposed peat is one of the best soils in the world, provided that water can be controlled effectively. Peat stores large quantities of plant nutrients, especially N, P, and K. The transformation of peat into agricultural soil is basically the change of a potential but unproductive ecosystem into a productive one. There are two opposing forces operating in the agricultural utilization of peats, namely the provision of adequate drainage for optimum crop yield and the maintenance of as high a water table as practical to prolong the life of the peat soil (Notohadiprawiro 1979).

In reclaiming peat for agriculture, the establishment of drainage canals seems to be a prerequisite for the success of crop production (Suryanto et a1 1974). Long before the government began to reclaim these problem soils for transmigrants, traditional farmers used to dig primitive canals on peat before they started growing crops. The purpose of this agricultural measure is to discharge acid surface water and to supply fresh water when the water table is gradually lowered. In other words, the primary objective is controlled drainage (Van Wijk 1951). The canals enhance drainage and leaching, and on the other hand facilitate the supply of plant nutrients during flooding. Drainage also encourages organic matter decomposition, leading to the formation of humus, which is advantageous for plant growth, and to the ready release of plant nutrients (Notohadiprawiro 1979). The drainage canals are also important to remove toxic organic acids, Al, and heavy metals.

The Indonesian Government invests heavily in constructing drainage canals in tidal swamp areas, which include peat soil. Three types of drainage systems have been introduced.

1. Polder system — introduced by Schophuys (1936). It consists of dikes, drainage canals, and irrigation canals. There are also pumps for the supply of water and for drainage.
2. Tidal swamp canalization system. A main canal is constructed between two rivers. It has two tasks, namely irrigation at high tide and drainage at low tide. This type of canal was introduced by Pangeran Mohamad Noor (1958).
3. Fork system. A main canal with two or three branches is constructed perpendicular to the river. The end of a branch canal is connected to a pond, 300 m × 300 m × 1.5 m, the purpose of which is to promote both drainage and supply of water. This system was introduced by Gadjah Mada University (1973).

Traditional farmers often cut the wild vegetation growing on peat and burn it. In so doing, the surface layer of the peat is also burned. After burning, annual crops like maize, cassava, rice, and *Colocasia* are grown. Usually the yields drop sharply after a few years, and the farmer then leaves the field, moving to another peat area and repeating the procedure. Traditional farmers seldom apply fertilizers. This practice of controlled burning of peat undoubtedly has a stimulating effect on plant growth. Kanapathy (1975) states that burning of peat reduces acidity; increases the availability of K, P, Cu, and other elements; and makes N more available indirectly by raising the pH and providing nutrients to microbes to decompose the peat. The increase in availability of nutrients was also mentioned by Polak (1946) and Van Wijk (1951). However, Van Wijk also stated that the mineral nutrients are rapidly exhausted since they are washed out by the abundant quantities of acid peat-water during the rainy season. Burning must therefore be repeated regularly, until finally all the organic matter has beendestroyed and only the physically bad and chemically poor clay soil is left. This method is practiced by the inhabitants of the western part of South Kalimantan.

Burning of peat seems to be beneficial but should be under strict control to prevent the fire from spreading. By keeping the ground water level close to the soil surface with ditches, the fire can be reasonably confined. Burning of peat over a large area may cause loss of nutrients and contaminate the air with smoke. Burned peat is readily blown away by wind or washed out by rain. The disadvantages of burning peat can be much reduced if it is done locally at each respective planting hole. Field demonstrations at Sei Rasau, West Kalimantan (Notohadiprawiro 1979) and Berengbengkel, Central Kalimantan (Bogor University 1982) indicated that, without burning, no crop can be grown on thick peat of over 4 m depth. Miyake (1981) suggested that at least 6 cm of mineral soils is essential for wetland rice cultivation on peat. The addition of clay has the following advantages: agricultural machines can be used more easily; rice seedlings can stand more firmly; the vertical and horizontal permeability of the soil is controlled; water management can be done more easily; the rapid decomposition of organic matter can be lowered; the mineral soil supplies nutrients and increases fertilizer efficiency; and surface soil is prevented from floating.

## FERTILIZER REQUIREMENTS AND SUITABLE CROPS

The productivity of peat soils and its crop performance vary among locations due to such factors as kind and composition of plant material, rate of decomposition, mineral content, availability of drainage water to remove harmful substances, salinity, and supply of nutrients from the surroundings (Driessen and Sudewo, undated; Kanapathy 1975; Polak 1948, 1952; Polak and Soepraptohardjo 1951; Driessen 1978). There are several ways to determine the fertilizer requirements of crops to evaluate productivity of peat soils, namely the use of deficiency or toxicity symptoms, pot tests, plant and soil analyses, and field experiments. Symptoms of nutritional disorders can be very useful as a guide for nutrient requirements. However, they can be misleading, since they can be confused with symptoms of disease. Furthermore, a multiple deficiency is sometimes very difficult to evaluate visually. However, some symptoms are very characteristic and they can be easily identified. Pot tests are another means to study the fertility of peats. “Minus one” tests are very useful in providing information on nutrient status. Plant and soil analyses are methods of studying the nutrient status of crops and soil, and can be a reasonable guide in determining fertilizer requirements. Field experiments are more expensive than the other techniques, but they give reliable information usable by farmers.

In many countries various kinds of crops can be grown on peat when it is properly managed after reclamation (Polak 1948). Rice is grown on peats by Indonesian farmers. Other crops grown on peat observed in West Sumatra and South Kalimantan were soybean, maize, sorghum, cassava, sweet potato, peanut, mungbean, taro (*Colocasia esculenta* L.), eggplant, cucumber, chili, string bean, jackfruit, citrus, rambutan (*Nephelium lappaceum* L,), coconut, clove, coffee, banana, mango, petai (*Parkia speciosa* Hort.), jengkol (*Pithecolobium lobatum* Benth.), sugarcane, pineapple, cashew nut, jambu biji (*Psidium guajava* L.), soursop (*Anona muricata* L.), and bamboo. Pineapple, maize, cassava, and taro are pioneer crops for peats (Kanapathy 1975; Driessen and Sudewo, undated; Polak 1952; Ismunadji, personal observation). Farmers in Sumatra and Kalimantan mention that *Colocasia* spp. is often planted on peat after the clearing of the forests, and that certain varieties seem to adapt better on peat than others.

Maize requires a pH of about 5.0, which can be achieved on acid peats by a combination of liming; burning of wood, roots, weeds, etc.; and distributing the ash (Kanapathy 1975). Fertilizer recommendations in the literature refer to different peat types and are not always in agreement. Recommmended dressings are in the range of 40-200 kg N, 30.6-39.0 kg P, 83.0 kg K, and 30-50 kg $CuSO_4$/ha (Kanapathy 1975, Andriesse 1974, Coulter 1950, Kanapathy and Goh 1970, Polak 1975).

Cassava is distinctly acid tolerant, but liming of very acid peats (pH 3.5) is still essential to get good growth. Cassava has a high nutrient-absorbing power, enabling it to grow on less rich peats, but it yields low if not fertilized (Driessen and Sudewo, undated). Lim et al (1973) reported the failure of cassava on virgin peat with a pH of 3.2, but Chew (1974) found that a pH of 3.6 was still tolerated. Good yields of tubers have been produced on shallow as well as deep peat (Kanapathy 1975). Copper was found to be the only micronutrient deficient in Malaysian peat, while Mn, Zn, Fe, Mo, and B were sufficient. Fertilizing with 10-20 kg $CuSO_4$/ha approximately tripled tuber yield (Chew et al 1978).

Information on rice performance on peat varies considerably. There have been cases where rice could not grow or grew very poorly (Kanapathy 1975, Bogor Agricultural University 1982, Dent 1980), and there are also reports that rice can grow quite well on peat (Polak 1948, Noorsyamsi 1975). In South Kalimantan an average yield of 2.3 t rough rice/ha was produced without any fertilizer application (Noorsyamsi 1975). Rices suffering from nutritional disorders have often been reported (Driessen 1978, Leiwakabessy and Wahyudin 1979, Noorsyamsi and Hidayat 1974); peat fertility seems to be site specific.

Most farmers grow an annual crop of local rice cultivars that have a 9- to 10-month growth duration. They practice the traditional tidal swamp rice culture, transplanting three times. The seeds are first seeded on a dry seedbed at the beginning of the wet season, about 50 seeds/plant hole with 15- × 15-cm spacing. Five kilograms of seeds on a 10-$m^2$ seedbed gives sufficient seedlings for 1 ha. After about 40 days, the seedlings are transplanted for the first time to a low-lying inundated field to strengthen them and to promote tillering. Land preparation for the second transplanting consists merely of cutting the vegetation. The debris is allowed to decompose and is distributed throughout the field. One third of the land area to be finally planted is prepared in this manner. After another 40 days, the seedlings are transplanted a second time, 50 cm apart, 3-4 seedlings/ hill, to promote tillering and to obtain sufficient seedlings for the final transplanting (Noorsyamsi and Hidayat 1974).

Land preparation is done by cutting the vegetation or scraping the soil surface. The debris remains in the field for about 10-15 days. Then the partly decomposed organic matter is collected in little heaps and turned over periodically to hasten decomposition. Finally, the almost entirely decomposed organic matter is distributed throughout the field. Neither plowing nor harrowing is practiced. Before the final transplanting the tops and roots of the 50- to 60-day-old seedlings are partly cut. Plant spacing is usually irregular, and two to three seedlings are planted per hill (Noorsyamsi and Hidayat 1974).

Some farmers have recently begun to plant rice twice a year. The first crop is a high-yielding cultivar like IR32, IR36, IR38, IR42, or IR50, followed by a local cultivar. Soil preparation for the modern cultivar is shallow to prevent the exposure of cat clay, which is very acidic and harmful to the rice plants.

The occurrence of diseases and pests is a major problem on peat. Certain rice diseases are very common, including blast, brown leaf spot, narrow brown leaf spot, sheath blight, leaf blight, panicle blight, and tungro-like disease or “habang” disease (Noorsyamsi 1975, Suryanto et al 1974, Ismunadji and Damanik 1981). *Ustilago virens* was also observed (Satari and Sosromarsono 1979). Recently *Curvularia lunata* was found to be the dominant disease of panicle blight (M. Mukelar 1980, pers. comm., Bogor Research Institute for Food Crops, Bogor, Indonesia); it was also reported that increasing the rate of N application increased blast incidence at the Palembang Rice Estate (Pramono 1980, pers. comm., Palembang Rice Estate, Palembang, Indonesia). Nutritional imbalance such as high N, low K, or low Si is one of the factors responsible for the serious incidence of rice diseases on peat.

The following pests were observed at the Delta Upang Test Farm, Palembang and Gambut district, South Kalimantan: rat, wild pig, stem borer, leaf roller, leaf folder, stink bug, black bug, brown planthopper, mole cricket, *Nezara viridula, Lema oryzae,* gall midge, seedling fly, armyworm, and grasshopper (Noorsyamsi 1975, Satari and Sosromarsono 1979).

Information on the occurrence of pests and diseases of other crops grown on peat is rather scarce.

The “surjan” system has been practiced by farmers in Java for a long time. It consists of dry, raised beds planted with dryland crops and sunken beds planted with rice. Preparing the dry beds prevents inundation by water, which is unsuitable for dryland crop production. The surjan system has recently been introduced in tidal swamp areas, including peat areas. Farmers in South Kalimantan plant annuals as well as perennials on the dry beds. Not only rice but also fish can be cultivated in the sunken beds.

Piling of the soil to make the dry beds removes acids and harmful substances stimulated by the heavy tropical rain showers. It also promotes the decomposition of organic matter and prevents waterlogging. The soil is thus more suitable for crop production, and many farmers now practice this technique.

## REFERENCES CITED

Andriesse, J. P. 1974. Tropical lowland peats in S. E. Asia. Comm. Royal Trop. Inst. Amsterdam 63.

Bogor Agricultural University. 1978. Soil fertility identification in tidal swamp lands of Lagan area, Jambi and Karang Agung area, South Sumatra [a greenhouse experiment]. Tidal swamp land development project. 24 p.

Bogor Agricultural University. 1982. Berengbengkel Test Farm, Central Kalimantan [in Indonesian]. Report, May 1982.

Brady, N. C. 1974. The nature and properties of soils. Macmillan Publishing Co. Inc. New York and Collier Macmillan Publishers, London. 539 p.

Chambers, M. J. 1979. Rates of peat loss on the Upang Transmigration Project, South Sumatra. Third National Symposium on the Development of Tidal Swamp Lands, Palembang, Indonesia, 5-9 February 1979. 7 p.

Chew, W. Y. 1974. Yield of some varieties of tapioca (*Manihot utilisima* Pohl.) grown on Malaysian peat as affected by different planting methods, plant densities, fertilizers and growth period. Mal. Agric. J. 49:392-402.

Chew, W. Y., K. T. Joseph, and K. Ramli. 1978. Influence of soil-applied micronutrients on cassava *(Manihot esculenta)* in Malaysian tropical oligotrophic peat. Exp. Agric. (U.K.) 14:105-112.

Coulter, J. K. 1950. Peat formation in Malaya. Mal. Agric. J. 33:63-81.

Dent, F. J. 1980. Major production systems and soil-related constraints in Southeast Asia. Pages 79-106 *in* International Rice Research Institute. Priorities for alleviating soil-related constraints to food production in the tropics. Los Baños, Philippines.

Driessen, P. M. 1978. Peat soils. Pages 763-779 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

Driessen, P. M., and M. Soepraptohardjo. 1974. Soils for agricultural expansion in Indonesia. Soil Res. Inst. (Bogor) Bull. 1. 63 p.

Driessen, P. M., and P. Sudewo. Undated. A review of crops and crop performance on Southeast Asian lowland peats. Soil Res. Inst. (Bogor) Bull. 4. 94 p.

Driessen, P. M., and H. Suhardjo. 1976. On the defective grain formation of sawah rice on peat. Pages 20-44 *in* Peat and podzolic soils and their potential for agriculture in Indonesia. Proceedings ATA 106 Midterm Seminar, Tugu, 13-14 October 1976. Soil Res. Inst. (Bogor) Bull. 3.

Farnham, R. S., and H. R. Finney. 1965. Classification of organic soils. Adv. Agron. 17:115-162.

Gadjah Mada University. 1973. New canal design for South and Central Kalimantan tidal swamp rice area [in Indonesian]. 29 p.

Gorham, E. 1957. The development of peat lands. Quart. Rev. Biol. 32:145-166.

Ismunadji, M., and M. Damanik. 1981. The nutrient status of tidal swamp rice in Kalimantan and Sumatra, Indonesia. International Workshop on Research Priorities in Tidal Swamp Rice, Banjarmasin, 22-25 June 1981. 8 p.

Kanapathy, K. 1975. Growing crops on peat soils. Ministry of Agriculture and Rural Development, Kuala Lumpur, Malaysia. 64 p.

Kanapathy, K., and A. K. Goh. 1970. Growing maize, sorghum, and tapioca on peat soil. Pages 25-35 *in* Proceedings of the Conference on Crop Diversification in Malaysia.

Leiwakabessy, F. M., and W. Wahyudin. 1979. Peat depth and rice production [in Indonesian]. Third National Symposium on the Development of Tidal Swamp Lands, Palembang, Indonesia, 5-9 February 1979. 13 p.

Lim, C. K., Y. K. Chin, and E. W. Bolle-Jones. 1973. Crop indicators of nutrient status in peat soil. Mal. Agric. J. 49:198-208.

Miyake, M. 1981. Improvement and management of peat soils in Japan. International Symposium on Distribution, Characteristics, and Utilization of Problem Soils. Tsukuba, Japan. 19-26 October 1981. 5 p.

Noor, P. M. 1958. Reclamation of tidal areas for wet rice cultivation. Paper presented at the VIth Congress of the Association of Engineers in Indonesia.

Noorsyamsi, H. 1975. Tidal swamp rice in Gambut district and the possibility for intensification [in Indonesian]. Ir thesis, Faculty of Agric., Lambung Mangkurat Unitersity, Banjarbaru. 67 p.

Noorsyamsi, H., and O.O. Hidayat. 1974. The tidal swamp rice culture in South Kalimantan. Contrib. Central Res. Inst. Agric. Bogor, No. 10.

Notohadiprawiro, T. 1979. Peat deposition — an idle stage in the natural cycling of nitrogen and its possible activation for agriculture. Workshop on nitrogen cycling in Southeast Asian wet monsoonal ecosystems, Chiang Mai, Thailand, 5-9 November 1979.

Polak, B. 1941. Veenonderzoek in Nederlandsch Indie. Landbouw 17:1033-1062.

Polak, B. 1946. Over veenonderzoek in Nederlandsch Indie. Natuurwet. Tijdschr, Ned. Indie 102:63-73.

Polak, B. 1948. Landbouw of veengronden. Landbouw 20:1-50.

Polak, B. 1952. Veen en veenontginning in Indonesia. Indonesian J. Natural Sci. 5/6. (September-December) : 146-160.

Polak, B. 1975. Character and occurrence of peat deposits in the Malaysian tropics. Pages 71-83 *in* Modern Quarternary Research in Southeast Asia, Balkema, Rotterdam.

Polak, B., and Soepraptohardjo. 1951. Pot and field experiments with maize on acid forest peat from Borneo. Contrib. Gen. Agric. Res. Stn. 125 p.

Russell, E. W. 1976. Soil conditions and plant growth. Longman, London, New York. 849 p.

Satari, U. S., and S. Sosromarsono. 1979. Problems of rice pests and management in a tidal swamp area [in Indonesian, English summary]. Third National Symposium on the Development of Tidal Swamp Lands, Palembang, Indonesia, 5-9 February 1979. 9 p.

Schophuys, H. J. 1936. Het stroomgebied van de Barito. Landbouwkundige kenschets and landbouwvoorlichting. Thesis, Wageningen University. 207 p.

Sjors, H. 1965. Surface pattern in Boreal peatland. Endeavor 20:214-224.

Soepraptohardjo, M., and P. M. Driessen. 1976. The lowland peats of Indonesia, a challenge for the future. Pages 11-19 *in* Peat and podzolic soils and their potential for agriculture in Indonesia. Proceedings ATA 106 Midterm Seminar, Tugu, 13-14 October 1976. Soil Res. Inst. (Bogor) Bull. 13.

Soil Research Institute. 1976. Agricultural development prospects of tidal swamp areas [in Indonesian]. Soil Res. Inst. (Bogor) Bull. 8.

Suryanto, S., J. Antap, and H. Moehansyah. 1974. Survey report of transmigration area in Luwak Bunter in Central Kalimantan [in Indonesian]. Directorate of Transmigration and Lambung Mangkurat University, Banjarmasin.

Tamhane, R. U., D. P. Motiramani, Y. P. Bali, and R. L. Donahue. 1970. Soils: Their chemistry and fertility in tropical Asia. Prentice-Hall of India Pty. Ltd., New Delhi. 475 p.

Van der Spek, J. 1950. Katteklei. Verslagen van Landbouwkendige Onderzoekingen, S'Gravenhage 56.2.

Van Wijk, C. L. 1951. Soil survey of the tidal swamp of South Borneo in connection with the agricultural possibilities. Contrib. Gen. Agric. Res. Stn. Bogor 123:1-49.

## DISCUSSSION

SCHARPENSEEL: In your peat classification, you indicated eutrophic peats. Eutrophic soil organic matter is originally correct for forest soils with C:N < 13. Soils with CN <13 should occur mainly in lacustrome or other shallow depressions in base rice (calcareous) environments. Are they farming in the wet tropics as a stable facies or more as a gyttja-like very finely dispersed material?

*ISMUNADJI:* Most of the tropical peat soils are oligotrophic with pH around 3.8, sometimes lower, and low in nutrient content. In its natural condition, i.e., waterlogged, the peat is relatively stable, but rapid decomposition will occur once it is drained.

# RESPONSE OF RICE TO ORGANIC MATTER: THE INDIAN EXPERIENCE

A. C. Gaur

## SUMMARY

Organic matter improves the growth of a rice crop directly as well as indirectly. Organic matter provides considerable macronutrients and micronutrients. The global estimate of plant nutrients from renewable organic materials indicates that about 129 million t of N, P, and K can be recycled in agriculture. Organic manures are valuable products of farming and agroindustries. India has a good potential for use of organic materials, which, if properly recycled, may provide about 18 million t of N, P, and K annually. Humic substances generated during the decomposition of organic materials in soils increase the growth and yield of rice plants. Besides humified farmyard manure (FYM), cereal straw can be utilized in rice culture. The yield of rice was significantly increased due to incorporation of straw in sandy loam soil 1 week before transplanting. In rice - rice and rice - wheat rotation in different agrolimatic conditions, rice showed a significant response to soil application of FYM at 15 t/ ha. The results also showed that the high yielding cultivars responded more markedly to organic manuring than did the traditional cultivars in earlier field trials. Moreover, organic matter was found to play an important role in augmenting the yield of rice crops in salt-affected soils. The results of a few long-term experiments have shown that use of FYM/compost at 10-15t/ha produces a moderate to high response, saves up to 40 kg chemical N/ha, and has a residual effect on the following crop.

The beneficial role of organic matter in improving the physical, chemical, and microbiological properties of soils is well understood (Kononova 1966; Gaur et al 1971, 1973). Organic matter provides considerable major nutrients and micronutrients. That can be advantageous, particularly when mineral fertilizers are scarce and costs are prohibitive for marginal farmers.

Organic manures from plants and animals are valuable by-products of farming and allied industries. Farmyard manures (FYM), rural and urban compost, green manures, and crop residues supply low quantities of major plant nutrients and therefore have to

---

Professor, Indian Agricultural Research Institute, New Delhi-12, India.

be applied in larger doses. Concentrated organic manures such as oil cakes, blood and meat meal, fish meal, guano, and poultry manures contain higher percentages of major plant nutrients. On the average, well-processed FYM contains 0.5% N, 0.1% P, and 0.4% K. Therefore an average application of 25 t farmyard manure/ha supplies 112 kg N, 25 kg P, and 93 kg K. Good compost, on the average, contains about 0.8-1.0% N, and an application of 5 t/ha can provide 40-50 kg N/ha in organic and available form. Organic manures work like slow-release fertilizers. Nitrogen is slow acting, and less than 30% P and 75% K become available to the immediate crop. The rest of the plant nutrients becomes available to the subsequent crop as a residual effect.

Compost is prepared from by-products of farming and organic wastes like leaves, crop residues, roots and stubble, straw weeds, aquatic weeds (water hyacinth), sawdust, and bagasse by the activity of microorganisms. FYM and compost possess the same characteristics. The concentrated bulky manures from sheep and goats contain 3% N, 0.4% P, and 1.7% K. Poultry manure, with 24% moisture, contains 3% N, 2.63% P, and 1.4% K. Oil cakes are rich in N (2.5% in mahua cake and 7.9% in decorticated safflower cakes).

An organic-based agricultural system is particularly attractive to small farmers because most of the organic materials are locally available at no cost or minimum expense. However, labor input is needed for collection and transportation of scattered organic matter.

The major manure resources are:

1. Animal wastes: cattle and buffalo dung and urine, sheep and goat droppings, by-products of slaughterhouse wastes.
2. Crop residues, tree leaves, and aquatic weeds: crop wastes of cereals, legumes, and oilseeds: leaves and stalks of cotton, jute, and trees; sugarcane trash; water hyacinth; seaweeds; and forest litter.
3. Green manures: sannhemp (*Crotalariajuncea*), *dhaincha* (*Sesbaniaaculeata*), clusterbean (*Cyamopsis tetragonoloba*), cowpea (*Vigna catjang*), *Phillipesara* (*Phaseolus trilobus*), etc.
4. Urban and rural compost: urban solid wastes, sewage and sludge, rural compost.
5. Agroindustrial by-products: rice husks and bran; by-products of sugar industry; sawmill wastes; cotton and wool wastes; tea, tobacco, fruit, and vegetable wastes.

## POTENTIAL FOR RENEWABLE ORGANIC RESOURCES AND PLANT NUTRIENTS

The annual Indian potential for organic resources generated through excreta of livestock and human beings and from crop residues, water hyacinth, compost, sewage sludge, and microbial resources and nutrients contained in them has been indicated by Gaur et al (1982). Summarized data on organic resources and the harnessing of atmospheric N are listed in Table 1. The major sources of plant nutrients are cattle and buffalo dung, which show a potential of 5.7 million t of NPK. The next most important resource is night soil, which if properly exploited can provide 4.2 million t of NPK.

**Table 1. Indian potential for organic and biological resources and plant nutrients.**

| Resource | Annual potential (million t) | | | Plant nutrients (million t) | | | |
|---|---|---|---|---|---|---|---|
| | Dung | Urine | Biomass | N | P | K | Total |
| Cattle | 744.6 | 480.1 | – | 2.977 | 0.345 | 1.100 | 4.420 |
| Buffalo | 258.0 | 178.7 | – | 0.745 | 0.121 | 0.404 | 1.270 |
| Goats and sheep | 12.2 | 7.9 | – | 0.214 | 0.028 | 0.017 | 0.259 |
| Pigs | 4.6 | 4.0 | – | 0.044 | 0.012 | 0.024 | 0.080 |
| Poultry | 3.4 | – | – | 0.027 | 0.008 | 0.008 | 0.043 |
| Other livestock | 6.0 | 4.1 | – | 0.079 | 0.008 | 0.053 | 0.140 |
| Human beings | 30.4 | 274.1 | – | 3.228 | 0.341 | 0.593 | 4.160 |
| Crop residues | – | – | 100 | 0.500 | 0.264 | 1.240 | 2.000 |
| Forest litter | – | – | 15 | 0.075 | 0.013 | 0.062 | 0.150 |
| Water hyacinth compost | – | – | 3 | 0.060 | 0.015 | 0.062 | 0.137 |
| Rural compost | – | – | 226 | 1.130[a] | 0.298[a] | 0.938[a] | 2.370[a] |
| Urban compost | – | – | 6 | 0.024 | 0.007 | 0.025 | 0.056 |
| Sewage sludge | – | – | 0.3 | 0.012 | 0.004 | 0.002 | 0.018 |
| Rhizobium | – | – | 7.2–96 × $10^5$ | 1.000 | – | – | 1.000 |
| Nonlegumes | – | – | 3.5 × $10^5$ | 0.150 | | | 0.150 |
| Blue-green algae | – | – | 7.5 × $10^5$ | 0.750 | – | – | 0.750 |
| | | | | | – | – | |
| Total | | | | 11.020 | 1.460 | 4.530 | 17.000 |

[a] Total excludes animal excreta and crop wastes, which are listed separately. Source: Gaur et al 1982.

Residues are important renewable organic resources and are readily available to farmers. About 200 million t of straw are produced annually, with 5 major crops — rice, wheat, sorghum, maize, and pearl millet — together generating about 173 million t. About 51 million t of this come from rice straw alone. Sugarcane trash (16 million t) is another major residue. In India the bulk of straw is used as cattle feed. Bhumbla (1980) estimated that 85 million t of farm wastes are available for composting. Adding other surplus wastes such as sugarcane trash and rice straw, the potential of crop residues can be estimated to be about 100 million t annually for recycling in agriculture. Theestimated NPK nutrient potential of these crop residues is 2 million (Table 1).

Water hyacinth is a nuisance and has a total area of about 292,000 ha throughout India. It can be used as compost, green manure, or soil mulch. It can contribute an estimated 0.14 million t of NPK (Table 1). Rural and urban composts are widely used by Indian farmers, and the 6 million t of urban compost produced during the current year can add about 0.06 million t of major plant nutrients.

Among the agroindustrial wastes, rice husk/bran, bagasse/press mud, and cotton and wool dust contribute around 35 million t annually. Other nutrient-rich organic materials like oil cakes, slaughterhouse wastes, and marine industry wastes are also in sizable quantities.

The most important microbial resources are *Rhizobium,* blue-green algae, and N-fixing organisms associated with cereals. The estimate indicates that the

*Rhizobium* in association with legume plants can fix about 1 million t of atmospheric N/year whereas blue-green algae, if properly exploited, can fix about 0.75 million t of N in rice fields. The other contributors are nonsymbiotic N-fixing bacteria like *Azotobacter* sp. and *Azospirillum* sp, which can fix about 20 kg N/ha.

The rock and insoluble phosphate dissolving bacteria and fungi such as *Pseudomonas striata, Bacillus polymyxa, Aspergillus awamori,* and *Penicillium digitatum,* which were isolated at the Indian Agricultural Research Institute (IARI), have shown promise in mobilizing native soil P and making it available to the plants during their growth. Recent studies have shown that low-grade rock phosphate can also be used as P fertilizer in neutral and alkaline soils if seeds or seedlings are treated with these promising cultures before sowing. If this technology is properly exploited, it can help in better utilization of this nonrenewable resource and save an appreciable amount of superphosphate (Gaur and Singh 1982).

## EFFECTS OF RECYCLING ORGANIC RESIDUES ON SOIL FERTILITY AND YIELD

Plant residues cover a broad spectrum of C forms. The following substrates, in the approximate order of biodegradability, commonly occur: soluble sugars, proteins, hemicelluloses, cellulose, lipids, and lignins. The predominant straw substrate for microorganisms are cellulose, hemicellulose, and lignin. The incorporation of C and N in the soil and the formation of humus are important for conservation of C and N. Simultaneously there are losses of gaseous $CO_2$, $CH_4$, $NO_2$, and $N_2O$, and leaching losses of $NO_3^-$. Much of the N in crop residues is in organic form; thus the rate of mineralization becomes the rate-limiting step for all the changes that follow. In the context of pollution, the rate of $NO_3^-$ production assumes considerable importance, as does denitrification.

### Conservation of N

Generally, mature crop residues do not contain sufficient N to meet the needs of a zymogenous population; hence net N immobilization occurs in the initial stages of decomposition (Gaur et al 1973, Mukherjee and Gaur 1980). This phase is temporary, and within a few days to weeks, when available C is depleted, net mineralization occurs. At a C-N ratio greater than 25:1, less and less N is available for plant growth. Nitrogen is thus conserved during the C mineralization process.

### Transformations of wheat straw and farmyard manure in soil

Mukherjee and Gaur (1980) reported that wheat straw application to microplot soil at three different rates (2,5, and 10 t/ha) 2 times at 3-month intervals increased the total organic C, humin C, humus C, and total N content of the soil. The increase depended on the amount of straw added. Addition of straw caused N immobilization during the first month, but the content of available N increased by the end of the second month. Humus C decreased in the check and with the lowest rate of straw application. The higher rates (5 and 10 t/ha) were able to maintain the humus C content of the soil. The increase in humin C with higher rates of straw application may be due to greater amounts of humus synthesized and possibly to the interaction of humus with clay particles, resulting in the formation of clay-humus complexes. The addition of straw increased the available soil P; a maximum increase of 20 ppm was recorded in the treatment with 10 t straw/ ha; 11.4 ppm was recorded in the 5 t straw treatment and 5.6 ppm in the control. The population of *Azotobacter* and anaerobes growing on a N-free medium were greater in the straw treatments. The stimulatory effect of straw was greater on anaerobic N-fixing organisms.

### Effects of incorporation of straw and farmyard manure on rice yield

The effects of incorporation of wheat straw and FYM in sandy loam alluvial soil on the changes in the organic and N fractions, on N uptake by rice, and on yield were investigated by Gaur and Mukherjee (unpublished). Chemical analysis of the soil follows: sand 65%, silt 15%, clay 20%, organic C 0.450%, total N 0.045%, available P 13.3 ppm, and pH 7.6.

Percentage of C, total percentage of N, and C-N ratio were 22.0, 1.1, and 20.0 for FYM and 44.0, 0.6, and 73.3 for wheat straw.

The check plots received only a basal dosage of 120 kg N/ha as $(NH_4)_2SO_4$ and 26 kg P/ha as superphosphate. The second and third treatments consisted of a basal application of N and P plus FYM or wheat straw at 0.5% (wt/wt). The required amounts of fertilizer and organic matter were incorporated in the 0- to 15-cm layer and were allowed to decompose for a week; then rice seedlings (Pusa 2-21) were transplanted. Soil samples were drawn at transplanting, tillering, and immediately after the harvest of the rice crop and were analyzed for organic C, forms of N, and available P. Rice yield was recorded after harvest.

Organic amendments increased the total C, humin C, and humus at all three samplings. The increase was more apparent with FYM. FYM, already stabilized organic matter, gets slowly mineralized in the soil and persists for a longer period than straw (Gaur et al 1970, 1971; Debnath and Hazra 1972). Likewise, the total N content of the soil was augmented by organic matter addition. Nitrogen immobilization in the straw treatment was noticed only in the soil sample collected after 1 week of decomposition; no such problem was seen in the samples obtained at tillering and after harvest, showing that a fair decomposition of straw had taken place before tillering and that the available N was in excess of the microbial demand. The available soil P was augmented due to application of FYM.

Compared to the check, grain and straw yields of rice increased by 41.2 and 26% with FYM application and by 25.5 and 11.0% with straw application (Table 2). Similarly N uptake by the crop was greater with organic matter treatments, but the FYM proved better than straw application in increasing rice yield.

**Table 2. Effect of organic matter on the yield and nitrogen uptake of rice,**

| Treatment | Grain yield (t/ha) | Straw yield (t/ha) | Uptake of N by grain (kg/ha) |
|---|---|---|---|
| Check | 4.45 | 5.54 | 42.3 |
| 0.5% farmyard manure | 6.28 | 6.69 | 66.6 |
| 0.5% wheat straw | 5.58 | 6.16 | 54.7 |
| C.D. at 5% level | 0.51 | 0.52 | |

## Humus level and rice yield

Humic substances contained in organic matter play an important role in improving the growth of crops and in the uptake of nutrients, particularly N (Gaur 1978). The effect of humus substances extracted from FYM on the growth and yield of rice (IR8) in pots (Mathur and Gaur 1977) was studied. The required amount of humus (humic and fulvic fractions) was added to 10 kg alluvial soil and was mixed thoroughly. A basal dressing of 112 kg N as $(NH_4)_2SO_4$, 40 kg P as superphosphate, and 37 kg K as muriate of potash/ ha was applied. A soil-based composite blue-green algal inoculum *(Tolypothrix tenuis, Aulosira fertilissima, Nostoc sp.,* and *Cylindrospermum muscicola)* was used after transplanting. The crop was frequently irrigated to maintain waterlogged conditions.

The application of humus substances significantly increased the grain and straw yields of rice over checks (Table 3). Humus at 0.05% increased the grain yield by 85% and lower levels (0.025 and 0.005%) augmented the grain yield by 56 and 34%, respectively. The highest dose of humus (0.05%) plus blue-green algae inoculation showed the maximum grain yield of 165%.

A progressive increase in N uptake by grain and straw was observed with the increasing levels of humus. The results showed that efficiency of nitrogenous and algal fertilizer was augmented in the presence of humus substances.

## Effect of organic matter on rice yield in multilocational trials

The response of crops to organic matter depends on several factors: degree of decomposition and C-N ratio, time of application, soil characteristics, and moisture regime during the growth period of the crop.

The major organic materials used in rice production are FYM, compost, green manures, and cereal straw. Numerous experiments have been carried out at various research stations in India to study the response of crops to organic manures. The main results obtained with different types of organic materials have been reviewed by Gaur et al (1982) and Gaur (1982). A good deal of agronomic research on the response of food crops under varied soil and agronomic conditions has been done in the All India Coordinated Agronomic Reseach Project.

**Table 3. Effect of humus on yield and nitrogen uptake of rice in pots.**

| Treatment | Grain | | Straw | |
|---|---|---|---|---|
| | Yield (g/pot) | N uptake (mg) | Yield (g/pot) | N uptake (mg) |
| Check | 9.95 | 102.9 | 19.2 | 74.3 |
| Humus 0.005% | 13.37 | 150.4 | 21.2 | 78.2 |
| Humus 0.025% | 15.50 | 195.3 | 22.3 | 90.3 |
| Humus 0.05% | 18.45 | 224.5 | 25.5 | 100.9 |
| Algae | 22.15 | 215.2 | 28.9 | 98.8 |
| Algae + humus 0.005% | 24.72 | 266.9 | 29.8 | 107.2 |
| Algae + humus 0.025% | 24.82 | 268.0 | 29.6 | 114.5 |
| Algae + humus 0.05% | 26.40 | 308.8 | 36.7 | 128.8 |
| C. D. at 5% | 7.61 | 84.6 | 8.85 | 28.2 |

The summarized results of rice experiments in several states of India show that the response to application of 12.6 t FYM or compost/ha varied from about 0.10 t rice/ ha in Maharashtra and Bihar States to 0.22 t/ha in Orissa. The average response, based on 341 experiments in more than 63 research stations, was 0.17 t/ha.

## Effect of FYM on rice in a fixed crop rotation

To study the direct, residual, and cumulative effects of farmyard manure on a fixed, single-year crop rotation, rice - rice and rice - wheat experiments were conducted in the ICAR Coordinated Agronomic Research Project. Treatments included 2 levels of FYM (0 and 15 t/ha) in 3 phases over a basal dressing of 100 kg N/ha to each crop. Some results obtained are discussed here.

### RICE - RICE ROTATION

The trials conducted at Tirupati (Andhra Pradesh) from 1972 to 1975 showed that application of FYM every season was beneficial, giving an annual response of 0.48 t/ha. During the same period, rice response to FYM at Mangalore (Karnataka) was spectacular. FYM applied to soil in kharif increased rice yield by 1.84 t/ha. Application in every season further increased the annual rice yield by about 0.41 t/ha. In 1975-76, the response of kharif rice was 1.04 t/ha when FYM was applied in rabi only. The response of rabi rice was 1.15 t/ha when FYM was applied every season. In 1976-77 the response of kharif rice was 1.61, 0.62, and 1.20 t/ha and the response of rabi rice was 1.45, 0.72, and 1.52 t/ha when FYM was applied during both seasons, in kharif only, and in rabi only, respectively. During 1978-79, the rice yield responses to 15 t FYM/ha applied in kharif and rabi were 1.25 t/ha and 1.46 t/ha, respectively.

Application of FYM in every season at Karamana (Kerala) gave an annual response of 0.88 t/ha from 1972 to 1975. In 1975-76 the response was 0.67 t/ha in kharif rice when FYM was applied in rabi only.

At Bhubaneswar (Orissa) during 1976 kharif, responses of rice to FYM were significant (0.54, 0.28, 0.42 t/ha) when FY M was applied every season, during kharif only, and during rabi only, respectively. In rabi, rice responses were 0.39, 0.48, and 0.57 t/ha, respectively. During 1978-79 the response was less marked: at Chiplima a response of 0.63/rice/ha was reported during rabi when FYM was applied in both seasons and 0.71 t/ha in rabi when it was applied during rabi only.

At Karairuppea (Tamil Nadu), the annual responses of rice to FYM, when averaged over 3 years (1971-74), were 0.40, 0.18, and 0.28 t/ha when FYM was applied in both seasons, in kharif only, and in rabi only, respectively. In 1975-76, the response was better when FYM was applied in rabi only, the yield of kharif rice being 0.30 t/ha and that of rabi rice 0.24 t/ha. The response of rice to FY M was poor in the coastal alluvium soil of Thanjavur.

### RICE - WHEAT ROTATION

Trials were conducted at four stations of Uttar Pradesh from 1969 to 1977.

The 1970-73 trials at Varanasi showed that application of FYM at 15 t/ha was significantly effective in the rabi crop of wheat only. When averaged over 3 years, a response of 0.5 t/ ha of total grain yield was obtained when FYM was applied in both seasons. In 1975-76 responses of 0.81, 0.68, and 0.9 t/ ha were observed in rice crops in different series, while the response was meager in wheat in 1975-76. In 1975-76 responses of rice to FYM were moderate, ranging from 0.29 to 0.49 t/ ha in different series; in wheat crops responses were fairly high: 0.42, 0.59. and 0.70 t/ ha in different series.

The 1969-73 trials at Bichpuri (agra) revealed that application of FYM was significantly effective in both rice and wheat crops. When averaged over 4 years, the total grain yield of the two crops increased by 0.90 t/ ha when FYM was applied in both seasons. This decreased by one-third when FYM was applied in only one season, kharif or rabi.

At Masodha, the 1972-75 trials showed that the total response of annual grain yield to FYM when applied during rabi only was in the order of 1.25 t/ ha. The additional response was only 0.11 t/ ha when FYM was applied in both seasons. In 1975-76 a direct response of 0.82 t/ ha was found for the wheat crop. In I976 kharif rice, responses to FYM were 0.66 t/ ha with application in kharif only and 0.81 t/ ha with application in rabi only; in 1976-77 rabi, the wheat response in different treatments ranged from 0.26 to 0.42 t/ ha.

At Pura Farm, the 1975 rice crop and the 1975-76 wheat crop responded with 0.52 and 0.45 t/ ha when FYM was applied in rabi only. The trend of results was similar in the 1976-77 responses of 0.36 t/ ha in rice and 0.29 t/ ha in wheat when FYM was applied in rabi only.

At Madhya Pradesh, trials were conducted from 1969 to 1977 at Kathulia Farm, Raipur, and Jabalpur. At Kathulia Farm, FYM was found effective in stepping up the yield of rice as well as that of wheat. The total annual grain yield (average of 4 years, 1969-73) increased by 0.82, 0.47, and 0.44 t/ha with application of FYM in both seasons, in kharif only, and in rabi only, respectively.

The data of the 1971 to 1974 trials at Raipur showed that application of FYM during kharif only was adequate and increased the annual grain yield by 0.92 t/ ha. In 1976-77 the response was in the order of 1.08 t/ ha in rice and 0.79 t/ ha in wheat when FYM was applied in rabi only.

The data of the 1972 to 1975 trials at Jabalpur brought out that the total response of the annual grain yield to FYM when applied in kharif only was 1.71 t/ ha. An additional response of 0.26 t/ ha was obtained when FYM was applied in both seasons.

## Response of rice to organic matter in salt-affected soils

The application of various types of organic matter is a very useful practice for reclamation of salt-affected soils. Besides providing a source of plant nutrients and a source of energy for microorganisms, organic matter influences the physical condition of soils favorably, counteracting the unfavorable effect of exchangeable Na. The decomposition products of plant residues and cattle manures such as $CO_2$ and organic acids dissolve any insoluble Ca salts in the soil solution and neutralize the alkali present. The decomposition of organic matter improves soil permeability, and the response of zymogenous groups of microorganisms helps to build up more water-stable aggregates.

Various organic materials such as FYM, compost, green manures, molasses, press mud, rice straw, crop residues, and different weeds, particularly *Argemone mexicana,* have been used in salt-affected soils. Some of the results are summarized below.

Application at 22.2 t/ha of FYM and green manure to highly sodic soil doubled the yield of rice in Uppal in 1955 (Table 4). Rice response was highest with green manure (*Sesbania* sp.).

The results of trials in alkali soils at Kamma (Punjab) from 1956 to 1959 (Table 5) showed high rice response to FYM applied annually at 38.2 t/ha and a pH decrease from 9.7 to 9.4 (Kanwar and Bhumbla 1961).

In other trials with alkali soils FYM applied to 10.2 t/ha together with *Sesbania* green manure at 13.9 t/ha proved superior to green manure alone at 27.7 t/ha (Singh 1959).

Dargan et al (1971) reported that in the first crop of rice grown in alkali soil having pH 10.6 and above, there was a high order of interaction in the combined application of FYM and gypsum (Table 6). The maximum increase in yield of rice was obtained

**Table 4. Response of rice in sodic soil to organic matter at 22.2 t/ha**

| Treatment | Yield (t/ha) |
|---|---|
| Check (leaching) | 1.31 |
| Press mud | 1.83 |
| Farmyard manure | 2.68 |
| *Sesbania* | 2.91 |

**Table 5. Response of rice to farmyard manure at 38.2 t/ha**

| Year | Rice yield (t/ha) | Response |
|---|---|---|
| 1956 | 0.18 | 0.14 |
| 1957 | 0.80 | 1.18 |
| 1958 | 0.96 | 1.31 |
| 1959 | 2.47 | 0.44 |

**Table 6. Yield of rice due to farmyard manure (FYM) and gypsum at CSSRI, Karnal (Haryana), India.**

| Treatment | Yield (t/ha) |
|---|---|
| Check | 2.45 |
| FYM at 25 t/ha | 3.59 |
| FYM at 50 t/ha | 3.74 |
| Gypsum at 25% G.R. | 4.23 |
| FYM at 25 t/ha + 25% GR | 5.29 |
| FYM at 50 t/ha | 5.46 |
| Gypsum at 50% GR | 5.70 |
| FYM at 25 t/ha + 50% GR | 5.76 |
| FYM at 50 t/ha + 50% GR | 6.89 |

**Table 7. Residual and cumulative effects of farmyard manure (FYM) on rice and berseem fodder yields at CSSRI, Karnal, India.**

| Treatment | 1971 rice yield– (t/ha) | 1971-72 berseem yield (t/ha) |
|---|---|---|
| No FYM | 7.05 | 0.88 |
| FYM at 25 t/ha | 7.85 | 4.18 |
| FYM at 50 t/ha | 8.35 | 14.5 |

with FYM at 50 t/ha plus gypsum (50% GR). The effect of FYM added to the first crop of berseem *(Trifolium alexandrinum)* was significant on succeeding crops of rice and berseem (Table 7). In the same fixed layout. there was no subsequent response to FYM in rice (1972) and berseem (1972-72), indicating that the residual effect was evident in one or a maximum of two seasons.

## Organic matter and fertilizer-use efficiency

Sahu and Nayak (1971) reported the results on wetland rice of a long-term experiment from 1956 to 1965 with continuous application of $(NH_4)_2SO_4$ alone and in combination with organic manure — FYM, green manures, and groundnut cake — to a sandy loam lateritic soil of Bhubaneswar, Orissa. The mean grain yield data are presented in Table 8. Application of organic manure at 45 kg N/ha gave a yield equal to that obtained with 67.5 kg N/ha as $(NH_4)_2SO_4$. The highest yield of 2.67 t/ha was obtained with 45 kg N/ha as $(NH_4)_2SO_4$ in combination with a dressing of FYM to supply 45 kg N/ha; it showed a response of 0.52 t/ha over the control (2.15 t/ha). The results indicate the complementary role of organic and inorganic fertilizers.

Shinde and Ghosh (1971) conducted field experiments on the manurial requirements of a fixed crop rotation of rice-gram from 1955 to I967 at Bagwai in Madhya Pradesh. They studied the effect of continuous use of FYM and fertilizers on the yield and fertility status of the medium black soil. Application of FYM at 5.6 t/ha significantly increased the rice yield and resulted in significant increase in organic matter and available P in the surface layer.

**Tablee 8. Grain yield of rice due to organic and inorganic manures. Bagwar, Madhya Pradesh, India, 1955-67.**

| N level (kg/ha) | Yield without organic manure (t/ha) | Yield (t/ha) with basal dressing of 45 kg N/ha [a] | | | Mean yield (t/ha) |
|---|---|---|---|---|---|
| | | FYM | GM | GNC | |
| 8 | 2.15 | 2.44 | 2.51 | 2.48 | 2.38 |
| 22.5 | 2.34 | 2.47 | 2.40 | 2.36 | 2.39 |
| 45.0 | 2.36 | 2.67 | 2.50 | 2.39 | 2.48 |
| 67.5 | 2.41 | 2.40 | 2.27 | 2.18 | 2.31 |
| 90.0 | 2.23 | 2.28 | 2.02 | 2.20 | 2.18 |
| Mean | 2.30 | 2.45 | 2.34 | 2.32 | |

[a] FYM = farmyard manure, GM = green manure, GNC = groundnut cake.

**Table 9. Grain yield of rice due to organic and inorganic manures. CRRI, Cuttack, India, 1967-73.**

| N level (kg/ha) | Grain yield t/ha | |
|---|---|---|
| | Without compost | With compost providing 80 kg N/ha |
| 0 | 4.13 | 4.54 |
| 40 | 4.59 | 4.97 |
| 80 | 4.89 | 5.04 |
| 120 | 4.84 | 4.83 |
| 160 | 4.77 | 4.76 |
| Mean | 4.64 | 4.83 |

Padalia (1975) reported the results of long-term experiments on a high yielding cultivar of rice conducted at CRRI, Cuttack, from 1967 to 1973. Compost at 0 to 80 kg N/ha was tested with and without inorganic N as $(NH_4)_2SO_4$. Seven years' mean grain yields of rice are presented in Table 9. The response of rice to compost alone to supply 80 kg N/ha was 0.41 t/ha; the increase over the check was thus about 10%, comparable to that from 40 kg N as $(NH_4)_2SO_4$.

## REFERENCES CITED

All India Coordinated Agronomic Project Annual Reports, ICAR, New Delhi.

Bhumbla, D. R. 1980. Paper presented in India/FAO/Norway seminar on maximising fertilizer use efficiency, held at Delhi, September 1980.

Dargan, K. S., B. L. Gaul, and I. P. Abrol. 1971. Annual report, CSSRI, Karnal. 68.

Debnath, N. C., and J. M. Hazra. 1972. Transformation of organic matter in soil in relation to mineralization of carbon and nutrient availability. J. Ind. Soc. Soil Sci. 20:95.

Gaur, A. C. 1978. Proc. India/FAO/Norad Seminar on the development of complementary use of mineral fertilizers and organic materials in India, New Delhi. 109-126.

Gaur, A. C. 1979. Organic recycling-prospects in Indian agriculture Fert. News 24:49-61.

Gaur, A. C. 1982. Review of soil research in India. Part 1. 12th International Congress of Soil Science, New Delhi. 278-305.

Gaur, A. C., R. S. Mathur, and T. N. Varshney. 1970. Decomposition of different types of added organic matter in soil. Agrochemica 14:524-532.

Gaur, A. C., K. V. Sadasivam, O. P. Vimal, and R. S. Mathur. 1971. A study of the decomposition of organic matter in an alluvial soil, $CO_2$ evaluation, microbiological and chemical transformations. Plant Soil 35:17-28.

Gaur, A. C., K. V. Sadasivam, O. P. Vimal, R. S. Mathur, and S. K. Kavimandan. 1973. Studies on the humification of organic matter in red rakar soils. Zbl. Bakt. Abt. II 128:149-161.

Gaur, A. C., and R. Singh. 1982. Integrated nutrient supply system. Fert. News 27:87-98.

Gaur, A. C., S. Neelakantan, and K. S. Dargan. 1982. ICAR Bulletin in Organic Manures (in press).

Kanwar, J. S., and D. R. Bhumbla. 1961. Annual progress report of the scheme on reclamation of saline alkali soils in the Punjab. Ludhiana (unpublished).

Kononova, M. M. 1966. Soil organic matter, its nature, its role in soil formation and in soil fertility. Pergamon Press, Oxford.

Mathur, R. S., and A. C. Gaur. 1977. Effect of humus and microbial inoculants on crop yields and nitrogen uptake. Mikrobiologiya 46:149-154.

Mukhejee, D., and A. C. Gaur. 1980. A study on the influence of straw incorporated on soil organic matter maintenance, nutrient release, and symbiotic nitrogen fixation. Zbl. Bakt. II Abt. 135:663-668.

Padalia, C. R. 1975. Effect of N, P, and K fertilizer with and without organic manures on a high-yielding variety of rice. Oryza 12:53-58.

Sahu, B. N., and B. C. Nayak. 1971. Soil fertility investigation under continuous application of ammonium sulphate alone and in combination with the organic manures in the Bhubaneswar long-term fertility trial. Proceedings of the International Symposium on Soil Fertility Evaluation 1:873-879. New Delhi, Indian Society of Soil Science.

Shinde, D. A., and A. B. Ghosh. 1971. Effect of continuous cropping and manuring on crop yield and characteristics of a medium black soil. Proceedings of the International Symposium Soil Fertility Evaluation. 1:905-916. New Delhi, Indian Society of Soil Science.

Singh, S. 1959. Studies in the cost of reclamation of alkali lands. Rep. Ind. Council Agric. Research Scheme. 1953-69. New Delhi (unpublished).

# MANAGEMENT AND EVALUATION OF ORGANIC MANURES IN RICE-BASED FARMING SYSTEMS

# ORGANIC MANURES IN INTENSIVE CROPPING SYSTEMS

Kanok Rerkasem and Benjavan Rerkasem

Organic manures play an important role in maintaining soil fertility under intensive cropping systems. Current and potential problems include rapid depletion of plant nutrients, specific problems of rice-based cropping systems, and management problems concerning the short turnaround time. The management of crop residues and animal manures in intensive cropping systems is examined.

From a holistic view, the recycling of organic matter can occur within and between farms as well as within and between other hierarchical levels of an agroecosystem. Farm management practices and decisions sometimes influence these interactions.

Multiple cropping is a widespread practice in traditional agriculture. The two major patterns of multiple cropping are intercropping and sequential cropping; each is a form of intensification. Sequential cropping is intensification in time; cropping intensity increases with the number of crops grown in succession in a field in a year. Single, double, and triple cropping denote one, two, and three crops per year, respectively. Intercropping is intensification in both time and space; two or more crops are grown simultaneously in the same field. In many systems of traditional agriculture, highly complex forms of mixed cropping involving several crops are often practiced in fields of shifting cultivation (Okigbo and Greenland 1976). In these situations the maintenance of soil fertility is achieved through long periods of fallow. Although intensity may be great at a particular point in time, over the long run these cropping systems are less intensive than a one-crop-a-year monoculture. However, in many of the traditional agricultural systems in the tropics, intensive cropping systems have become necessary because of the limitation of arable land. Organic manures have played a most prominent role in maintaining soil fertility in these systems.

---

Multiple Cropping Project, Faculty of Agriculture, Chiang Mai University, Chiang Mai, Thailand.

## SOIL PROBLEMS IN INTENSIVE CROPPING SYSTEMS

Farmers in traditional systems of agriculture know that long-term productivity of the soil may decline as cropping systems become more intensive unless efforts are made to maintain soil fertility. Organic manures have been the major input used to maintain soil fertility partly because they are readily available in many primitive systems of agriculture. Also, organic manures have the potential to correct several soil problems at the same time: they may supply organic matter, create favorable air and water regimes around the plant roots, and act as carriers of some micronutrients (Russell 1973).

### Nutrient depletion

In a single season the amount of various nutrients taken up by a crop is considerable. For example, Table 1 shows the amounts of nutrients removed by a crop that yielded 7.9 t rough rice/ha and 7 t straw/ha (De Datta 1981). The amounts removed from farmers' fields at lower yield levels are somewhat less (Table 2).

Without fertilizer application, biological N fixation is the primary contributor to the N balance in wetland rice and legumes. For other nutrients the only source of replacement is mineralization of clay minerals and also sedimentation in alluvial soils. In the Chiang Mai Valley of northern Thailand, the rice yields have appeared sustainable with the increase in cropping intensity to a double cropping system of rice - soybean since the end of the 1960s (Gypmantasiri et al 1980) with little fertilizer application. A further intensification to a triple cropping system of rice - soybean - rice in limited areas has begun to show reduction in the yield of the first rice crop. However, when the third crop is one of the modern cultivars like RD1 or RD7 and is fertilized with N, P, and K, yields have remained stable. The first crop, a traditional glutinous rice, is not normally fertilized; yield reduction in this crop has been reported to be as much as half of the normal yield obtained in a double cropping system of rice - soybean (A. Ganjanapan, pers. comm.). But there was no yield reduction when the first crop was occasionally RD7, which normally receives application of N, P, and K.

**Table 1. Nutrients removed by a single rice crop, Philippines, 1981 (De Datta 1981).**

| Element | Amount (kg/ha) |
|---|---|
| N | 123 |
| P | 21 |
| K | 120 |
| Ca | 31 |
| Mg | 27 |
| S | 13 |
| Fe | 1.7 |
| Mn | 4.4 |
| Zn | 0.29 |
| Cu | 0.06 |
| B | 0.09 |
| Si | 634 |
| Cl | 25 |

**Table 2. Yield and nutrient uptake by different crops from farmers' fields.**

| Crop | Harvested yield (t/ha) | Nutrient uptake[a] (kg/ha) | | | | |
|---|---|---|---|---|---|---|
| | | N | P | K | Ca | Mg |
| Rice (Boonduang and Thodey 1974) | | | | | | |
| Grain | 2.41 | 26 | 8 | 6 | 2 | 3 |
| Straw | 3.81 | 16 | 76 | 3 | 14 | 7 |
| Total | 6.23 | 42 | 84 | 9 | 16 | 10 |
| Soybean (deMooy et al 1973) | | | | | | |
| Grain | 2.60 | 164 | 45 | 16 | 7 | 8 |
| Straw | 1.80 | 42 | 18 | 3 | 111 | 66 |
| Total | 4.40 | 206 | 63 | 19 | 118 | 74 |
| Chili pepper (Kibreab 1980) | | | | | | |
| Fresh fruit | 5.97 | na | na | na | na | na |
| | (3.35 | 25 | 31 | 5 | na | na)[b] |
| Dry matter | 8.20 | 258 | 185 | 34 | na | na |
| Tobacco (Martin et al 1976) | | | | | | |
| Leaves | 2.00 | 32 | 33 | 35 | 50 | 52 |

[a] na = not assayed. [b] Fruit harvested in 120 days.

Sequential cropping involves the accentuation of nutrient removal; double and triple cropping mean that the amount of nutrients removed each year will be two or three times that under single cropping. One advantage of mixed cropping most often cited is the increase in water and nutrient uptake efficiency with the use of different crop species and genotypes; Sanchez (1976) reviewed many reports that substantiated this.

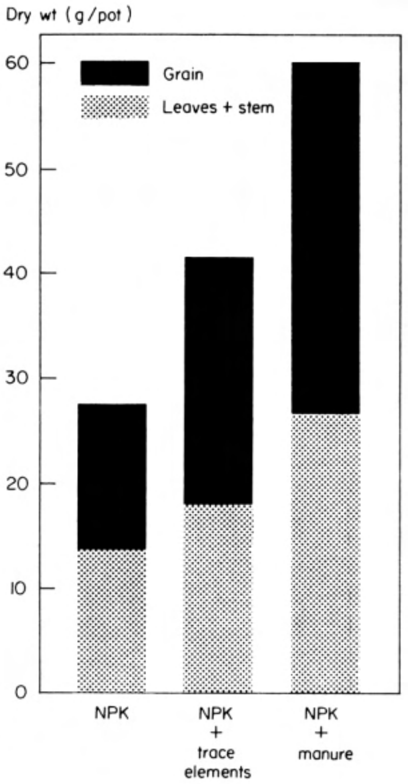
Data on the removal of nutrients other than N, P, and K are less commonly available; but depletion of these nutrients can pose a serious problem in intensive cropping systems. In many developing countries, the use of N, P, and K fertilizers has become more common in the last 20 years. Increased productivity resulting from their use, coupled with increased cropping intensity, has tended to bring about the deficiency of the other elements.

In the Chiang Mai Valley, where cropping intensity of mainly sequential systems has been increasing steadily over the last 20 years, the problem of yield decline has been observed both in farmers' fields and in a long-term experiment (Gypmantasiri et al 1980, Rerkasem and Gypmantasiri 1981). The problem appears to be related to several factors, one of which is quite likely to be the trace element nutritional status of the soil.

A pot experiment showed that, given sufficient N, P, and K, both dry matter and grain yield of wheat were significantly increased with application of trace elements, including Zn, B, Cu, and Mg. However, an application of animal manure increased yields even more effectively (Fig. 1).

## Rice-based cropping systems

Rice-based cropping systems involving wetland rice and dryland crops are somewhat of an anomaly. The soil and water management requirements for wetland rice are opposite those for dryland crops. Nevertheless, rice-based systems are widespread in rice-growing areas of Asia.

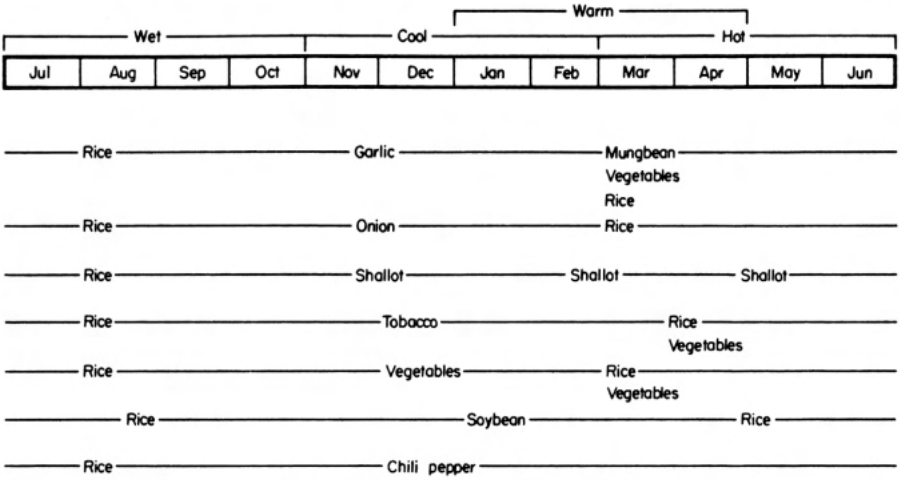


**1.** Effects of trace elements (Zn, B, Cu, and Mg) and organic manures on total dry matter and grain yield in wheat (P. Srikaew and B. Rerkasem, unpublished results).

Irrigation, a key to intensification, has been traditionally associated with the cultivation of wetland rice. In the Chiang Mai Valley irrigation systems, some cropping systems dating from before 1200 A.D. were originally designed to control water for the wet-season rice crop. Some of the larger systems, mainly river or stream diversions, also provide water for a wide range of dry-season cropping (Fig. 2).

Numerous publications have described the changes that occur in soils under wetland rice cultivation (Ponnamperuma 1965, Russell 1973, Sanchez 1976, Moormann and van Breeman 1978, IRRI 1978, De Datta 1981). Only a few papers deal with the changes that occur after the soil is drained.

*Physical changes and puddling.* The physical changes that occur in soil upon flooding include the swelling of soil particles, reduction in aggregate stability, and lowered permeability (Russell 1973, Sanchez 1976, De Datta 1981). These are further accentuated by puddling, the process of applying mechanical force to the soil at high moisture content to break down soil aggregates into a uniform mud (Sanchez 1976). Pore spaces are either destroyed or blocked, and water seepage is minimized. When the soil is allowed to dry out toward harvest time, the original soil structure may be regenerated, but this is largely dependent upon the soil type. Harwood (1975) suggested that the possibility of growing dryland crops in rice-based systems depends on soil texture, water status, and tillage capacity. Large increases of 4-12%



**2.** Climate and intensive cropping systems in the Chiang Mai Valley, northern Thailand. Planting time of the crop is denoted by the beginning of its name in the figure.

in soil bulk density as a result of puddling indicate low multiple cropping potential. Coarser textured soils, which allow for faster conversion from wetland rice to wheat, have been given as the reason for the widespread rice-wheat system areas in China, India, Nepal, Pakistan, Bangladesh, and Korea (Harwood and Price 1976). For many other soils the transition from wetland rice to dryland crops can be achieved only with management practices designed to modify the soil structure, at least in the microenvironment around the roots, by appropriate water and tillage management and application of organic manures.

*Residual effects of the reduced condition.* Two of the major chemical reactions that are likely to have adverse effects on dryland crops following wetland rice are the reduction of Fe and Mn. The amount of soluble manganous ions in the soil solution under wetland rice can reach 90 ppm; while this amount is not toxic to rice (Sanchez 1976), Mn toxicity may occur on the dryland crops that follow.

Studies in solution culture have shown that 1-4 ppm Mn depresses yields of lespedeza, soybean, and barley, whereas 15 ppm Mn is tolerated by maize (Olsen 1936, Morris and Pierre 1949). Cowpea grown on 6 ppm Mn accumulated in its leaves 2,000 ppm Mn, which resulted in a 50% reduction in growth (Kang and Fox 1980). Symptoms of Mn toxicity, mainly chlorosis of the leaves, have been observed in soybean sown after wetland rice in the Chiang Mai Valley (Wivutvongvana 1979). When the soil is drained, the potentially toxic manganous ions are reoxidized; but in the field the reaction is largely biological and is inhibited at pH lower than 5.5 (Bromfield 1976).

Iron is another element made soluble under rice cultivation, with the potential to cause problems in subsequent dryland crops. In the Murrumbidgee and Coleambally irrigation areas in southeastern Australia, the poor growth of maize and sunflower in rotations with wetland rice was attributed to the immobilization of P by amorphous gels of the freshly precipitated iron oxides (Willett et al 1978, Willett and

Higgins 1978). These authors found that amorphous gels of iron oxides can immobilize phosphates more strongly than the crystalline forms normally present in soils that have not been flooded. This capacity to adsorb phosphate declines with time after drainage, as the gel crystallizes. The rate is largely dependent on soil type. In some soils in Australia it was found that at 19 months after drainage, P sorption in one soil was still 2-4 times greater than in the soil that was not flooded (Willett and Higgins 1978). The immobilization of Mo could occur in the same manner. The implication of these observations for rice-based cropping systems, particularly on high-Fe soils and where wetland rice is followed directly by dryland crops, merits further attention.

Waterlogging, by causing the formation of manganous and ferrous ions, which can take part in cation exchange, will increase the amounts of exchangeable Ca, Mg, and K that come into solution. When water slowly percolates through the waterlogged soil, these cations will be removed (IRRI 1967). Water infiltration under wetland rice is not completely prevented, particularly in coarser soils suited for dryland crops after rice. Furthermore, percolation is sometimes recommended as a means to leach out some potentially toxic organic compounds (Russell 1973).

*Microbiological changes.* The microbial oxidation of Mn is important to the transformation of the potentially toxic manganous ions to insoluble oxides of Mn. Under rice-based cropping systems it is not known how these organisms survive the period of submergence under rice. Two other microbes that are important to the dryland crops in rice-based systems are *Rhizobium* and the vesicular arbuscular mycorrhyzas (VAM). *Rhizobium* bacteria are strictly aerobic; their number declines rapidly when the soil is flooded, but 100-1,000 cells/g soil normally survive in the flooded soil over the rice season (Rerkasem and Tongkumdee 1981, Rerkasem and Gypmantasiri 1981). Maximum nodulation of the leguminous crops following rice will depend on the buildup of the rhizobial population from drainage to the time of legume sowing. Legumes grown after wetland rice without rhizobial inoculation nodulate more profusely with the application of some well-decomposed animal manure. Dryland crops that respond to the infection by VAM include wheat, maize, soybean, cotton, tomato, potato, onion, groundnut, cowpea, cassava, and bean (Tinker 1982). Tinker (1982) also reported that excess water, low oxygen levels, and reduced conditions inhibit mycorrhyza formation. However, it is not known how the fungi adapt to the wet-and-dry cycle of rice-based cropping systems.

## Management problem: the turnaround time

The time between the harvest of one crop and the sowing of the next crop, the turnaround time, becomes shorter as the intensity of sequential cropping increases. This can pose serious problems for soil management. Of particular interest are soil remedies such as liming and application of organic matter. The heavy use of $(NH_4)_2SO_4$ in triple cropping systems based on rice can lead to the development of severe soil acidity (Gypmantasiri et al 1980). To remedy with lime is simple enough, but when to lime is a serious question. The materials, particularly CaO, commonly used in places where facilities for fine crushing of hard limestone are not available, react readily with ammonium N, causing heavy losses of $NH_3$ unless sufficient time is allowed between the applications of the two materials. In addition, other side effects of liming such as immobilization of P and Zn and leaf burning of young seedlings may pose a serious problem. The short turnaround time may also limit the use of organic manure in intensive cropping systems to well-decomposed materials to prevent problems such as organic acid toxicity and nutrient immobilization.

## MANAGEMENT OF ORGANIC MANURES

Debates on the importance of soil organic matter to crop productivity, particularly in the tropics, have been going on for some time (e.g., see Howard 1972, Russell 1973, and Sanchez 1976). The arguments for organic matter conservation have stemmed partly from a generally held view that tropical soils have less organic matter and thus lower fertility than temperate soils. Systematic comparison of random samples of 61 profiles from the tropics and 45 profiles from the temperate regions has not shown this premise to be valid (Sanchez et al 1982). There was no significant difference in the concentration of C or the C-S ratio between the two groups at any depth to 100 cm. Organic matter is not essential to plant growth if the nutrient elements and water can be provided in the right amount at the right time (Russell 1973). However, in the field this is a condition not always easy to meet. In traditional systems of agriculture, the extra inputs of the nutrient elements and water can be minimal; in these situations soil organic matter can be important.

### Green manure

The potential benefits of green manure crops are many: they can help improve soil structure, reduce nutrient losses through leaching, and, in the case of legumes, markedly increase the nitrogen content of the soil (Russell 1973). However, the practice has not been favored by farmersfor a purely economic reason; the costs of a green manure crop in terms of labor, land, and water utilization often outweigh the return, which often is less than the gain from an alternative cash crop. Several variations of green manuring developed in Africa and Asia to improve the real cost-and-return ratio of the practice include intercropping with legumes, in-situ mulch, and relay cropping (Agboola 1982, La1 and Kang 1982, Krishnamoorthy and Kothanadaraman 1982). Although there are many reports of the yield advantages of legume-nonlegume intercropping, the direct benefit to leguminous N fixation has not been clearly demonstrated, either on current productivity of the nonlegume or on the long-term productivity of the system (Willey 1979).

*Azolla* and *Sesbania rostrata* are two examples of green manure crops that have the potential to fix large amounts of N within a relatively short time. In sequential systems they can fit into situations where the growing season is not sufficient for a full cash crop. *S. rostrata* has been reported to fix 267 kg N/ha within 52 days (Dommergues 1982). As a green manure crop before rice, it markedly increased yield, N content of the crop, and soil N.

There have been many reports of the potential benefits of azolla as a N source for wetland rice in recent years (e.g., Liu 1979, Tuan and Thuyet 1979, Singh 1979, Li 1982). Many of these papers reported increases in rice yields and N content of the rice crop and long-term improvements in soil fertility. From China it was reported that azolla use in the wetland rice crop improved soil for the succeeding crop of wheat or ape (Liu 1979). Apart from the possible residual N, the use of azolla may improve soil structure for dryland crops in the system. A study in Chiang Mai has shown that incorporation of azolla left the soil at the rice harvest with lower bulk density, increased aggregate stability, decreased soil resistance, and slightly improved water availability (Table 3).

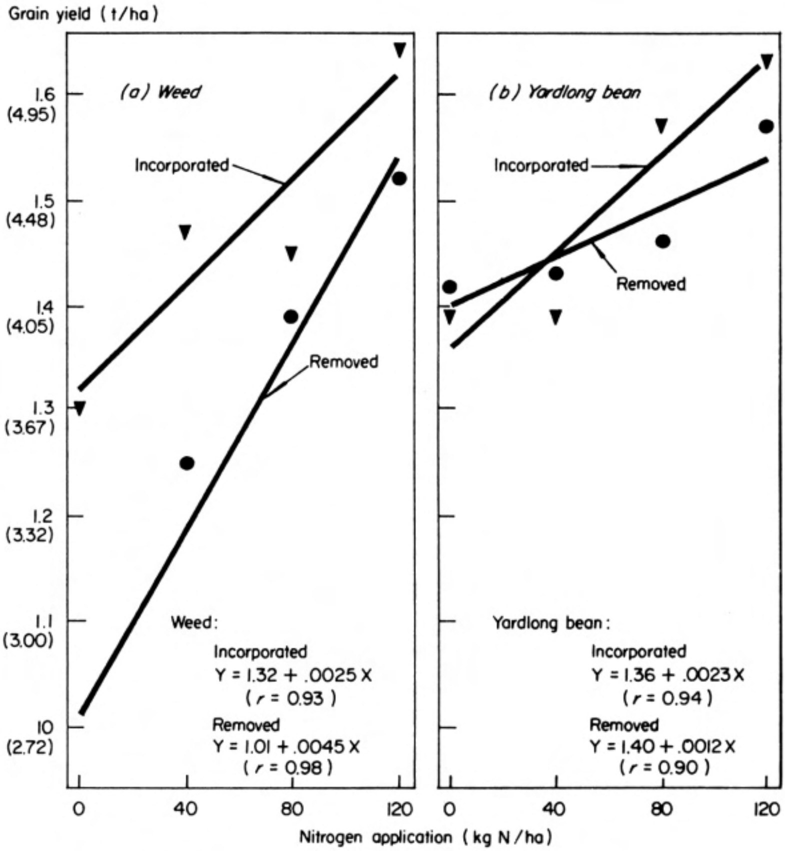
## Crop residues

Results of long-term experiments at IRRI showed that double cropping of wetland rice caused a slow and steady increase in soil N (IRRI 1980). This was true even when the straw was removed, but the increase was greater when the straw was burned, and greatest when it was incorporated. An experiment in Chiang Mai showed that the yield and the response to N of wetland rice can be markedly affected by the removal or incorporation of organic residues (Fig. 3). In a field heavily infested with weeds, mainly *Eleusine, Digitaria,* and *Echinochloa* spp., if the weeds were removed, the rice yielded only 2.6 t/ha and responded strongly to N. If the weeds were incorporated, the yield of unfertilized rice was increased by 40%, and the response to N fertilizer became less marked. With the yard-long bean *Vigna unguiculata* var. *sesquipedalis,* which is picked for the green pods, incorporation or removal of the tops had little effect on the rice yield, with or without N fertilizer.

The practice of incorporation of organic residues in multiple cropping is not common. Traditional farm elements are often inadequate for incorporation of large amounts of rough organic residues. In Thailand, at the beginning of the wet season, weeds are piled up on the bunds and burned. The introduction of walking tractors in the last 10-15 years has led to improvements in organic matter incorporation. With intensive cropping systems there is also less time for organic matter to break down between crops. In Japan, before 1960, cereal straws were used as animal bedding and mixed with fresh manure to make compost (Matsuzaki 1982); these materials were then applied to the soil. In the tropics straws are fed to animals, burned, and occasionally used as mulch; rice husk is generally burned at the rice mills. Thus only a small proportion of the crop residues finds its way back to the field. An example from the Chiang Mai Valley shows how intensive cropping systems may utilize more crop residue. The valley covers an area of 160,000 ha in contiguous paddy land. Intensive double, triple, or sometimes quadruple cropping systems are practiced on more than half this land. Estimates of straw production and utilization are shown in

**Table 3. Changes in physical properties of paddy soils caused by different levels of *Azolla pinnata* inoculations (K. Prasertchai, A. Promsiri, and T. Klodpeng, unpublished results, Department of Soil Science, Chiang Mai University.**

| Fresh wt of *A. pinnata* (t/ha) | Bulk density ($g/cm^3$) | Aggregate stability (%) | Available moisture (%) | soil resistance ($kg/cm^2$) | Saturated hydraulic conductivity (cm/h) |
|---|---|---|---|---|---|
| 0 | 1.42 | 30.9 | 9.8 | 3.12 | 0.51 |
| 20 | 1.36 | 32.1 | 10.2 | 3.11 | 0.50 |
| 40 | 1.34 | 36.5 | 10.3 | 2.98 | 0.50 |
| 60 | 1.22 | 37.5 | 10.2 | 2.48 | 0.54 |
| 80 | 1.25 | 43.6 | 10.3 | 2.54 | 0.54 |



**3.** Relationships between grain yield of rice (RDI) and nitrogen application when residues of weed (a) and yardlong bean (b) were incorporated or removed (S. Ratanawichai and B. Rerkasem, unpublished results). Note: Vertical axis is 1n-transformation. Values of back transformation are in parentheses.

Table 4. Rice straw is the main crop residue used. A small amount is kept as feed for the draft cattle and buffaloes, which average one or two animals per household (Tongsiri et al 1975). For intensive cropping systems, the straw is either burned before planting the soybean or used as mulch in high-value crops.

*Burning.* Soybean grown in the Chiang Mai Valley is largely sown into rice stubble with no tillage. After the rice harvest the stubble may be cut again just above the ground. Straw from the preceding rice crop is spread over the field and burned. Soybean is sown into preirrigated soil. A hole may be made at each former rice crown; or the seeds (3-5/hill) may simply be lodged among the old rice tillers. A mixture of ash, well-decomposed manure, and soil is sometimes used to cover the seeds. This mixture may be an ideal carrier of rhizobial inoculation. On the other hand the effect of this energy and nutrition source on the soil rhizobial population should also be considered. Although proponents of organic matter conservation consider burning wasteful, the practice is an easy way to return most of the nutrients,

**Table 4. Estimated amount of straws produced and used in Chiang Mai, Thailand, 1978.**

| Crop | Area planted (ha) | Straw[a] (t) | Use |
|---|---|---|---|
| Rice | 126,400 | +560,000 | |
| Soybean | 27,800 | –123,000 | Burning |
| Garlic | 13,200 | –175,230 | Mulching |
| Shallot and onion | 3,000 | - 40,000 | Mulching |

[a] (+) = straw produced, (–) = straw used.

except N and S, to the soil. Among the numerous cropping systems found in the Chiang Mai Valley (Fig. 2), the rice - soybean system is one of the most widespread and requires a minimum of inputs. The rice grown in this system is normally a traditional, often glutinous cultivar, which is not fertilized. The soybean crop also receives little fertilization. Yet the system has appeared to sustain economically viable yield levels over the last 20 years.

*Mulching.* The Chiang Mai Valley produces a large proportion of Thailand's crop of garlic, onion, and shallot. Mulching is essential for good yields of these crops, and rice straw is a particularly suitable mulching material. Sawdust has been tried as an alternative but has proved to be much inferior (Ongprasert 1981). Generally 3 ha of rice are required to provide straw for 1 ha of garlic, onion, or shallot. Roles of the mulch other than improving soil water and temperature regimes for these shallow-rooted crops are not known. The low volume of straw left at the end of the season is piled up and burned. Before this, a considerable amount of nutrients could have been returned to the soil through leaching from irrigation and decomposition of the layer of straw next to the soil surface.

## Animal manures

Animal manures are most widely used to maintain soil fertility in intensive cropping systems in traditional agriculture (Okigbo and Greenland 1976). Their role in replenishing the store of plant nutrients in the soil seems more important than the improvement of soil structure. In agricultural systems of industrialized countries (e.g., the case of Japan in Matsuzaki 1982) the use of chemical fertilizers has largely replaced the use of animal waste. Intensive cropping usually means limited land; the available resources within the farming system are concentrated on the crop activities, with less attention being paid to the livestock. Therefore, despite the increasing need, less animal manure can be expected from within the farming system. In Africa, supplies from outside the farming system such as guano and fish meal are used heavily (Okigbo and Greenland 1976), and the consumption of chemical fertilizers is also increasing. The recent development of a relatively large-scale intensive livestock industry, mainly poultry and pigs, quite independent of the development of intensive cropping systems, has provided another useful source of animal manures. In the Chiang Mai Valley, those crops with high value per hectare such as tobacco, garlic, and vegetables, which account for 30-40% of the area planted to second and third crops after the wet-season rice, all receive some animal manure along with chemical fertilizers. Typical rates for tobacco and garlic are shown in Table 5. Even with the chemical fertilizers (N, P, and K), animal manure appears to be essential for these dryland crops in most areas in the valley. An exception is the areas along the river where the soils are mostly alluvial, receiving fresh materials each year from floods. One clear role of the animal manures is the improvement of the air and water regimes around the roots of these shallow-rooted crops, hence improving soil structure. However, possible effects on soil microbes and trace element nutrition also need to be examined. With the livestock industry depending largely on the feeds that come from outside the valley, the possibility of importation of some essential nutrients such as B cannot be overlooked. Those cropping systems receiving a considerable amount of animal manure each year appear to be more stable than the rice - soybean system when cropping intensity increases from double to triple cropping. The yield decline in the unfertilized wet-season rice crop in the rice - soybean - rice system discussed earlier has not been observed in the rice - onion - rice or rice - garlic - rice systems. Animal manures appear to have a decided price advantage over the chemical fertilizers, even when only the nutrients N, P, and K are considered (Table 6).

## ORGANIC MATTER RECYCLING IN AS AGROECOSYSTEM

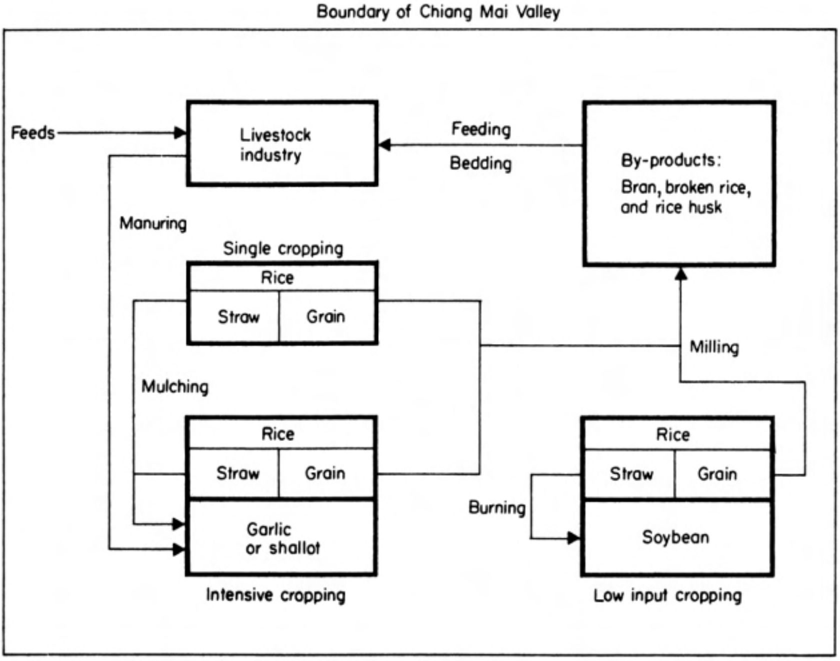
The recycling of organic matter may significantly affect the productivity and sustainability of intensive cropping systems. This whole process may, in turn, influence many decisions and practices on the farm. The pathways of organic matter recycling in the Chiang Mai Valley are shown in Figure 4. Most of the organic matter recycling occurs between subsystems of the valley agroecosystem. These have been defined (Gypmantasiri et al 1980) as localities in the valley characterized by a certain

**Table 5. Animal manure and chemical fertilizers used in tobacco and garlic cultivation in the Chiang Mai Valley.**

| Crop | Animal manure (t/ha) | Chemical fertilizer (kg/ha) | | | Others |
|---|---|---|---|---|---|
| | | N | P | K | |
| Tobacco | 12 | 30 | 90 | 120 | B, Mg |
| Garlic | 12-15 | 100 | 62 | 62 | – |

**Table 6. Nutrient contents and prices of animal manures as sold to farmers in comparison with chemical fertilizer.**

| | Price ($/t) | Moisture (%) | Organic matter (%) | N (%) | P (%) | K (%) |
|---|---|---|---|---|---|---|
| *Chemical fertilizer* | 300 | – | – | 15 | 15 | 15 |
| *Manure* | | | | | | |
| Chicken | 7.5 | 18 | 41 | 1.8 | 0.6 | 1.1 |
| Duck | 7.5 | 20 | 39 | 1.5 | 0.3 | 0.8 |
| Pig | 8.4 | 27 | 29 | 1.6 | 0.9 | 0.6 |
| Cattle | 6.6 | 24 | 34 | 1.1 | 0.4 | 0.9 |



**4.** Flow diagram showing interactions between intensive cropping systems and livestock industry in the Chiang Mai agroecosystem.

cropping system, such as single rice, rice - soybean, rice - garlic, and so on. A typical farm in the valley is about 1 ha, which seems too small to be self-sufficient in the organic matter required in most of the intensive cropping subsystems. The rice - soybean subsystem, with the rice straw burned for the soybean, is the only one that uses only the organic matter produced within it.

The movement of rice straw for mulching is between single-rice areas and the rice - garlic and rice - shallot areas. It requires 3 ha of rice to provide mulching straw for 1 ha of garlic or shallot. Farmers in the rice - garlic area must depend on the straw from the single-rice areas. At the garlic-planting season, a farmer in the single-rice area may earn some $30-$40 from the straw from 1 ha of rice. Thus in single-rice areas, the straw yield and the early-rice harvest have become important in catching the peak of season for high demand for straw.

Most farmers in the Chiang Mai Valley grow wet-season rice for subsistence. The rice is kept in individual rice barns and small amounts for home consumption are milled at a time at a small local mill. The broken rice and bran are usually brought home and fed to a few farm livestock — perhaps one pig and a few chickens. The manure produced by these farm animals is seldom used in the rice-based cropping systems.

The animal manures used in the rice–based systems come mainly from the intensive poultry and pig enterprises with an average size of 10,000 chickens, 200 ducks, or 400 pigs. Farmers who operate these livestock enterprises are usually the richer landowners in the village; they may own some farm land but are not directly involved in the cropping activities.

Some of the rice reaches the larger mills; the bran and broken rice may be used for feeds; but much of the animal feeds — fish meal and concentrates — come from outside the valley. The role of this flow of mineral elements in supplying some of the trace elements such as B deserves further attention.

About half of the rice straw produced in the valley is used incropping systems and to feed draft animals. Most of the residues from other crops, such as soybean and peanut tops and tobacco stalks, are not used. A survey of the intensive livestock industry showed that about 10-20% of the animal waste is sold each year to farmers who operate intensive cropping systems. These figures may be further improved, but only with a better understanding of the specific role of organic matter and the problems associated with each of the recycling pathways, including the balance of loss and gain within a farming system and within and between other hierarchical levels of the agroecosystem.

## REFERENCES CITED

Agboola, A. A. 1982. Organic manuring and green manuring in tropical agricultural production systems. Pages 198-222 *in* Non-symbiotic nitrogen fixation and organic matter in the tropics. Transactions of the 12th International Congress of Soil Science. Symposia papers 1. New Delhi, India.

Boonduang, A., and A. R. Thodey. 1974. Village rice study. III. Yield variations in farmers' fields. Pages 151-165 *in* Annual report 1973-1974, Multiple Cropping Project, Chiang Mai University, Chiang Mai, Thailand.

Bromfield, S. M. 1976. Sorption and oxidation by a cell suspension of a manganese oxidising bacterium. Soil Biol. Biochem. 8:37-43.

De Datta, S. K. 1981. Principles and practices of rice production. John Wiley and Sons. A Wiley-Interscience Publication. 618 p.

deMooy, C. J., J. Fesek, and E. Spaldon. 1973. Mineral nutrition. Chapter 9 *in* B. E. Caldwell, ed. Soybeans: improvement, production, and uses. American Society of Agronomy Monograph 16. Madison, Wisconsin. 681 p.

Dommergues, Y. R. 1982. Scarcely explored means of increasing the soil N pool through biological N fixation. Pages 138-149 *in* Whiter soil research. Panel discussion papers. Transactions of the 12th International Congress of Soil Science. New Delhi, India.

Gypmantasiri, P., A. Wiboonpongse, B. Rerkasem, I. Craig, K. Rerkasem, L. Ganjanapan, M. Titayawan, M. Seetisarn, P. Thani, R. Jaisaard, S. Ongprasert, T. Radanachaless, and G. R. Conway. 1980. An interdisciplinary perspective of cropping systems in the Chiang Mai Valley: key questions for research. Faculty of Agriculture, Chiang Mai University, Chiang Mai. 238 p.

Harwood, R. R. 1975. Farmer-oriented research aimed at crop intensification. Pages 12-32 *in* International Rice Research Institute. Proceedings of the Cropping Systems Workshop. Los Baños, Philippines.

Harwood, R. R., and E. C. price. 1976. Multiple cropping in tropical Asia. Pages 11-40 *in* R. I. Papendick, P. A. Sanchez, and G. R. Triplett, eds. Multiple cropping. American Society of Agronomy special publication number 27. Madison, Wisconsin.

Howard, A. 1972. An agricultural testament. Rodale Press special edition. 253 p.

IRRI (International Rice Research Institute). 1967. Annual report for 1967. Los Baños, Philippines. 308 p.

IRRI (International Rice Research Institute). 1978. Soils and rice. Los Baños, Philippines. 825 p.

IRRI (International Rice Research Institute). 1980. Annual report for 1979. Los Baños, Philippines. 538 p.

Kang, B. T., and R. L. Fox. 1980. A methodology for evaluating the manganese tolerance of cowpea (*Vigna unguiculata*) and some preliminary results of field trials. Field. Crop Res. 3:199-210.

Kibreab, T. 1980. Chili pepper response to moisture stress and nitrogen fertilization. Special report. Multiple Cropping Project, Chiang Mai University, Chiang Mai Thailand.

Krishnamoorthy, K. K., and G. V. Kothandaraman. 1982. Organic manuring and green manuring in tropical soils: Indian experience. Pages 179-188 *in* Non-symbiotic nitrogen fixation and organic matter in the tropics. Transactions of the 12th International Congress of Soil Science. New Delhi, India.

Lal, R., and H. T. Kang. 1982. Management of organic matter in soils of the tropics and subtropics. Pages 152-178 *in* Non-symbiotic nitrogen fixation and organic matter in the tropics. Symposia papers I. Transactions of the 12th International Congress of Soil Science. New Delhi, India.

Li, Z. 1982. Nitrogen fixation by *Azolla* in rice fields and its utilization in China. Pages 83-95 *in* Non-symbiotic nitrogen fixation and organic matter in the tropics. Symposia papers 1. Transactions of the 12th International Congress of Soil Science. New Delhi, India.

Liu, C. C. 1979. Use of Azolla in rice production in China. Pages 375-394 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Martin, J. H., W. H. Leonard, D. L. Stamp. Principles of field crop production. Collier Macmillan International, 1,118 p.

Matsuzaki, T. 1982. Utilization of agricultural wastes as manures. Pages 223-234 *in* Non-symbiotic nitrogen fixation and organic matter in the tropics. Transactions of the 12th International Congress of Soil Science. Symposia papers 1. New Delhi, India.

Moormann, F. R., and N. van Breeman. 1978. Rice: soil, water, land. International Rice Research Institute. Los Baños, Philippines. 185 p.

Morris, H. D., and W. H. Pierre, 1949. Minimum concentrations of manganese necessary for injury to various legumes in culture solutions. Agron. J. 41:107-112.

Okigbo, E. N., and D. J. Greenland. 1976. Multiple cropping in tropical Africa. Pages 63-101 *in* R. I. Papendick, P. A. Sanchez, and G. B. Triplett. eds. Multiple cropping. American Society of Agronomy special publication number 27. Madison, Wisconsin.

Olsen, C. 1936. Absorption of manganese by plants. II. Toxicity of manganese to various plant species. Compt. Rend. Lab. Carlsberg, Ser. Chim. 21:129-145.

Ongprasert, S. 1981. The effects of sawdust mulch on garlic yield in comparison with rice straw mulch. Multiple Cropping Project. Special research report. Chiang Mai University. 24 p.

Ponnamperuma, F. N. 1965. Dynamic aspects of flooded soils. Pages 295-328 *in* International Rice Research Institute. The mineral nutrition of the rice plant, Los Baños, Philippines, John Hopkins Press, Baltimore, Maryland.

Rerkasem, B., and P. Gypmantasiri. 1981. Some key processes in the nitrogen cycle of rice-based multiple cropping systems. Pages 96-100 *in* R. Wetselaar, J. R. Simpson, and T. Rosswall, eds. Nitrogen cycling in Southeast Asian wet monsoonal ecosystems. Australian Academy of Science. Canberra.

Rerkakem, B., and D. Tongkumdee. 1981. Legume-Rhizobium symbiotic development in rice-based multiple cropping systems. Pages 435 *in* A. H. Gibson and W. E. Newton, eds. Current perspectives in nitrogen fixation. Australian Academy of Science, Canberra.

Russell, E. W. 1973. Soil conditions and plant growth. Longmans, London. 849 p.

Sanchez, P. A. 1976. Properties and management of soils in the tropics. Wiley-Interscience publication. 618 p.

Sanchez, P. A., M. P. Gichuru, and L. B. Katz. 1982. Organic matter in major soils of the tropical and temperate regions. Pages 99-114 *in* Transactions of the 12th International Congress of Soil Science, Symposia Paper I. New Delhi, India.

Singh, P. K. 1979. Use of Azolla in rice production in India. Pages 407-418 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Tinker, P. B. 1982. Mycorrhyzas: the present situation. Pages 150-166 *in* the Transactions of the 12th International Congress of Soil Science. Panel discussion papers. New Delhi, India.

Tongsiri, B., P. Lerttamrab, and A. R. Thodey. 1975. Agro-economic characteristics of the Chiang Mai Valley, 1972-73. Multiple Cropping Project. Agricultural economics report number 5. Faculty of Agriculture, Chiang Mai University.

Tuan, D. T., and T. Q. Thuyet. 1979. Use of *azolla* for rice production in Vietnam. Pages 395-405 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Willett, I. R., W. A. Muirhead, and M. L. Higgins. 1978. The effects of rice growing on soil phosphorus immobilization. Aust. J. Exp. Agric. Anim. Husb. 18:270-275.

Willett, I. R., and M. L. Higgins. 1978. Phosphate sorption by reduced and reoxidized rice soils. Aust. J. Soil Res. 16:319-376.

Willey, R. W. 1979. Intercropping — its importance and research needs. Part I. Competition and yield advantages. Field Crop Abst. 32:1-10,

Wivutvongvana, F. 1979. Oxidation of iron and manganese following drainage of a reduced soil and manganese toxicity in soybeans. Unpublished Ph D thesis, Cornell University. 119 p.

# MICROECONOMIC STUDY OF ORGANIC FERTILIZER USE IN INTENSIVE FARMING IN JIANGSU PROVINCE, CHINA

Thomas B. Wiens

The Suzhou District of southern Jiangsu Province is one of the most intensively cropped areas of China and has the country's highest annual yields of grain. These yields have been associated with the vigorous promotion of triple cropping (barley - rice - rice) since 1971. Insufficiency of chemical fertilizers and fear of soil degradation have led to concomitant promotion of the use of organic fertilizer, including waterlogged compost, pig manure, green manure, and azolla.

A detailed quantitative description of fertilizer use is constructed from data provided by two production teams in the district. Plant nutrient removal and replenishment balances suggest that existing practices entail excess supply of nitrogen but deficiencies of soil phosphorus and potassium, and that triple cropping places a greater strain on nutrient supplies than do traditional forms of double cropping — without compensating increases in net yield.

A whole-farm linear programming model, including detailed nutrient balances designed to ensure conservation of soil nutrients, is used to demonstrate that, whereas triple cropping is advantageous only in limited proportions under specific conditions, heavy organic fertilizer use (with certain exceptions) is at present economical in the Chinese institutional framework, in which labor surplus exists and supplies of chemical fertilizers other than nitrogenous ones are limited.

The Suzhou District, encompassing eight counties and two municipalities in southern Jiangsu Province, is representative of the frontiers of high-yield, intensive technology in present-day China. Triple cropping has become extensive there (287,000 ha, or 75% of the grain-cultivated area in 1978), partly because of favorable natural conditions — 1,100 mm of rainfall annually, 16°C average annual temperature, over 2,000 hours of sunlight annually, and rich, alluvial soil. Labor is abundant (roughly 1 / 15th ha of grain field per capita) and mechanization developed (1 garden tractor/20 ha cultivated). The irrigation and drainage system is among the

---

This paper is based on research completed before the author's employment at the World Bank and is unrelated to his present responsibilities; the opinions expressed are not those of the World Bank.

most reliable in China. In addition to using chemical fertilizers, farmers recycle the manure from some 15 pigs/ ha, grow nearly 70,000 ha of winter green manure and an additional 70,000 ha of azolla, and use nearly 30,000 ha of water surface to grow crops such as water hyacinth for use as feed and fertilizer. Annual applications of waterlogged compost per sown hectare average more than 60 t. Only the short growing season (220-230 frost-free days) is unfavorable to multiple cropping. In 1978, annual yields of unprocessed grain reached 11.5 t/ ha, of which 8 t were rice and the remainder wheat, barley, and naked barley.

In 1980, the author, in cooperation with three colleagues from the Jiangsu Academy of Agricultural Sciences, carried out a detailed quantitative study of production conditions in two production teams in this district, East No. 1 and No. 6 Teams of the Baimao People's Commune, Changshu County, which totaled 76 households farming 29 ha of collectively owned land (Liu Guangyu et al 1980). The objective was to construct a linear programming model to examine the optimality of the proportions of double and triple cropping sequences used by the teams. Because the economics of these sequences was closely related to availability of nutrients from organic and chemical fertilizers, the study also considered the bionomics of cropping practices.

This paper summarizes portions of the study that describe and analyze organic fertilizer-use practices, along with the contextual information needed to understand them. Approximate plant nutrient balance tables are constructed; these compare crop offtake with soil replenishment and allow judgments about influence of individual crops, crop sequences, and type of fertilizer on each type of balance (N, P, K, and organic matter). When the balances are built into the whole-farm linear programming models, model solutions allow comparison of actual and optimal use, as well as actual and shadow prices of sources of plant nutrient. Thus generalizations about the economic optimality of present and projected fertilizer-use practices may be made.

## CROPPING SYSTEMS AND FERTILIZER USE

### Historical development

The Suzhou District traditionally has been a high yielding, intensively farmed area, which for centuries has practiced double cropping of winter wheat, barley, or rapeseed with summer indica rice cultivars. The last 3 decades have seen substantial further development, as improved control of irrigation and drainage has promoted increased winter crop yields; plant breeding achievements have led to the replacement of late indica cultivars with high yielding, early, dwarf japonica cultivars. These improvements have been facilitated by the growth in use of organic (and lately chemical) fertilizer, including cultivation of leguminous green manure crops, recycling of pig manure from an augmented pig stock, and promotion of practices new to the area such as cultivation of azolla and water hyacinth.

However, yields of single-cropped late japonica in Suzhou generally peaked in 1966, under ideal weather conditions. The average gross yield was 6.9 t/ ha, and it was believed that breaking through this "frontier" required a major change in the cropping system. The experience of some production units in the 1960s and improvements in underlying production conditions described above led to the application of considerable pressure after 1970 for rapid and large-scale conversion to triple cropping based on two crops of rice.

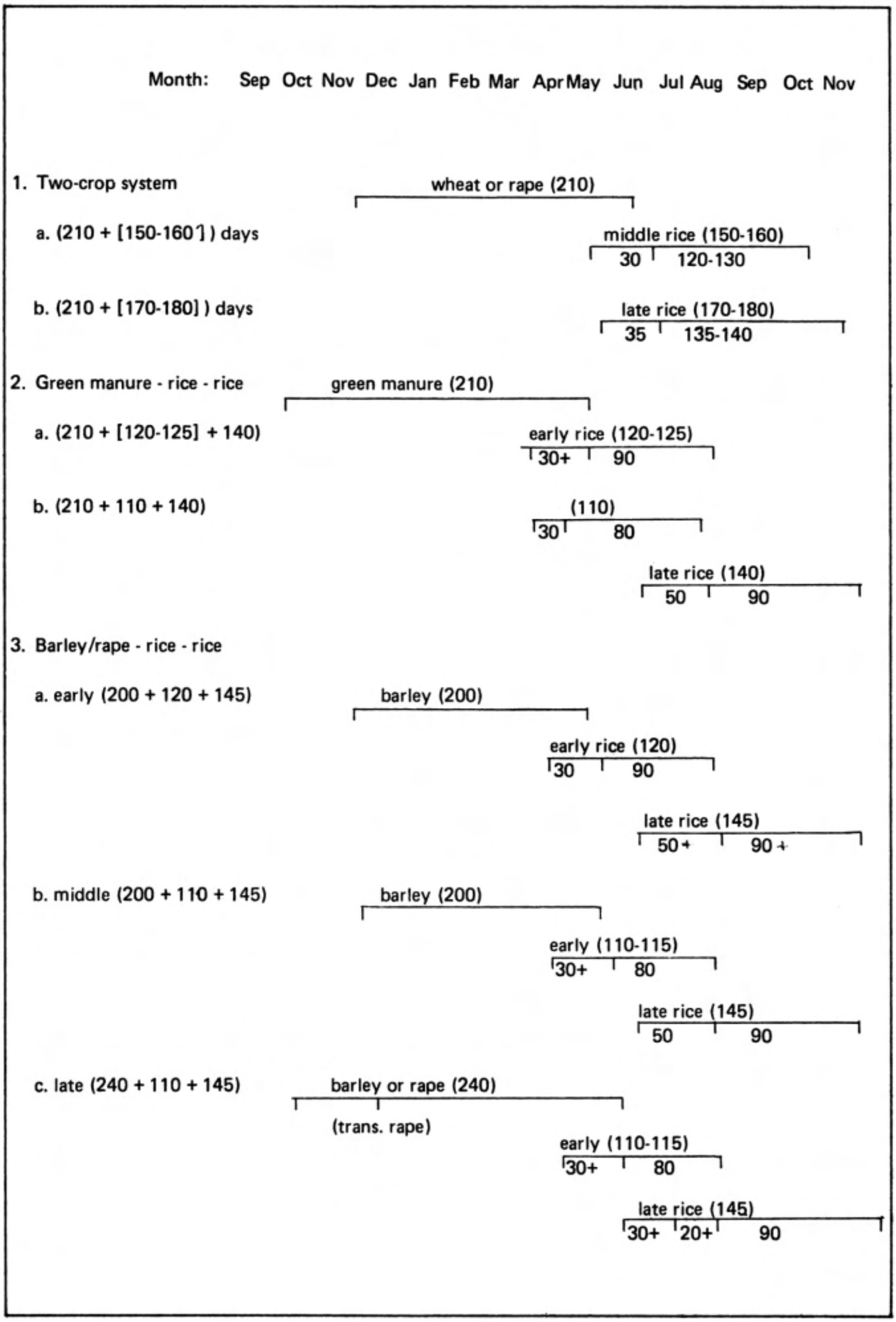
### Cropping sequences

The characteristics of the old and new cropping sequences are compared in Figure 1. Of the two variants of the traditional double cropping system, based on duration of the rice crop, only the variant using higher yielding, late, single-cropped (SC) japonica is now common. The green manure - rice - rice sequence (hereafter, GM -rice - rice; milk vetch is the normal green manure crop) is the least difficult triple cropping system to implement. Early rice cultivars used in triple cropping are indicas; the late crop is the same as that used in the double cropping sequences, but the seedlings are started later, transplanted after 50 days rather than after 35, and the total growing period is reduced to about 140 days. The second form of triple cropping uses a winter crop of barley, naked barley, or rapeseed, with three timing variants. In 1978, about 26% of the hectarage of the Suzhou District was under wheat - rice - rice, 48% in barley - rice or wheat - rape double cropping, 15% in GM - rice - rice, and 11% in rape - rice - rice.

Comparison of total duration of the crop sequences with the length of the growing season, and estimation of plant nutrient offtake suggest that the conversion to triple cropping required or created a demand for 1) short-maturation, high yielding, early rice cultivars (105-110 days is the usual duration for current cultivars); 2) chemical fertilizers, to supplement organic fertilizers, especially on late rice; 3) machinery that could reduce the seasonal peak labor burden; and 4) reliable powered irrigation equipment. Also, inadequacy of supplies of chemical P and K required the expansion of organic fertilizer sources (the “three water crops,” azolla, green manure, and pig manure), despite substantial reduction of the slack period during which these could be accumulated, processed, and applied.

### Controversy over triple cropping

Despite its officially promoted expansion to nearly three quarters of Suzhou hectarage, triple cropping has not been popular with farmers or even specialists who acknowledged its yield potential (experimentally, up to 22 t/ ha), and recently its demerits have been thoroughly aired. With recent increases in decision-making freedom, Suzhou production teams have reduced the triple-cropped hectarage to about 45%. Triple cropping is unprofitable: compared with double cropping, it involves a one-third increase in labor and input costs but adds only 10-15% to gross yields, about 7% to milled yields net of seed requirements, and almost nothing to sales value (because of differences in desirability and price between wheat and barley, japonica and indica). The sharp seasonal peak labor requirements under triple cropping must be met by long, hot hours of work, or else even the gross yield advantages disappear. Moreover, new medium-maturity hybrid rice cultivars are now available, too early for inclusion in triple cropping sequences, and exceed in yield and profitability the best previous cultivars. Thus wheat - hybrid rice double cropping may offer greater potential for yield increases than any triple cropping sequences.



**1.** Double and triple cropping systems in Suzhou, 1979. Source: Huang Zhangxi (agronomist, Jiangsu Academy of Agricultural Sciences). Numbers in parentheses represent total growing periods; those below the lines distinguish seedling and main field growing periods.

Soil scientists also attacked triple cropping (barley - rice - rice) on the grounds that supplies of plant nutrients did not keep pace with the intensification of cropping. The argument applied to organic matter and nutrients other than N, chemical forms of which were increasingly abundant. Inability to increase recycling of crop wastes because of fuel demands, and pressure to substitute grain for green manure hectarage were notable concerns. There was evidence that intensive cropping with inadequate use of organic fertilizers has led to soil depletion.

The present study of two production teams generally confirmed the economic arguments against the triple cropping system. The following analysis considers questions raised about adequacy of nutrient replenishment.

## SOURCES AND USES OF ORGANIC AND CHEMICAL FERTILIZERS

The basic sources of plant nutrients in the teams studied included straw, green manure, water hyacinth, pig manure, river silt, azolla, nightsoil, rapeseed cake, ammonium bicarbonate, industrial waste water, and superphosphate. The first five are applied to crops as components of compost, although pig manure is also applied separately. The supply and uses of each ingredient will be examined in turn.

### Straw

Table 1 gives estimates of the distribution of straw supply by source and use. Rice straw, which is preferred for use in compost, as bedding for sties, and as fodder, may be distinguished from straw or stalks from wheat, barley, or rape, which are used strictly as fuel or building materials (for fences, sheds, etc.). Sales of rice and wheat straw to the state are restricted lest recycling be reduced.

About 40% of rice straw is directly recycled. Because compost cannot be used on double cropped late rice (for want of green manure) due to time constraints, and because high temperatures guarantee rapid decomposition, a proportion of early rice straw is cut and plowed under; otherwise, rice straw is composted. A large proportion of the 60% that is not directly recycled goes to the collective pigs; it is either processed by the brigade for use as fodder, used directly as bedding, or burned as fuel in cooking the feed mash. Most of the remainder is distributed to team members for use as fuel — the local rule of thumb is that the per capita weight of distributed straw should be roughly equal in weight to the grain ration. Since the straw bedding for collective pigs is mixed with manure and earth and recycled as “fertile earth” (FAO 1977), 50% of all straw is returned to the fields and the remainder is converted to fuel, building materials, and fodder or sold for industrial use.

### Green manure

Milk vetch or legumes are grown as winter crops. Harvested in early May, these crops yield 30-38 t/ha (fresh weight). Winter field borders are also planted in green manure, adding about one quarter to the total supply. All green manure in these teams is composted (elsewhere in China it may also be plowed under or used as fodder or both). The early harvest date permits the use of this compost on early and SC rices.

**Table 1. Supply and uses of straw, 1979 crop year, East No. 1 and No. 6 teams.**

| | Straw (t) | | | |
|---|---|---|---|---|
| | East No. 1 | | No. 6 team | |
| | Rice | Other | Rice | Other |
| Supply[a] | 83 | 33 | 146 | 46 |
| Uses[b] | 84-86 | 32 | 143-147 | 45 |
| Composted, plowed under[c] | 35 | | 55 | |
| Collective pigs[d] | 28 | 10 | 54 | 10 |
| Fodder | 5 | | 10 | |
| Bedding | 23 | | 39 | |
| Fuel | | 10 | | 10 |
| Private pigs[e] (fodder @ 0.75 t/pig) | 3 | | 5 | |
| Fuel distributed[f] | 17-19 | 15 | 28-32 | 26 |
| Repairs[g] | | I | | 10 |
| Collective buildings | | 2 | | 2 |
| Private buildings | | 5 | | 8 |
| Sold to state[g] | 2 | | 2 | |

[a] Estimated from 1978 grain production except 1979 early rice. Ratios of straw to grain are 1.1:1 for wheat; 1:1 for barley, early rice, and late rice; 0.8:1 for naked barley, hybrid rice, and single-cropped late rice. [b] Sums of estimates of components. [c] As reported. Most of early rice straw plowed under. [d] Fodder and fuel as reported; bedding estimated as 4% of total weight of stable manure ("fertile earth"). [e] Based on number of pigs sold or slaughtered plus number of sows. [f] Rice and "three wheats" straw reported; plus all rape straw. [g] As reported.

## Water hyacinth

Water hyacinth provides the only source of composted green matter for use on overwintering crops. It is harvested in August at around 45 t/ha water surface; 10% of it is used as pig forage.

## Pig manure

Pig manure is provided by privately and collectively raised pigs. Team members are obliged to deliver a quota of 2 t manure/private pig, for which they receive $6.67/t and are penalized $0.22 for every 50 kg of underfulfillment. The contribution of collective pigs (urine and feces) is about 0.25 t/month per pig or, combined with soil and bedding straw, about 1.25 t of low-quality stable manure ("fertile earth") containing roughly 20% urine and feces, 4% straw, and the remainder dry soil.

## River silt and composting

Compost pits (1% of total field area) are located in field corners. Straw and pig manure, mixed with river or pond silt and frequently turned over to promote decomposition, are accumulated until green manure can be added in early May. By weight, the mixture contains about 83% silt, 2% straw, 10% green manure (or water hyacinth), and 5% high-quality pig manure (plus some weeds and grasses). The river silt recycles leached P and K and promotes an anaerobic condition.

### Azolla

Azolla was grown in 1979 on less than half the hectarage of SC rice. The restriction is due to its lack of cold tolerance, which requires overwintering in plastic-protected plots. Multiplication (in stages) requires that a small amount of paddy land be left fallow in winter, and a larger amount — some 20% of fully expanded hectarage — be planted in barleys, which are harvested in May, leaving several weeks in which the land can be used for azolla multiplication before the rice is transplanted.

Because the barleys have lower yields than wheat, azolla cultivation requires a sacrifice of potential winter crop production, although further south, drainage conditions preclude winter wheat, and enough land must be fallowed anyway to permit use of azolla on early rice. The brigade subsidizes azolla use by bearing the cost of overwintering azolla: 1 ha of overwintering field is required for more than 300 ha of fully multiplied azolla. Costs per expanded hectare include:

| | |
|---|---|
| Cash cost ($) | 8.45 |
| Plastic sheet | 6.94 |
| Framework material | 0.83 |
| Water/eledricity | 0.06 |
| Rice straw (0.7 t) | 0.62 |
| Labor (days) | 3.7 |

There is also the substantial labor cost of multiplication and azolla turnover in the fields. The turnover labor is estimated to be 38-75 labor days/ha (including plot weeding).

The multiplied azolla is seeded into the flooded paddy fields 5-10 days before tractor plowing, which partially incorporates it into the soil. It is locally estimated that the yield of N from azolla equals 26 kg chemical N/ha. On one-third of the azolla fields. the azolla is turned over again following regeneration 7-10 days after transplanting, adding another 13 kg chemical N equivalent/ ha. These N equivalents imply an average green matter yield of 8.6 t/ha (fresh weight). Cash costs (excluding labor) of N from this source are about $0.29/kg, compared with $0.52 from ammonium bicarbonate.

### Nightsoil

Nightsoil is used primarily by families on their private plots, but a small amount is purchased by the team at $4.44/t for use on dryland vegetable hectarage.

### Rapeseed cake

Rapeseed cake is obtained as a byproduct of rapeseed processing at 55% by weight and is purchased from the state in proportion to amounts of rapeseed sold at $0.11/kg (teams are said to buy back all they can). The cakes are either used directly as fertilizer on dryland vegetable plots, or exchanged with cotton-producing areas for ammonium bicarbonate at approximate parity by weight.

### Ammonium bicarbonate ($NH_4HCO_3$)

The most important chemical fertilizer in Changshu County is $NH_4HCO_3$. Of the total supply, 70-80% is a “planned allocation” to each team, tied to sown hectarage in different crops and now averaging 116-134 kg complete N/ha, reflecting an increase of about 38 kg/ ha (50%) in 1978-79. Extra supplies of chemical fertilizers are linked to a variety of incentive schemes, such as the pig bonus (an extra allocation for each collectively or privately raised pig sold to the state); the above-quota grain and rapeseed sales bonuses; and a small bonus to encourage growing of green manure. All of the above allocations are purchased at $0.09/kg. With the greater abundance of chemical N, the incentives are probably no longer very effective.

### Industrial waste water

The teams apply, in addition to $NH_4HCO_3$, tons of “ammonia water,” i.e., industrial waste water with perhaps 0.1-0.2% N content, which must be boated or trucked from a factory; losses to air of $NH_3$ content are probably too high to justify the transport cost.

### Superphosphate

Superphosphate is readily available at $0.06/kg. The recommended application level is 230 kg/ ha (product weight), but supply is not formally restricted. The teams are aware of the need for P, at least on their poorer soils, and they apply it in proportions of 2.6-3.5:1 $N:P_2O_5$. Chemical K fertilizers are unavailable, Chinese domestic production and imports being insignificant.

## BIONOMICS OF INTENSIFICATION

It is generally agreed that a precondition for the expansion of triple cropping is the availability of adequate supplies of fertilizers, both organic and chemical. Also, it is often stressed that Suzhou’s success in implementing triple cropping is attributable to its abundant sources of such fertilizers. But how abundant is sufficient? How much more of each nutrient does triple cropping require, and from what sources has it been derived? Which sources can be further expanded with efficiency?

### Soil characteristics

The local soils are classified into four types, which differ in structure, nutrient content, and drainage. The best soils are loosely structured, high in nutrients (especially P), and well drained. The poor drainage of the two worst soil types precludes the planting of barley and naked barley. Consequently the rotation scheme has been keyed to soil type, with barley - rice - rice, GM - rice - rice, and wheat - hybrid rice rotated on the two best soil types, and wheat - late SC rice rotated with rapeseed - late SC rice on the two worst soils.

Samples of each soil type were obtained and analyzed for organic matter content, total N, soluble N, and available P (Table 2; equipment for analysis of K content was not available). Most samples contained organic matter and complete or soluble N in the ranges characteristic of middle-to-high fertility soils in this region; however, one of the two best (triple-cropped) soil types tested was rather poor on these criteria. All soils tested were P deficient, and three of the four samples of the best, triple-cropped soils were extremely P deficient.

Table 2. Soil analysis: East No. 1 and No. 6 teams, samples 6 April 1980.

| Soil type | Area (ha) | Organic matter (%) | Total N (%) | Soluble N[a] (mg/100 g) | Available P[b] (ppm) |
|---|---|---|---|---|---|
| East No. 1 | | | | | |
| Shanxue huangnitu | 2.3 | 2.25 | 0.150 | 14 | 5 |
| Huangnitu | 3.7 | 1.74 | 0.121 | 12 | 3 |
| Wushantu | 1.9 | 2.08 | 0.135 | 12 | 8 |
| Shutou wushantu | 2.5 | 2.23 | 0.141 | 13 | 11 |
| No. 6 | | | | | |
| Shanxue huangnitu | 2.7 | 2.56 | 0.162 | 15 | 3 |
| Huangnitu | 3.7 | 1.95 | 0.121 | 11 | 11 |
| Wushantu | 5.5 | 2.55 | 0.163 | 15 | 6 |
| Shutou wushantu | 6.1 | 2.39 | 0.149 | 14 | 3 |

[a] With 1.2 N NaOH, 50°C, 24 h, ϕ 120 mm, Conway dish method. [b] With 0.5 M $NaHCO_3$, 1:20, continuously mixed, 1/2 h (Olsen method).

Although the before-and-after comparison, which would be conclusive, is lacking, it may still be conservatively inferred, from the tendency of the best soils (all triple cropped) to show the most serious nutrient deficiencies, that the teams were not fully meeting the nutrient requirements of the triple-cropping system.

## Intensive cropping and fertilizer requirements

Because of the lack of local experimental data, the technical literature was examined for information on the relationship between intensification and fertilizer requirements. Some general conclusions follow:

It was once believed in China and abroad that, through natural processes, most paddy soils contain sufficient P and K to meet plant requirements and that there would be no yield response to applications of these nutrients. However, long-term research at the International Rice Research Institute has indicated that under intensive multiple cropping with high yielding cultivars, and even on initially fertile soils, the response to P and K increases over successive crop seasons, whereas the response to N decreases if sufficient P and K are not applied (De Datta and Gomez 1975). Studies in other Asian countries have come to much the same conclusions (von Uexkull 1976).

In China, in the past, recycling of large volumes of organic matter was believed to supply P and K adequate for plant needs, and the concern was almost exclusively for chemical supplements of N. Suzhou experiments in 1965 indicated that P and K had little effect on rice yields. However, experience and opinions have recently changed; it is now believed that on most paddy soils in the Suzhou area, at least some potash is required because of the changeover to triple cropping, great increases in use of other chemical nutrients, and insufficient increases in use of organic fertilizers. Recent experiments uniformly show significant response to K in the range of 3.1-7.2 kg/ kg K, lower with unusually large compost applications, and higher under poor weather conditions (cold, drought). The effectiveness of phosphates is less certain, depending largely on soil content (the Suzhou area, on the average, appears to be a borderline case), but increases with increased N use, and also is greater on the winter crops than on rice (Xie et al 1979, Chang et al 1978).

**Table 3. Fertilizer utilization in tons of product weight, East No. 1 team, 1979.**

| Fertilizer | Wheat/ barley | Early rice | Late rice | Hybrid rice | SC late | Rape- seed | Green manure | Feed vegetables | Total |
|---|---|---|---|---|---|---|---|---|---|
| Compost | 188 | 400 | – | 240 | 320 | – | – | – | 1,148 |
| Straw | 4 | 4 | – | 6 | 9 | – | – | – | 23 |
| Green manure | – | 54 | – | 17 | 25 | – | – | – | 96 |
| Water hyacinth | 19 | – | – | – | – | – | – | – | 19 |
| Pig manure | 10 | 23 | – | 10 | 15 | – | – | – | 57 |
| River silt | 156 | 319 | – | 206 | 272 | – | – | – | 953 |
| Private pig manure | 21 | – | 15 | 2 | 6 | 14 | – | 13 | 71 |
| Collective pig manure | 19 | 27 | 15 | 27 | 19 | 12 | – | – | 116 |
| Bedding straw | 4 | 5 | 2 | 5 | 4 | 2 | – | – | 23 |
| Azolla | – | – | – | – | 20 | – | – | – | 20 |
| Straw plowed in | – | – | 12 | – | – | – | – | – | 12 |
| Nightsoil | – | – | – | – | – | – | – | 12 | 12 |
| Rapeseed cake | – | – | – | – | – | – | – | [b] | [b] |
| Ammoniated water [a] | 2 | 1 | 1 | [b] | [b] | [b] | – | [b] | 4 |
| $NH_4HCO_3$ (kg) | 514 | 420 | 458 | 244 | 430 | 91 | 40 | 17 | 2,214 |
| Deep application | 180 | – | – | – | – | 49 | – | – | 229 |
| Other base | 79 | 127 | 185 | 74 | 44 | 24 | 40 | – | 572 |
| Top dressing | 255 | 293 | 274 | 171 | 387 | 18 | – | 17 | 1,414 |
| Superphosphate (kg) | 133 | 222 | 174 | 179 | 119 | 69 | 59 | 17 | 972 |
| Hectarage | 6 | 4 | 5 | 2 | 3 | 1 | 3 | 1 | 25 |

[a] Converted from original wt to equivalent wt in terms of $NH_4HCO_3$ containing 18% N (based on content *ex factory*). [b] * = less than 0.5.

It is generally accepted that the best quality soils are unusually high in organic content and that adequate replacement of soil organic matter is necessary for long-term yield stability. But what are the most efficient sources of replacement, and how much replacement is required? Chinese experimental work indicates that, of the four major sources of humus replacement available to these teams (rice and wheat straw, green manure, water hyacinth, and azolla) straw is the most efficient. For example, the straw yield from winter wheat can contribute as much humus as the equivalent hectarage in green manure (Shi et al 1978, Wen et al 1979). The necessary experimental work to determine requirements is lacking, but U.S. long-term experiments under continuous single cropping of maize (with no fertilizer use) indicate annual losses of organic N through decomposition of around 1% (Russell 1975). Considering Suzhou yield levels and the chemical processes involved, one might guess that 1.5-4% of soil humus should be replaced each year.

Local cadres were convinced that the large increments in chemical N added in 1978-79 had not resulted in increased yields. This was confirmed by regression analysis of crop yield data over the 1970-1979 period, which indicated that yield increases in 1978-79 were not statistically significant when weather influences were taken into account. Local experiments also confirmed a marked effect of P applications. Because of the unavailability of K fertilizers, no evidence on their efficacy had been accumulated.

## Use of organic and chemical fertilizers at Baimao

The information obtained from the two teams on the production or purchase and utilization of organic fertilizers enabled compilation of complete sets of estimates for all fertilizers used (Table 3). The large proportion of labor involved in organic fertilizer collection, preparation, and application (17% for winter grain, up to 30% for rice) is explained by the application of some 60 t/crop ha, equivalent to 4% of the weight of the top 10 cm of soil. However, two-thirds is merely diluted river silt which, in its own right, contributes little to fertilizer nutrient composition.

Table 3 quantifies patterns of utilization discussed above. Compost, including green manure, is applied to early and SC rice and to winter grains, with water hyacinth replacing the green manure. Lacking the compost applications, late rice in triple-cropping sequences benefits from straw and stubble plowed under after the harvest of early rice, and rapeseed from heavier use of pig manure. Locally, azolla is grown only in conjunction with late SC rice. Deep applications of $NH_4HCO_3$ on winter crops are employed to maximize utilization rates. On flooded paddy fields it can only be broadcast and is primarily used for top dressing, although applications as basal fertilizer are no longer insignificant. Superphosphate is applied to all crops, but (contrary to extension advice) in greater amounts on rice and rapeseed than on winter grains.

## Plant nutrient balance table

Table 4 gives an estimate of total offtake of plant nutrients per ha for each crop at the normal level of crop yields for the production team, and of the amounts supplied from each type of fertilizer. The latter is estimated as a product of three factors — the amount of each fertilizer, the percentage of each nutrient it contains, and the

**Table 4. Balance of nutrients by crop in kilograms per hectare, East No. 1. at 1979 normal yield and fertilizer application levels.**

| Nutrient | Wheat/ barley | Early rice | Late rice | Hybrid rice | SC late rice | Rape-seed | Green manure | Total | % |
|---|---|---|---|---|---|---|---|---|---|
| N (immediate) | | | | | | | | | |
| Required | 53 | 43 | 25 | 66 | 30 | 66 | 0 | 39 | – |
| Supplied | 66 | 57 | 30 | 52 | 63 | 90 | 4 | 50 | 100 |
| Compost | 6 | 21 | – | 19 | 19 | – | – | 9 | 19 |
| Stable manure | 3 | 3 | 2 | 5 | 3 | 11 | – | 3 | 6 |
| Azolla | – | – | – | – | 4 | – | – | 1 | 1 |
| Straw plowed in | – | – | *a* | – | – | – | – | *a* | *a* |
| Ammoniated water | 2 | 2 | 1 | 1 | 1 | 1 | – | 1 | 3 |
| $NH_4HCO_3$ | 53 | 30 | 26 | 27 | 36 | 79 | 1 | 35 | 70 |
| N (total) | | | | | | | | | |
| Absorbed | 113 | 101 | 83 | 145 | 123 | 115 | – | 97 | – |
| Supplied | 139 | 272 | 92 | 258 | 278 | 156 | 11 | 168 | 100 |
| Compost | 39 | 162 | – | 142 | 145 | – | – | 70 | 42 |
| Stable manure | 12 | 26 | 9 | 43 | 22 | 46 | – | 18 | 11 |
| Azolla | – | – | – | – | 16 | – | – | 2 | 1 |
| Straw plowed in | – | – | 12 | – | – | – | – | 2 | 1 |
| Ammoniated water | 4 | 4 | 2 | 1 | 1 | 2 | – | 3 | 2 |
| $NH_4HCO_3$ | 83 | 79 | 69 | 71 | 95 | 108 | 11 | 73 | 43 |
| $P_2O_5$ (available) | | | | | | | | | |
| Absorbed | 47 | 43 | 37 | 62 | 59 | 59 | 40 | 47 | – |
| Supplied by | | | | | | | | | |
| Fertilizer | 21 | 63 | 16 | 67 | 52 | 36 | 8 | 35 | 100 |
| Soil | 25 | –15 | 21 | –2 | 6 | 23 | 31 | 13 | – |

Continued on opposite page.

**Table 4 continued.**

| Nutrient | Wheat/ barley | Early rice | Late rice | Hybrid rice | SC late rice | Rape seed | Green manure | Total | % |
|---|---|---|---|---|---|---|---|---|---|
| Restored to soil | 8 | 22 | 5 | 23 | 19 | 12 | 3 | 12 | – |
| Supplied by | | | | | | | | | |
| Compost | 11 | 38 | – | 36 | 36 | – | – | 17 | 50 |
| Stable manure | 2 | 2 | 2 | 3 | 2 | 8 | – | 2 | 6 |
| Azolla | – | – | – | – | [a] | – | – | [a] | [a] |
| Straw plowed in | – | – | 1 | – | – | – | – | [a] | [a] |
| Superphosphate | 8 | 22 | 14 | 28 | 14 | 28 | 8 | 15 | 44 |
| $K_2O$ (exchangeable) | | | | | | | | | |
| Absorbed | 94 | 144 | 112 | 179 | 195 | 116 | 126 | 127 | – |
| Supplied by | | | | | | | | | |
| irrigation water | 15 | 17 | 17 | 21 | 29 | 15 | – | 16 | – |
| Fertilizer | 35 | 101 | 10 | 103 | 100 | 33 | – | 52 | 100 |
| Soil | 44 | 42 | 85 | 63 | 67 | 68 | 126 | 67 | – |
| Soil availability | | | | | | | | 66 | – |
| Supplied by | | | | | | | | | |
| Compost | 27 | 93 | – | 89 | 89 | – | – | 43 | 82 |
| Stable manure | 8 | 9 | 7 | 14 | 9 | 33 | – | 9 | 17 |
| Azolla | – | – | – | – | 1 | – | – | [a] | [a] |
| Straw plowed in | – | – | 3 | – | – | – | – | 1 | 1 |

[a] Less than 0.5.

utilization rate for each nutrient from each fertilizer source. (The estimates of nutrient contents and utilization rates, available from the author, are in part rough approximations or extrapolations from limited experimental data.) A distinction is made between proportions immediately available and utilized by the current crop, those lost forever (through evaporation, leaching, erosion, and the formation of compounds unavailable to plants), and those left in the soil in a form usable by succeeding crops. In the model, a portion of plant requirements (limited by soil composition and time required for chemical processes to operate) is absorbed from the soil and the remainder from fertilizer (limited by the release of nutrients into the soil in usable chemical form). Since amounts absorbed from the soil are only partially replenished by natural weathering, etc., we are also concerned with the restoration of soil nutrient composition levels from the portion of fertilizer that is neither immediately absorbed nor lost.

These two types of balances are shown in Table 4. For N, we distinguish a balance for immediate N — that which is required from fertilizers (given absorption from the soil) and that which is released by fertilizers and converted to available forms in a single crop season — and total N, i.e., the amount mentioned plus amounts absorbed from and restored to the soil. Research on the other nutrients is much weaker, and the estimates correspondingly fragile, but we still distinguish an available (for P) or exchangeable (for K) proportion of fertilizer-supplied nutrient that the crop can absorb, a residual drawn from the soil, and an additional proportion of fertilizer nutrient that tends to restore usable-nutrient content of the soil (the last currently cannot be estimated for K).

The balances indicate that some 60% of total plant N requirements can be drawn from the soil, the remainder coming from mineralizable N supplied by fertilizer. However, the teams are actually supplying mineralizable, available N equivalent to about 50% of plant requirements at normal yield levels, giving an overall surplus of some 10%. (An equivalent statement would be that the utilization rate of fertilizer N is less than the normal indicated by experimental results.) Of this available fertilizer N, 70% is supplied from $NH_4HCO_3$, 19% from waterlogged compost, 6% from uncomposted stable manure, and 1% from azolla. Thus the team's N supply has already become heavily dependent on chemical sources. Of course, of total N derived from fertilizer, excluding losses but including amounts restored to the soil in organic and inorganic form, only 45% is derived from chemical sources, but the total supply exceeds total crop absorption from soil and fertilizer by about 70%. This surfeit is inescapable because of the low immediate utilization rates of fertilizer N — a large amount of complete N must be applied so that a small amount can be absorbed, the balance being tied up in the soil or lost.

More than two-thirds of plant requirements of P appear to be met from fertilizer applications. If only 10% of the unavailable portion of P applied will ultimately be transformed to available forms, then there will be an overall deficit — more usable P would be withdrawn than replaced. Of total P applications, 50% is supplied from compost, 6% from manure, 44% from superphosphate, and less than 1% from other sources.

We estimate that 13% of the total absorbed K may be supplied from irrigation water, 41% from fertilizer, and the remainder from the soil. If local K content of the soil is as high as the average for the region, total requirements can be met in the short run (on optimistic assumptions about utilization rates). However, we found no research results that indicated whether or how fast K restored to the soil can be made available for plant absorption; hence our balance is incomplete. Since potash is not commercially available, 82% of absorbable K comes from compost and the remainder from hog manure or straw returned to the fields.

For individual crops, there is some evidence of unbalanced nutrient applications. For example, hybrid rice has received treatments similar to those received by late SC rice. Yet, because it has higher yield, shorter growing period, and greater rate of total N offtake than late SC rice, the hybrid's requirement of N from fertilizer should be higher than the conventional cultivar's. At the same time, all crops except hybrid rice

**Table 5. Nutrient balance by crop sequence, in kilograms per cultivated hectare, 2 teams, at 1979 normal yield and fertilizer application levels.**

| Nutrient | Barley-rice - rice | GM - rice - rice | Wheat - late rice | Rape - late rice | Wheat - hybrid rice |
|---|---|---|---|---|---|
| East No. 1 team | | | | | |
| N-immediate required | 104 | 72 | 76 | 87 | 115 |
| N-immediate supplied | 135 | 87 | 121 | 141 | 112 |
| Surplus (deficit) | +31 | +15 | +45 | +55 | +3 |
| Complete N required | 256 | 193 | 225 | 222 | 251 |
| Complete N supplied | 436 | 333 | 399 | 414 | 384 |
| Surplus (deficit) | +180 | +333 | +399 | +414 | +384 |
| Effective $P_2O_5$ required | 107 | 111 | 109 | 114 | 119 |
| Supplied by fertilizer | 86 | 77 | 72 | 84 | 87 |
| Supplied by soil (residual) | 22 | 35 | 37 | 30 | 32 |
| Restored to soil | 29 | 26 | 26 | 29 | 30 |
| Surplus (deficit) | +7 | –9 | –11 | –1 | –2 |
| Exchangeable $K_2O$ required | 299 | 342 | 302 | 312 | 305 |
| Supplied by irrigation water | 44 | 31 | 41 | 27 | 34 |
| Supplied by fertilizer | 122 | 98 | 130 | 128 | 135 |
| Supplied by soil | 150 | 150 | 150 | 150 | 150 |
| Surplus (deficit) | +17 | –62 | +19 | –7 | –14 |
| No. 6 team | | | | | |
| N-immediate required | 90 | 68 | 69 | 87 | 114 |
| N-immediate supplied | 135 | 86 | 117 | 127 | 114 |
| Surplus (deficit) | +45 | +18 | +48 | +40 | 0 |
| Complete N required | 247 | 184 | 208 | 221 | 250 |
| Complete N supplied | 440 | 331 | 395 | 393 | 394 |
| Surplus (deficit) | +193 | +147 | +187 | +171 | +145 |
| Effective $P_2O_5$ required | 103 | 109 | 102 | 115 | 119 |
| Supplied by fertilizer | 73 | 68 | 70 | 83 | 74 |
| Supplied by soil (residual) | 30 | 41 | 31 | 32 | 45 |
| Restored to soil | 26 | 24 | 26 | 30 | 27 |
| Surplus (deficit) | –4 | –17 | –5 | –2 | –18 |
| Exchangeable $K_2O$ required | 292 | 337 | 286 | 312 | 312 |
| Supplied by irrigation water | 44 | 31 | 41 | 27 | 34 |
| Supplied by fertilizer | 134 | 105 | 150 | 153 | 147 |
| Supplied by soil | 150 | 150 | 150 | 150 | 150 |
| Surplus (deficit) | +30 | –50 | +55 | +18 | +20 |

appear to receive more N than their offtake at current normal yield levels. Thus the balance tables are in accord with the general belief that N is in surplus.

The winter crops and late rice in the triple-cropping sequences appear to receive inadequate applications of P and K because the lack of raw materials and labor time for preparation limit use of compost on these crops, and insufficient superphosphate and no potash are being applied to make up for the difference.

The balance tables may be aggregated over complete crop sequences (Table 5). The amount of nutrient absorption is basically proportionate to yields; hence the price of higher yields under either triple cropping or wheat - hybrid rice is a higher nutrient demand. However, two-crop rice, with shorter durations, absorbs a smaller proportion of the residual soil N, and so must depend more on supplemental N from chemical sources, contributing to higher cash production costs (Zhu et al 1978, Hsi et al 1978). Although the N requirements of each sequence are apparently met by current application levels (albeit just barely for wheat - hybrid rice), it seems that some fertilizer could be profitably diverted from late SC rice and rapeseed to the GM - rice - rice and wheat - hybrid rice sequences. The latter sequences on the whole are also most likely to be deficient in P and K (only relative magnitudes of nutrient surplus or deficit should be taken as serious indicators). This is due partly to the redistribution of nutrient absorbed by green manure to other cropping sequences (via compost), and also to the high requirement for P and K of hybrid rice (Jiangxi Academy of Agricultural Sciences 1978). Both of these sequences are employed in the 3-year rotation on the better soils, which, therefore, bear the brunt of any deficit.

It is estimated that in 1979 some 76-79% of contributions to soil humus (ignoring plant roots) came from recycled straw (plowed under, composted, or included in stable manure), compared to 14-17% from green manure and 3-5% each from water

**Table 6. Restoration of humus in tons per hectare, sources and amounts, East No. 1 and No. 6 teams, 1979 crop year.**

| Source | Rate of conversion[a] (%) | East No. 1 | | No. 6 | |
|---|---|---|---|---|---|
| | | Amount[b] | Humus | Amount[b] | Humus |
| Green manure | 2.3 | 9.3 | 0.2 | 10.5 | 0.3 |
| Water hyacinth | 2.6 | 1.8 | 0.1 | 1.5 | [d] |
| Azolla | 2.6 | 1.7 | [d] | 2.3 | 0.1 |
| Rice straw | 21.4 | 5.6 | 1.2 | 5.2 | 1.1 |
| Total increase in humus | | | 1.5 | | 1.5 |
| Weight of topsoil (10 cm) | | 1,500 | | 1,500 | |
| Increased humus as percent of soil weight | | | 0.1 | | 0.1 |
| Av total organic matter content of soil[c] (%) | | | 2.0 | | 2.4 |
| Increased humus as percent of total humus | | | 4.9 | | 4.1 |

[a] Cited (on a dry basis) in Wen et al (1979). Converted to fresh (or, in the case of straw, wind-dried) weight basis using moisture contents given in Shi et al (1978) or as suggested by soil scientists Deming Yu and Jiahua Gao of the Jiangsu Academy of Agricultural Science. [b] Excluding water hyacinth and rice straw used as animal feed. [c] Weighted average of estimates for each soil type derived from soil assay in Table 2. [d] less than 0.05.

hyacinth and azolla (Table 6). Overall addition of humus through recycling of organic matter totaled some 4-5% of original soil humus content, an amount that should be more than sufficient for replacement purposes. In view of the high conversion rate of rice or wheat straw, it would seem that most cropping sequences potentially create more soil humus than they degrade (the amount degraded should be proportional to residual N absorbed from the soil, as opposed to fertilizer). This depends on the extent of recycling, however. As seen earlier, in these 2 teams about 50% of straw was recycled, the remainder being distributed to be used as fuel, building materials, and pig feed. The lack of alternative fuels in the area is the main source of this problem.

Summing up what has been learned from the soil analysis, the technical literature, and the balance tables, it must be concluded that fertilizer allocation practices in these two teams, and probably in many others in Suzhou, do not maximize production; moreover, there is cause for concern that current yield levels cannot be indefinitely sustained without major increases in the application of P and K. Insufficient N is being applied to hybrid rice, primarily because it is being managed as if it were a conventional middle rice, while other crops receive excessive applications. Late rice and the winter crops still receive insufficient P and K. The teams are depleting their best land at rates that differ by crop sequence.

## Crop sequence compared: bionomic efficiency

A more useful estimate of the bionomic efficiencies of various crop sequences can be gained if we consider the amounts of each nutrient that must be supplied from fertilizer if soil fertility is to be maintained, i.e., if the soil is not to be depleted. In making such a comparison, we measure net nutrient offtake at the margin, assuming

**Table 7. Efficiency of nutrient use by crop sequence.**[a]

| Nutrients required | Nutrient (kg) | | | | | |
|---|---|---|---|---|---|---|
| | Barley - rice - rice | GM - rice - rice | Wheat - late rice | Rape- late rice | Barley - late rice | Wheat - hybrid rice |
| | | | *Per kg grain* | | | |
| N (available) | 0.009 | 0.006 | 0.007 | 0.009 | 0.007 | 0.010 |
| $P_2O_5$ (available) | .010 | .011 | .011 | .013 | .010 | .011 |
| $K_2O$ (exchangeable) | .009 | .015 | .010 | .014 | .008 | .010 |
| Humus | –.060 | –.137 | –. 107 | –.088 | –.086 | –.120 |
| | | | *Per yuan*[b] *net income* | | | |
| N (available) | .090 | .066 | .058 | .070 | .066 | .094 |
| $P_2O_5$ (available) | .097 | .116 | .089 | .098 | .095 | .101 |
| $K_2O$ (exchangeable) | .086 | .159 | .081 | .109 | .078 | .094 |
| Humus | –.602 | –1.410 | –.902 | –.669 | –.809 | –1.102 |

[a] Based on requirements that must be supplied from fertilizer to maintain nutrient balance, netting out potential contributions from straw and green manure production in each sequence, which are assumed to be composted (the nutrients are assumed to be utilized at the same average utilization rates as for compost as a whole). Computations assume normal yields of each crop as estimated for East No. 1 team, with rapeseed converted to grain-equivalent at the ratio of rape-seed to wheat prices. Grain yields net out seed requirements; net income is based on within-quota prices and deducts cash costs excluding fertilizers, fixed costs, and labor. [b] $1 = ¥1.80.

that by-products like green manure and straw can be recycled, and take as denominators measures of output, specifically grain production (net of seeds) and net revenue (ignoring costs of fertilizer, labor, and fixed inputs). We may therefore consider these to be measures of the marginal relative bionomic efficiencies of the alternative crop sequences (Table 7).

A comparison of the ratios in Table 7 leads to the conclusion that the traditional double-crop sequences, wheat - late SC rice or barley - late SC rice, are most efficient, especially in minimizing nutrient requirements per yuan net income. Surprisingly, barley - rice - rice is not far behind, and is superior to wheat - hybrid rice (although the comparison does not account for the fact that a larger proportion of barley - rice - rice nutrients must come from chemical sources, raising cash costs). At the bottom of the ranking are green manure - rice - rice and rapeseed - late SC rice. Green manure, of course, is efficient in its use of soil N and also appears to conserve more humus than other sequences — not so much because, of the conversion to humus of recycled green manure, but because, by assumption, GM's absorption of one-third of its N from the soil is balanced by the one-third of plant weight remaining in the roots, which are not harvested and so contribute to new humus formation. The low ranking of rapeseed - late SC rice may be attributed to undervaluation of rapeseed relative to grain in the state pricing scheme.

## ECONOMICS OF INTENSIFICATION

In this section, the elements previously discussed are linked together in the context of a whole-farm analysis, by mathematically modeling the situation and opportunities of the production team, and solving the model for the mix of activities that satisfies the constraints on a farm's behavior, yet best meets its objectives. A linear programming model consisting of some 32 activities and 27 constraints has been constructed. The activities include the production of different crop sequences, sales of above-quota grain and rapeseed, collective and private pig raising, and use or purchase of each distinct type of organic and chemical fertilizer. The constraints reflect limits on team resources of labor, land, and purchased or recycled inputs and the requirements of these in each production activity; restrictions on team decisions imposed by the quota *cum* rationing system for inputs and outputs; and the important restriction that plant nutrient replenishment must at least equal offtake so that soil availability is not degraded. The model has been used to study several issues: Is the mix of activities practiced by the Baimao farms optimal with respect to their own (presumed) objectives? If not, what changes would be advantageous and how much of a difference would they make? What would the farms likely do if the state dropped some of the existing restrictions on their decision-making freedom, if the supplies of some scarce inputs were increased, or if relative prices changed? And since the farms studied differ (particularly in labor-land ratio) from the average Suzhou team, to what extent can the findings be generalized to the district as a whole? The following summarizes those findings having bearing primarily on the optimality of organic fertilizer use.

Tables 8 and 9 present basic solutions for the two teams, including the optimal values of activities and the corresponding nonzero shadow prices of constraints.

**Table 8. Basic model solutions, East No. 1 team.**

| | | Maximization objectives | | | |
|---|---|---|---|---|---|
| Activities | Actual[a] | Net revenue pigs > k[b] | Net revenue with AQP[c] | Net revenue without AQP[d] | Gross revenue[e] |
| Key indicators | | | | | |
| Net revenues[f] (¥) | 20,930 | 21,700 | 23,420 | 21,780 | 21,400 |
| Cash costs (¥) | 18,300 | 15,810 | 12,700 | 16,400 | 16,390 |
| Grain yields[g] (t/ha) | 9.6 | 9.0 | 9.2 | 9.0 | 9.0 |
| Above-quota sales[h] (t) | 12 | 8 | 19 | 7 | 7 |
| Rape above-quota sales (t) | 0.1 | 0 | 0 | 0 | 0 |
| Vegetable sales (ha dryland) | 0 | 0.1 | 0.4 | 0 | 0 |
| Private hogs[i] (100 kg) | 47 | 47 | 47 | 47 | 47 |
| Collective hogs[i] (100 kg) | 31 | 31 | 0 | 0 | 35 |
| Collective shoats[i] (100 kg) | 13 | 9 | 6 | 36 | 10 |
| Market shoat sales (100 kg) | 2 | 0 | 0 | 30 | 0 |
| Crop sequence mix (percent of hectarage) | | | | | |
| Barley - rice - rice | 22 | 0 | 9 | 0 | 0 |
| GM - rice - rice | 23 | 19 | 10 | 19 | 19 |
| Barley - late SC rice | 3 | 10 | 4 | 0 | 2 |
| Wheat - late SC rice | 18 | 29 | 30 | 33 | 32 |
| Rape - late SC rice | 10 | 10 | 10 | 10 | 10 |
| Wheat - hybrid rice | 19 | 22 | 26 | 26 | 24 |
| Barley - hybrid rice | 5 | 0 | 0 | 0 | 0 |
| Winter fallow - late rice | 0 | 6 | 9 | 8 | 8 |
| GM seeds - hybrid rice | 0 | 5 | 4 | 5 | 5 |
| Fertilizers used[j] (t) | | | | | |
| Straw | 42 | 43 | 57 | 47 | 48 |
| Green manure | 96 | 95 | 68 | 94 | 95 |
| Water hyacinth | 19 | 19 | 20 | 19 | 19 |
| Hog manure | 272 | 262 | 173 | 257 | 274 |
| Azolla | 17 | 48 | 46 | 16 | 24 |
| Nightsoil | 7 | 7 | 7 | 7 | 7 |
| Rapecake | 0 | 0 | 0 | 0 | 1 |
| $NH_4HCO_3$ | 22 | 15 | 16 | 15 | 15 |
| Superphosphate | 10 | 10 | 10 | 10 | 10 |

[a] Output-dependent figures are adjusted to a "normal year" basis, and so differ from reported 1979 statistics. Current, "actual" solution violates the crop nutrient balance constraints and thus "infeasible." [b] Collective pig production constrained to current actual level. [c] Maximum revenues, accounting for above-quota premium. [d] Maximum revenues, assuming no above-quota premium. [e] Maximum gross revenue (ignoring cash costs), subject to restriction that no market sales of shoats are allowed. [f] Including labor compensation and earnings from private pigs. $1 = ¥1.80. [g] Net of seeds. [h] Excluding rapeseed. [i] At live weight. [j] At fresh weight.

(Shadow prices are measures of the value of an additional unit of any resource or the unit gain from relaxing any constraint in terms of the farm's objectives.) For comparison, the actual current situations are shown in the first column of each table. These situations are not feasible solutions of the model because current applications of fertilizer do not fully satisfy plant requirements at normal yields, a condition disallowed by the model. Three revenue-maximizing solutions are shown for each team: the first (column 2) assumes that teams cannot reduce collective pig production below current levels; the second (column 3) assumes that they can freely

**Table 9. Basic model solutions, shadow prices in yuan, East No. 1 team.**

| Constraint | Maximization objective | | | | |
|---|---|---|---|---|---|
| | Actual price[a] | Net revenue pigs >k[b] | Net revenue with AQP[c] | Net revenue without AQP[d] | Gross revenue[e] |
| Labor | | | | | |
| Work year | 294 | 108 | 110 | 103 | 75 |
| 6/16-6/30 (man-days) | 2 | 7 | 7 | 7 | 5 |
| Land (ha) | | | | | |
| Paddy | – | 1,420 | 1,196 | 590 | 2,033 |
| Dryland | – | 584 | 582 | 3,230[f] | 4,492[f] |
| Nutrient (kg) | | | | | |
| N-immediate | 4 | 4 | 4 | 4 | 4 |
| $P_2O_5$-effective | 3 | 10 | 12 | 5 | 14 |
| $K_2O$-exchangeable | – | 8 | 6 | 4 | 11 |
| Fertilizers (t) | | | | | |
| Straw | 40 | 57 | 50 | 32 | 79 |
| Green manure | – | 52 | 46 | 29 | 70 |
| Water hyacinth | – | 46 | 40 | 26 | 63 |
| Hog manure | 12 | 16 | 16 | 10 | 21 |
| River silt | – | 7 | 7 | 4 | 8 |
| Azolla (ha) | 14 | 14 | 15 | 14 | 14 |
| Nightsoil | 8 | 14 | 14 | 10 | 12 |
| Rapecake | 200 | <200 | <200 | <200 | 119 |
| $NH_4HCO_3$ | 160 | 160 | 160 | 160 | 160 |
| Superphosphate | 130 | 468 | 598 | 264 | 686 |

[a] Prevailing prices, unit values, or cash costs of production. For labor, these represent average wages in brigade or commune industry (including compensation to teams); for nutrients, as supplied in the cheapest available chemical forms; for fertilizers, as paid by the state (straw), paid to team members (manure and nightsoil), or paid to the state (all others), except azolla, which is cash cost. [b] Collective pig production, constrained to current actual level. [c] Maximum revenues, accounting for above-quota premium. [d] Maximum revenues, assuming no above-quota premium. [e] Maximum gross revenue (ignoring cash costs), subject to restriction that no market sales of shoats are allowed. [f] Unreasonably high due to importance of pig production in solution and inflexibility of pig-raising technology assumed.

abandon this enterprise; the third (column 4) assesses the effect of dropping above-quota prices. Finally, column 5 presents solutions maximizing gross revenue, i.e., disregarding cash production costs. To conserve space, only basic solutions for one team are shown; additional solutions, including extensive sensitivity analysis, underlie the following generalities regarding the overall farming situation:

1. *Neither crop yields nor gross revenues can be significantly improved on through a change in the mix of existing activities,* given current prices and constraints on input levels. This result follows from the relatively small differences among major crop sequences in yields or gross values. Moreover, since the seasonal labor constraints and quota requirements dictate a considerable degree of diversification, changes in the objective function have less than drastic effects on crop proportion.
2. *Net revenues could be significantly increased, but partially at the expense of the state.* Three forms of deintensification would improve net revenues by a total of 12-25% — reduction of triple cropping, abandonment of the unprofitable

collective pig raising, and curtailment of purchases of chemical nitrogen. But the cost to the state would be high, as the latter would have to accept greatly increased above-quota grain sales at high prices and would lose the benefits of the effective tax on collective pig production (that is, the losses would be transferred to the state if it replaced the lost meat production with state enterprise production).

3. *Although sharp curtailment of triple cropping is called for at Baimao and in Suzhou generally, regardless of the objective function, triple cropping sequences are useful in satisfying the seasonal labor, nutrient, and grain quota constraints.* Contrary to conventional wisdom, a shortage of labor or chemical P is favorable to limited triple cropping. Because of the complementary seasonal pattern of labor requirements, triple cropping can help to level the demands for labor. Because more of the nutrient absorbed by green manure is ultimately recycled, it is less burdensome than other winter crops and therefore green manure - rice - rice may be favored when sufficient P cannot be purchased. But these advantages disappear with greater availability of labor or P compared to those at Baimao.

   On the other hand, if fixed responsibilities (including quotas and ration requirements) are high, (forcing choice of sequences with high gross yields, then production teams may again have recourse to barley - rice - rice. As suggested by the "Suzhou model" solutions, which consider the optimal solutions, if both labor and each kind of ration are doubled to the level prevalent on the average in Suzhou District, such pressures may be significant elsewhere in Suzhou. They also raise the demand for organic fertilizers.
4. *The optimal crop mix is very sensitive to differences in situation among teams, including differences in relative crop yields as well as in resource availability.* For example, increased availability of K and other nutrients induces the model for one farm to emphasize barley - rice - rice while the other favors rape - rice, as a result of relatively small differences in normal yields between the two farms.
5. *An increase in pig procurement prices approaching 40% is required to make collective pig raising economically worthwhile, however admirable the heavy use of pig manure in Suzhou farming.* In other words, the political pressure now required to sustain collective pig production imposes an implicit tax burden on the production teams equivalent to about 40% of the gross value of their pig sales.
6. *Labor is basically surplus in Suzhou.* Even at Baimao, where labor-land ratios are half the Suzhou norm, the shadow price of labor (in the basic solution) is only one-third of the average annual earning per worker, reflecting a brief seasonal labor shortage. The Baimao farms could absorb about 30% more labor before its shadow price falls to zero, but this would add less than 10% to net product, not enough to feed the extra mouths involved. In the average Suzhou team, with twice as much labor, some 35% of the agricultural labor force, judged from the Suzhou model solution, may be entirely surplus to cultivation.

In the context of the model solutions, heavy use of organic fertilizers appears economically efficient in the Chinese institutional context at the current level of development. Although in basic optimal solutions of the model, the total amounts of recycled green manure and pig manure are reduced by reduction of hectarage in green manure and abandonment of collective pig raising. this is offset by increased recycling of straw, water hyacinth, and azolla. An important reason is the absence of wage labor: the production team's labor force receives a share of the surplus divided according to labor input. The model does not account for the labor costs of recycling separately from those attached to each cropping system, but the shadow price of labor is zero in all except the late June period, and only a tiny portion of labor associated with organic fertilizer use falls into this period. On the other hand, the shadow prices of recycled organic materials are high, reflecting the scarcity of nutrients and the costs of chemical alternatives. On the average, labor expended in collection, processing, and application of organic fertilizers (compost plus pig manure) is less than 2 days/t, or under $1.94 at the average 1979 value of income distributed per workday. The time seems distant when the opportunity cost of labor will discourage use of organic fertilizers.

There are some interesting qualifications, however. For example, the farms currently meet most of the expansion requirements for azolla production by keeping some hectarage in early-maturing barley or naked barley followed by middle or late rice crops. The model solves the same problem by leaving some winter hectarage fallow, thus also reducing the total plant nutrient requirements in crop cultivation. But under three circumstances, winter fallow should be reduced, in which case the opportunity cost of planting potential wheat hectarage in barleys proves too high for azolla to be worthwhile: 1) increased labor availability, making it possible to specialize in wheat - late rice, which in turn has low nutrient demands so that fallowing is not necessary; 2) increased grain quotas or rations to be met, making fallowing a costly luxury; 3) greater availability of P and K fertilizers, making fallowing unnecessary. Since these circumstances bracket the average condition in Suzhou as a whole, and the future at Baimao as well, azolla clearly has a limited prospect in areas with drainage adequate for good yields of winter wheat.

At present the shadow prices of the organic fertilizers that are purchased from team members or could be sold to the state exceed their prices by enough to cover the cost of transport and application labor. This will not be true indefinitely, however. Greater availability of superphosphate and introduction of chemical K into the model causes drastic falls in the shadow prices of organic fertilizers to below current price levels. If side industry were to develop enough to absorb the small surplus of labor in the May-15 June period, heavy use of organic fertilizer might begin to seem less economical.

Some types of recycling appear to be uneconomical at present. Rapeseed cakes, purchased from the state at a high price in terms of nutrient delivered, appear worthwhile only when there are severe pressures to produce more grain without any increase in P or K supply. Industrial waste water, penalized by the model for its volatility and trivial nutrient content, never enters an optimal solution.

## CONCLUSIONS

Could any of the present sources of nutrients be efficiently expanded? On the contrary, these teams would profit by reduction of some fertilizer-producing activities. Exceptions probably include the growing of water hyacinth and azolla. The former involves minimal production costs and labor, and provides the green matter for compost used on winter crops, but it contributes minimally to P and K balances and its expansion is limited by availability of water surfaces.

Azolla appears to be a cheaper source of N than of $NH_4HCO_3$ if only cash and labor costs are considered, but its real opportunity cost is the need to reserve for azolla multiplication fields that would otherwise be planted to winter crops. This cost is minimized in this locality by limiting azolla to use on hybrid or late SC rice and requiring that 20% of expanded azolla hectarage be reserved for barley - late SC rice, which allows time for azolla expansion during the crop turnover period. Barley - rice is lower yielding than wheat - rice, but more nutrient efficient, as seen above. The economic evaluation of this trade off (which depends on the relative yields of barley and wheat, and the relative scarcities of fertilizer nutrients) probably determines the marginal profitability of increased azolla use. Where winter grains are precluded by poor drainage (as in many parts of south China), azolla is likely to be quite cost competitive with chemical sources of N under current labor-surplus conditions.

Green manure (milk vetch) appears to be a dubious choice of winter crop in regions with profitable alternatives. Its main advantage is that, by fixing atmospheric N, it makes a net addition to the nutrient balance. For that reason, it was advantageous before the availability of cheap chemical N. Green manure makes no net contribution to P and K, but apparently degrades less humus than do other winter crops. But in this locality, where N supplies are more than adequate, the opportunity cost of N from green manure exceeds that supplied by chemical fertilizer, and humus maintenance is not a problem, green manure hectarage should generally be cut back.

Pig manure, composted or used directly, is a major source of recycled nutrient, especially rich in P and K. More than half of total supplies are derived from private pig raising, the profit of which depends on underutilized family labor, grain millings, and table scraps. Because these free family resources are limited, expansion potential for private pig raising is not great. On the other hand, collective pig raising can be expanded, but from the teams' viewpoint should be contracted or eliminated in the interest of increased sales of above-quota grain. This may not be advisable from the state's point of view, but in any case expansion cannot be justified by the utility of the pig manure alone. The pig-raising enterprise removes more nutrient from the system (in feed, fuel, and bedding) than it returns (as manure), and so can only be judged in terms of the profitability of the joint products of meat and manure — which at present procurement prices is negative.

One source of fertilizer — particularly P, K, and organic matter — which could be efficiently expanded is the recycling of straw. Contraction of green manure hectarage and collective pig raising would increase the amounts available for recycling. If fossil or other fuels were to be made available to replace straw as fuel (or at minimum if care were taken to return the ashes, rich in P and K, to the collective), the P and K deficits could be greatly relieved. Apparently Wuxi County has a program to substitute coal for straw as fuel and simultaneously to eliminate green manure hectarage. Of course, Wuxi has a stronger stimulus (as the most intensively cropped county) and better access to coal (as an industrial center with water and railroad transport links to producing regions); such a program might be impractical elsewhere in the Suzhou District.

Considering the limited economic potential for further expansion of organic sources of nutrient, increased chemicalization surely is a prerequisite to further intensification. Whether these teams — and by extrapolation, the Suzhou District or much of south China — are to turn to triple cropping or double cropping with hybrid rice as a vehicle for this intensification, it appears that lack of chemical sources of K is going to be the major constraint on future yield increases. With China's total production of potash a mere 16,000 tons in 1979, increased imports and rapid exploitation of known deposits should be given high priority in government plans.

## REFERENCES CITED

Chang, H. P., C. L. Tu, M. T. Ma, C. H. Chen, Y. Chia, and C. C. Hsieh. 1978. The potassium supplying capacity of Jiangsu soils and the use of potassium fertilizers. Acta Ped. Sinica. 15:61-74.

De Datta, S. K., and K. A. Gomez. 1975. Changes in soil fertility under intensive rice cropping with improved varieties. Soil Sci. 120:361-366.

FAO (Food and Agriculture Organization of the United Nations). 1977. China: Recycling of organic wastes in agriculture. Food and Agriculture Organization, Rome. Soil Sci. Bull. 40.

Hsi, C. P., Y. C. Pien, A. C. Kuang, T. P. Liu. and M. Y. Liu. 1978. Studies on peak nutrient uptake of double-cropped rice and the method of basal dressing with volatile nitrogen fertilizer to the whole plowed layer. Acta Ped. Sinica 15:113-125.

Jiangxi Academy of Agricultural Sciences, Soil and Fertilizer Section. 1978. Plant nutrient absorption of hybrid paddy rice. Turang Feiliao [Soil Fert.] 5:25.

Liu Guangyu, H. S. Dai, Cao Jusheng, and T. B. Wiens. 1980. Study of economic efficiency of rice cropping sequences in Suzhou District. Jiangsu Nongye Kexue [Jiangsu Agric. Sci.] 6:18.

Russell, J. S. 1975. A mathematical treatment of the effect of cropping system on soil organic nitrogen in two long-term sequential experiments. Soil Sci. 120:37-44.

Shi Shu-lian, L. L. Cheng, H. H. Lin, C. L. Shu, and C. H. Wen. 1978. The effect of azolla in increasing yields and improving soil. Acta Ped. Sinica 15:54-60.

von Uexkull, H. R. 1976. Aspects of fertilizer use in modern high-yield rice culture. International Potash Institute, Bern. IPI Bull. 3.

Wen Qi-xiao, X. X. Lin, and S. L. Shi. 1979. The content and renewal of organic matter in the soils of the Taihu region. *In* Soils Research Institute, Nanjing, ed. Taihu Dichu Shuidao Tufeili Yenjiu Lunwenji: Gangyao [Collection of Research papers on Paddy Soil Fertility in the Taihu Region: abstracts].

Xie J. C., C. L. Du, and Y. Q. Gu. 1979. The status of potassium in the paddy soils of the Taihu Region. *In* Soils Research Institute, Nanjing, ed. Taihu Dichu Shuidao Tufeili Yenjiu Lunwenji: Gangyao [Collection of research papers on paddy soil fertility in the Taihu Region: abstracts].

Zhu Zhao-liang, H. L. Liao, K. S. Tsai, and C. C. Yu. 1978. Soil nutrition status under rice-rice-wheat rotation and the response of rice to fertilizers in Suzhou District. Acta Ped. Sinica 15:126-37.

# TRENDS AND ECONOMIC FACTORS AFFECTING ORGANIC MANURES IN JAPAN

Natsuki Kanazawa

The use of organic manures in Japan has steadily decreased since 1955, when total consumption of N from chemical sources overtook consumption of N from organic sources. After World War II, application of organic manures decreased with increased farm mechanization, the economy shifted from rural to urban, and chemical fertilizers became less expensive. Today, machines have replaced draft animals, 90% of all farmers are engaged in agriculture only part-time, and chemical fertilizers remain relatively cheap in relation to the price of rice. Given the present conditions, it is legitimate to ask why Japanese farmers have an interest in organic manures. The reason is in part that the Agricultural Basic Law of 1960 caused the specialization of dairy, beef, hog, and poultry farms, and the wastes from animals used for food are a source of pollution. Then in 1970, the Japanese Government, in an attempt to reduce rice surpluses, began recommending that farmers plant dryland crops such as barley, wheat, soybean, and forage in place of rice. When organic manures were in widespread use before the 1950s, they were used primarily as basal applications on dryland crops. The present waste problem caused by specialized animal feeding operations, combined with the increased emphasis on dryland crop production in Japan, provides the opportunity to reconsider the importance of organic manures in crop production.

Many soil scientists have emphasized that organic manures are not indispensable for crop production and that almost all the functions of soil productivity can be covered artificially without their application. They present, as evidence, data that show increased rice yield per hectare for the last 20 years under decreasing application of organic manures. But the question arises as to why many excellent and diligent farmers still believe in the effectiveness of organic manures.

In Japan, national statistics show the use of a decreasing amount of organic manure year by year, but the main factor involved is the increasing number of part-time farmers. In fact, relatively large and full-time farmers are now making a great effort to apply organic manures to their fields. They are aware of differences in the effectiveness of organic manure applied on wetland and dryland fields, and of that applied on well-drained and poorly drained fields. (The term "wetland fields" is used here to designate irrigated rice fields.) It is evident, then, that some classes of farmers are clearly aware of the importance of organic manures.

---

Professor, Nihon University, 3-34 Shimouma, Setagaya-ku, Tokyo, Japan.

Japanese farmers seem not to consider the use of organic manures indispensable because good soil conditions, water, and nutrients can be retained by deep tillage, soil disinfection, and use of chemical fertilizer; but they are aware that such methods require careful and intensive cultivation practices and sometimes a large investment. The application of organic manures might be a simple alternative to such methods for maintaining soil in good physical, chemical, and biological conditions. Of course, the production of manure, which requires a large amount of labor, is difficult for part-time farmers who have off-farm jobs. But to certain full-time farmers the effectiveness and simplicity of organic manures create a viable alternative to modern management and investment.

## HISTORICAL REVIEW OF FERTILIZATION IN JAPAN

### Fertilization during the Meiji Era

Max Fesca, a German soil scientist invited by the Japanese Government at the beginning of the Meiji Era (1867-1912) to guide the future direction of Japanese agricultural development, strongly influenced Japanese agricultural policies. He pointed out four weak points of Japanese agricultural technology: 1) underutilization and high price of fertilizer, 2) shallow tillage, 3) poor drainage of paddy fields, and 4) inadequate crop rotation systems (Fesca 1888).

Fesca was very much impressed by the importance of human feces and urine as sources of fertilizer and was surprised that Japanese farmers worked so hard every day to cut wild grass for fertilizer and animal feed. He emphasized that wild grass has very low plant nutrition content and thus cannot be expected to be a good fertilizer. Leading farmers, in southwestern Japan in particular, strongly opposed Fesca’s suggestions concerning fertilizer use. In view of the hot and humid climate in those areas, their opposition may have been reasonable; they were aware that heavy application of fertilizer would create danger of lodging, insect and disease damage, and other problems. However, following Fesca’s advice, the Japanese Government began encouraging farmers to apply much more fertilizer, and the development of technology suitable for heavy fertilizer application became the main issue in agricultural experimental stations and research institutes. By 1935, Japan had become a country of comparatively high fertilizer use (Kayo 1964).

Before the Meiji Era, commercial organic fertilizers such as fish manure and soybean cake were used for dryland commercial crops in areas near cities but were seldom used in wetland fields. At the beginning of the Meiji Era, night soil and raw and dry wild grass were applied to nursery beds in rice fields; night soil and organic manure (supplementary commercial organic fertilizers such as oil cake and fish manure) were applied to main fields. Of course, the actual use of fertilizer differed from area to area, and the high price Fesca pointed out referred to commercial organic fertilizers. Generally, for rice fields, the use of self-supplied manures was common.

By the middle of the Meiji Era, the area of crop land had expanded in line with the food production policy of the Government, which aimed at increasing the production of rice to meet the demands of the rapidly growing population. Consequently, a very large area of wild grassland and forest, which had been the main sources of grass, had been converted into crop lands, resulting in an increased rate of commercial fertilizer use; Japan began importing increasing quantities of soybean cake from China (Kurokawa 1978).

At the end of the Meiji Era, Japan started domestic production of superphosphate and $CaCN_2$. Just after World War I, cheap synthetic $(NH_4)_2SO_4$ was imported, but was domestically produced from the beginning of the Showa Era (1926-present). The consumption of commercial fertilizer has since increased rapidly, and Japan has become a large consumer of commercial fertilizers.

Changes in the pattern of fertilizer consumption in Japanese agriculture may be summarized as follows (Kayo 1964):

- 1902-1906. The main commercial organic fertilizer changed from fish and animal products to plants.
- 1904. In the total consumption of P, commercial chemical fertilizer overtook commercial organic fertilizer.
- 1911. In the total consumption of K, commercial chemical fertilizer overtook organic fertilizer.
- 1926-1930. The dominant commercial fertilizer changed from organic to chemical fertilizer.
- 1955. In the total consumption of N, commercial fertilizer overtook self-supplied manures.

## Fertilization in rice fields before World War II

Before World War II, Japanese farmers in commercialized farming areas used less fertilizer in wetland fields than in dryland fields (Kanazawa Agricultural Experiment Station 1954). Especially in dryland farming areas near Tokyo and Osaka, where commercial farming had a long history, various kinds of commercial organic fertilizer were used. But in these commercialized areas the farmers did not use organic manures. After the transition from commercial organic fertilizer to chemical fertilizer, these areas were further developed as suburban vegetable gardening areas with more intensive fertilizer use. However, in most cases the farmers did not use organic manures because their type of farm management lacked animal husbandry. In suburban areas, the price of land was so high that it was not economical to cultivate forage crops. The use of organic manures by farmers in dryland areas is a recent trend, even though organic manure produced from fallen leaves had been used widely from early days in Tokyo’s suburban dryland farming area.

In contrast, in relatively underdeveloped dryland areas where no particular commercial crops were grown the farmers applied organic manures from hogs and hens. Since these animals were raised to maintain the dryland soil rather than to be sold, the number raised was very small.

In 1930, about three of five farmers in Japan raised a cow or horse as a draft animal, mainly for use in paddy production (Kayo 1958). The actual period of utilization, however, was as short as 30 days/year in most cases. The animals were fed mainly with wild grass, rice straw, and a small amount of rice and barley bran, while almost no forage crops were grown. Even though organic manures were very important fertilizers, the amount of application per hectare was relatively small compared with that in European countries.

Dairy farming was developed from rather early days only in suburban areas, with no land devoted to the cultivation of forage crops. After World War II, the combination of rice farming and dairy cattle raising was recommended by the Japanese Government in rice-growing areas, where wetland fields were to be utilized for rice and Italian ryegrass (Ministry of Agriculture and Forestry 1962). However, this type of farming has not yet been successful for three reasons. The first relates to the competition of harvesting time of Italian ryegrass with rice transplanting. High yielding cultivation and mechanization of rice operations resulted in a much earlier transplanting, which made double cropping difficult, especially in cold districts. The second reason is the smallness of farm size. If a farmer wished to raise more than 10 cows, he had to rent some land from others, which was virtually impossible under land reform regulations. Third, a large proportion of Tohoku and Hokuriku Districts, the main rice farming areas in Japan, have poorly drained rice fields. In fact, about 60% of all wetland fields in Japan have been considered poorly drained as of 1981. In such fields, the use of organic manures is sometimes not effective and can even be dangerous. Thus, the rice-dairy combination has not been as successful as expected.

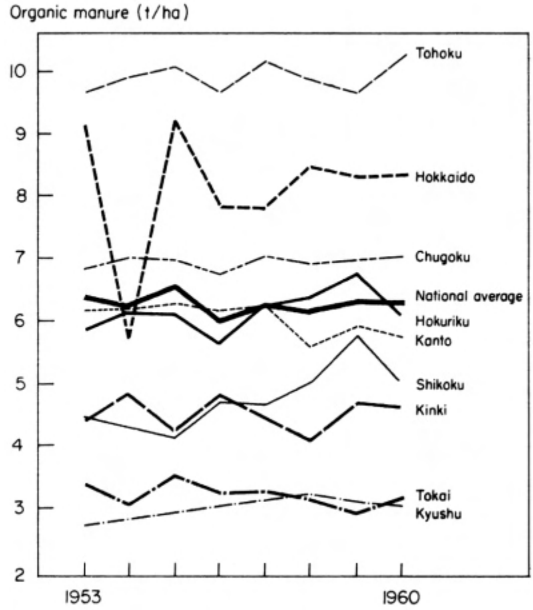
On the basis of the "Survey on Customary Amount and Time of Fertilizer Input for Paddy Cultivation" of the Japanese Ministry of Agriculture in 1931 (Ministry of Agriculture and Forestry 1931), the following features of fertilization in rice cultivation were evident when draft animals were popular among farmers:

- The total amount of fertilizer applied (basal and topdressing) was almost the same in cold Northeastern districts and warm Southwestern districts (Table 1).

**Table 1. Nutrient contents by kind of fertilizer and type of application under customary fertilizing in Northeast and Southwest Japan, 1931.**[a]

| | Nutrient content (kg/ha) | | | | | |
|---|---|---|---|---|---|---|
| | Basal application | | | Topdressing | | |
| | N | P | K | N | P | K |
| Northeast<br>(Shonai, Yamagata) | | | | | | |
| Organic manure | 5.6 | 2.8 | 4.6 | – | – | – |
| Grass ash | – | 0.7 | 2.2 | – | – | – |
| Soybean cake | 1.8 | 0.4 | 0.6 | – | – | – |
| Fishmeal cake | 0.9 | 0.6 | – | – | – | – |
| Superphosphate | – | 2.2 | – | – | – | – |
| Calcium cyanamide | 1.4 | – | – | – | – | – |
| Total | 9.7 | 6.7 | 7.4 | – | – | – |
| Southwest<br>(Saga plain, Saga) | | | | | | |
| Organic manure | 4.5 | 2.3 | 3.8 | – | – | – |
| Soybean cake | 2.4 | 0.5 | 0.8 | – | – | – |
| Ammonium sulfate | – | – | – | 3.0 | – | – |
| Superphosphate | – | 5.6 | – | – | – | – |
| Potassium sulfate | – | – | – | – | – | 3.6 |
| Total | 6.9 | 8.4 | 4.6 | 3.0 | | 3.6 |

[a] Source: Ministry of Agriculture and Forestry, Japan (1931).



**1.** Changes in organic manure input for rice production in Japan, by district, 1953-60. Source: Ministry of Agriculture, Forest and Fishery, Japan (1960).

- In Northeastern districts, basal dressing was the main form of fertilization, and in most cases topdressing was not carried out. In Southwestern districts, the rate of topdressing was relatively high.
- Organic manures were used mainly in basal dressing, not in topdressing. Therefore, the rate of organic manure input was higher in Northeastern districts than in Southwestern districts (Fig. 1).

At the time of the survey of customary fertilizing in 1935, chemical fertilizer was already commonly used in topdressing, and commercial organic fertilizers were additional in many districts.

Japanese agricultural historians point out that transplanting was already prevalent 1,500 years ago (Hurushima 1975). Before that, direct seeding was the common method throughout the country. Even after the introduction of transplanting, direct seeding remained for a long period in poorly drained fields. In fact, direct seeding was done until just after World War II, although the area in which it was practiced was very small.

Many agricultural articles written in the Tokugawa period referred to the direct seeding method. They referred to rice fields where transplanting was carried out as *ueda,* and to those where direct seeding was done as *tsumida,* which literally means rice fields that require thinning of rice plants. The farmers knew through long experience that direct seeding would result in overluxuriant growth or spindly growth, lodging, and serious weed problems. Thus, they usually used a very small amount of fertilizer, mainly dried grass (after 1930 a small quantity of chemical fertilizer), without any organic manures in such poorly drained rice fields. By the end of the Tokugawa period, farmers, particularly in Kyushu, appeared to have learned from experience that fertilization would require much caution, since the excessive use of fertilizer, especially in poorly drained paddy fields, would lead to decreased yield.

After World War II. a new type of direct seeding appeared in some districts in well-drained paddy fields. Its purpose was to permit intensive cropping systems, and to save labor through mechanization. At present, the hectarage under this method is not so large (only 2,000 ha), and luxuriant growth and weeds are still serious problems (Ministry of Agriculture and Forestry 1980a).

Just after the Russo-Japanese War of 1904-1905, fertilizer attained an important place in Japanese agricultural policies (Kurokawa 1978). At that time, animal organic fertilizers such as fish meal cake had already been surpassed in importance by soybean cake imported from China and Manchuria. During the War, the unstable supply of soybean cake forced the Government to encourage domestic production of chemical fertilizer. Such production has gradually increased, and in the early 1930s, chemical fertilizer overtook organic fertilizer as far as N consumption was concerned.

What has been the place of organic manure in the government's fertilizer policy? It appears that the government recommended, at least three times, that rice farmers increase production of self-supplied manure:

1. during the Russo-Japanese War, when soybean cake imported from China, which had been the dominant commercial fertilizer, became scarce;
2. for about 10 years after World War I, when the economy in Japan, including rural areas, was in a serious depression and ordinary farmers could not afford to buy commercial fertilizers;
3. five or six years during and after World War II, during which domestic production of chemical fertilizers was very low.

The government established a controlled distribution scheme for commercial fertilizers and at the same time provided subsidies for increased production of organic manure, e.g., encouragement of cutting wild grass and improvement of organic manure barns during these three periods.

## PRESENT SOCIOECONOMIC SITUATION AND PROBLEMS OF ORGANIC MANURES

### Decreasing application of organic manure

Since World War II, agricultural mechanization in Japan has progressed remarkably; farm machinery has completely replaced draft animals.

While the number of draft animals has declined rapidly. beef cattle and dairy cows have increased greatly. The number of dairy cows increased from 0.82 million in 1960 to more than 2.0 million in 1980 (Ministry of Agriculture and Forestry 1980b). During the same period the number of dairy farmers decreased from 410,000 to 123,000, meaning that the number of dairy cows per farm increased from 2.0 (1960) to 16.8 (1980). Almost the same trend can be observed in beef cattle.

These trends show that specialized farming developed rapidly, which in turn means that multifarming or diversified farming declined. The relationship between crop production and animal husbandry on the individual farm has become very weak.

The amount of labor available for farming has also declined sharply, and at present about 90% of all farmers are part-time (Ministry of Agriculture and Forestry 1980c). These farmers are not in favor of using so much labor to prepare organic manures. Furthermore, most operations in rice cultivation are done by machines, and it is troublesome to gather rice straw chopped into small pieces by a combine harvester.

The price of chemical fertilizers has fallen relative to that of rice (Table 2). This means that rice farmers can now buy chemical fertilizers relatively cheaply. Another important reason for the decreased use of organic manure is the increase in the amount of topdressing in both relative and absolute terms in the last 2 decades in both the Southwestern and Northeastern districts (Kanazawa 1982). Therefore, even in the Northeastern districts, the input of organic manure, which was used mainly as the basal dressing, has declined. Organic manure input (including rice straw) was about 6 t/ha for rice in 1965. By 1980, organic manure input had dropped to 2.7 t/ha (Table 3). Nowadays, topdressing is a well-established practice among rice farmers throughout the country.

### Shallow tillage by machine and application of organic manure

There have been some discussions of the relationship between mechanization and the decline of soil fertility, but what is the relationship between plowing by large-scale machinery and the holding of soil crumb structure? What relationship can be observed between puddling and permeability? These questions may interest soil scientists.

Here, only shallow tillage will be discussed. The rapid transition from draft animals to machinery resulted in shallower tillage of the soil, from 16 to 13 cm. This shallow tillage has continued until the present, when plowing is done by much larger machines.

Farmers have been worried about the depression of rice plant growth at later stages that results from the shallow tillage. Furthermore, the widespread use of the mechanical transplanter requires very delicate transplanting of young seedlings at the same depth such as that attained by traditional hand transplanting. Therefore, some farmers deliberately till their fields shallow to meet this requirement.

Under contract farming systems, which are becoming quite popular, no detailed agreements are made as to the technical standard of each operation. Often an extremely shallow tillage of 10-cm depth is done. In such a case, fertilization may be a mere broadcasting of fertilizers, which can easily lead to the depression of rice plant growth at later stages. Especially in unusually cold years, a heavy dosage of chemical fertilizer in shallowly tilled fields will lead to a low yield. In this sense, the effectiveness and usefulness of organic manure are being reappreciated, and farmers' interest is growing because of the comprehensive functions of manure.

### Intervillage diversified farming

The appearance in recent years of large-scale specialized dairy, beef, hog, and poultry farms has caused waste problems, which are regarded as a kind of pollution. At the same time, the rice farming is becoming specialized for two reasons. First, the number of part-time farmers has dramatically increased and their farming is being concentrated on a single crop, rice, because of developments in mechanization.

**Table 2. Changes in fertilizer and rice prices and farm wage rate, Japan, 1950-1980.**[a]

| | Price (Yen/kg) | | | | | Price ratio | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Ammonium sulfate (1) | Super-phosphate (2) | Potassium chloride (3) | Rice (4) | Farm wage rate (Yen/day) (5) | (1)/(4) (kg/kg) | (2)/(4) (kg/kg) | (3)/(4) (kg/kg) | (5)/(4) (kg/day) |
| 1950 | 19.7 | ... | ... | 40.3 | 248 | 0.49 | ... | ... | 6.2 |
| 1955 | 22.0 | ... | ... | 65.0 | 357 | 0.34 | ... | ... | 5.5 |
| 1960 | 21.0 | 13.3 | 26.0 | 84.0 | 440 | 0.25 | 0.16 | 0.31 | 5.2 |
| 1965 | 20.5 | 14.8 | 28.7 | 87.0 | 972 | 0.24 | 0.17 | 0.33 | 11.2 |
| 1970 | 19.2 | 19.2 | 21.6 | 134.0 | 1,834 | 0.14 | 0.14 | 0.16 | 13.7 |
| 1975 | 30.0 | 42.0 | 44.3 | 210.0 | 4,145 | 0.14 | 0.20 | 0.21 | 19.3 |
| 1980 | 36.4 | 50.9 | 53.7 | 241.3 | 5,667 | 0.15 | 0.21 | 0.22 | 23.5 |

[a] Source: Ministry of Agriculture, Forestry and Fishery, Japan (1981).

**Table 3. Changes in organic manure and rice straw inputs for rice production, Japan, 1955-1980.**[a]

| Year | Input (t/ha) | | | |
|---|---|---|---|---|
| | Organic manure (1) | Rice straw (2) | Rice straw cut by combines (3) | Total[b] |
| 1955 | 6.5 | 0.1 | – | 6.7 ( 100) |
| 1960 | 6.3 | 0.1 | – | 6.5 ( 97) |
| 1965 | 5.4 | 0.3 | – | 6.0 ( 90) |
| 1970 | 4.5 | 0.5 | – | 5.6 ( 84) |
| 1975 | 2.7 | 0.9 | – | 4.6 ( 69) |
| 1976 | 2.5 | 0.4 | 0.6 | 4.6 ( 69) |
| 1977 | 2.0 | 0.4 | 0.8 | 4.4 ( 66) |
| 1978 | 2.1 | 0.4 | 0.9 | 4.7 ( 70) |
| 1979 | 2.1 | 0.4 | 0.9 | 4.7 ( 70) |
| 1980 | 2.0 | 0.3 | 0.8 | 4.2 ( 63) |

[a] Figures inside parentheses are indexes (1955 = 100). Source: Ministry of Agriculture, Forestry and Fishery, Japan (1981). [b] (1) + [(2) × 2] + [(3) × 2].

Nowadays, even small and part-time farmers have mechanized their rice farming to save labor for off-farm employment. Second, some full-time farmers have expanded the size of their rice farms by renting fields from small farmers in the village. Sometimes, these rented lands are scattered in many places. However, progress in mechanization has stimulated the single-crop farming of rice among not only small and part-time farmers but also large farmers. Accordingly, multicropping has rapidly decreased.

Since 1970, rice production regulation resulting from the overproduction of rice has emerged as a very important issue in Japanese agriculture. About 20% of all paddy fields are currently under the government's rice production regulation. Very soon, this percentage will increase to 30%. Under the regulation, farmers are required to devote 20% of their paddy fields to the cultivation of dryland crops instead of rice. The government recommends barley, wheat, naked barley, soybean, forage crops, pasture, vegetables, etc. But there are at least two difficulties in the cultivation of these crops in wetland fields. First, the area of well-drained wetland fields is rather small in Japan. Although wel-drained fields constitute about 30% of the total, these good fields are, in fact, concentrated in certain areas. Many farmers thus have no well-drained fields; that forces them to leave some of their fields fallow to meet the government requirement. It appears that negotiations among farmers are needed to exchange their plots. Second, if a farmer is to promote a rotation system for rice and dryland crops, the use of organic fertilizer will be very important. In addition, farmers believe that more organic fertilizer is needed in fields shallowly tilled by machine. However, as mentioned earlier, livestock farming is specialized nowadays and ordinary farmers do not raise animals. Of course, irrigation water plays a very important role in maintaining soil fertility, but Japanese farmers, vegetable growers in particular, have recognized the real importance of main crop, rotation crop, and cleaning crop. In this connection, they recognize the effectiveness of organic manures.

Some cooperation has been established as a result of mutual negotiations among farmers. The cooperation can be observed between individual farmers as well as between groups of farmers. Usually the rice production regulation is implemented at the village-unit level: the hectarage under regulation is determined on the basis of a village. The head of the village allocates the regulated hectarage to individual farmers, which means that mutual negotiation within the village is essential.

One type of cooperation between individual farmers within a village is as follows. Farmers who have a relatively large area of well-drained rice fields and wish to continue their intensive farming may also wish to cultivate dryland crops in an area larger than actually allocated under the regulation. Through negotiations, small farmers who do not have well-drained fields and plant a single crop of rice free themselves from the government requirement of dryland crop cultivation by paying farmers who cultivate dryland crops in their place. The usual amount of compensation is $195/ha.

The other type of cooperation between individual farmers is the exchange of fields between a well-drained area and a poorly drained area. This type takes place between groups of farmers and between villages. One village where rice farming is dominant and livestock is lacking makes a contract with another village where livestock is raised to exchange rice straw and organic manure. This type of farming may be called intervillage diversified farming. Although the exchange of rice straw and organic manure is between individual farmers, a systematic scheme of exchange between groups of farmers in different villages is being promoted.

In short, the waste problem and rice production regulation provide an opportunity to reconsider the importance of organic manures. Full-time farmers are reexamining their farm management, which has been too extensive; but labor-intensive practices cannot be expected in rice farming. Because the farmers recognize the comprehensive effects of organic manure, the exchange system of rice straw and organic manure can be expected to prevail in the near future.

## REFERENCES CITED

Fesca, M. 1888. Nogyo kairyo ron (The program of agricultural improvements). *In* Meiji zenki Kanno jiseki shuroku (Collections of recommended farming practices in the early Meiji era). Ministry of Agriculture and Commerce, Tokyo.

Hurushima, T. 1975. Nihon nogyo gijutsushi (History of Japanese agricultural technology). Tokyo University Press, Tokyo.

Kanazawa, N. 1982. Nogyo keieigaku (Lecture on farm management). Yokendo, Tokyo.

Kanazawa Agricultural Experiment Station. 1954. Sehi kaizen gorika no shishin kakuritus ni kansuru chosa kenkyu (Research on rational fertilization). Kanazawa.

Kayo, N. 1958. Nihon nogyo kiso tokei (Basic statistics of Japanese agriculture). Nosei Chosa Iinkai, Tokyo.

Kayo, N. 1964. Nihon nogyo no hiryo shohi kozo (Structure of fertilizer consumption in Japanese agriculture). Ochanomizushobo, Tokyo.

Kurokawa, K. 1978. Nihon ni okeru Meiji iko no dojyo hiryo ko (Treatise on soil and fertilizer science in Japan since Meiji Era) Vol. 2, Nihon-Seisakusha, Tokyo.

Ministry of Agriculture and Forestry, Japan. 1931. Suito kanko sehiryo to jiki ni kan suru chosa (Survey on customary amount and time of fertilizer inputs for cultivation). Bureau of Agriculture, Tokyo.

Ministry of Agriculture and Forestry, Japan. 1960. Kome seisanpi chosa (Survey on rice production costs 1953-1960). Department of Statistics, Tokyo.

Ministry of Agriculture and Forestry, Japan. 1962. Nogyo-kihonho kaisetsu (Guidance of the Basic Law of Agriculture). Minister Secretariat, Tokyo.

Ministry of Agriculture, Forestry and Fishery, Japan. 1980a. Statistics of crops. Department of Statistics and Information, Tokyo.

Ministry of Agriculture, Forestry and Fishery, Japan. 1980b. Trend of livestock farming in Japan. Department of Livestock, Tokyo.

Ministry of Agriculture, Forestry and Fishery, Japan. 1980c. Statistics of farm household economy. Department of Statistics and Information, Tokyo.

Ministry of Agriculture, Forestry and Fishery, Japan. 1981. Noson bukka tokei chosa (Statistical survey of prices in rural areas 1959-1980). Department of Statistics and Information, Tokyo.

## DISCUSSION

SINGH: Why does reduction in cultivation depth from 16 to 13 cm decrease rice yield and give very low response when chemical fertilizers are used?

*KANAZAWA:* In the case of shallow tillage, only chemical fertilizer input, particularly topdressing, will easily lead to the depression of rice plant growth at later stages in the northern part of Japan, especially in cold years.

ROGER: What is the status and percentage of part-time farmers in Japan?

*KANAZAWA:* About 90% of all farmers are part-time. Part-time farmers are divided into two classes: those whose farm income is more than their off-farm income (20%), and those whose farm income is less than their off-farm income (70%).

CHOUDHARY: What is the scope or possibility of using organic manures in conjunction with inorganic fertilizers in increasing rice yields in Japan?

*KANAZAWA:* Full-time farmers have the possibility of using organic manures, but most part-time farmers in Japan do not have this possibility. However, in the future, if the concentration of land into the hands of full-time farmers is promoted by the rental system, this possibility will be large.

NEUE: You have demonstrated clearly that in Japan the use of organic materials has been a function of socioeconomic factors like part-time farming, mechanization, labor cost, and the price of chemical fertilizer. Do you think that these socioeconomic factors will change in the near future so that the farmer will reconsider the use of organic materials?

*KANAZAWA:* In the near future, these socioeconomic factors will not change. But among excellent full-time farmers, very serious consideration of organic materials has occurred.

MORACHAN: Will not the exchange of organic matter between villages be costly because of transport charges?

*KANAZAWA:* The exchange of organic matter between farmers does not create transportation problems. At present, specialization of both rice farming and dairy farming has progressed so that exchange of straw and animal waste manure has become important. Straw is necessary as roughage for cows, and animal waste manure is necessary for rice production.

# ECONOMIC EVALUATION OF AZOLLA USE IN RICE PRODUCTION

Masao Kikuchi, Iwao Watanabe, and Leo Dale Haws

The biological potential of azolla as a green manure in rice production is great. Under favorable experimental conditions, a layer of azolla covering a 1-ha rice field releases 20-30 kg organic N. It is not difficult to supply more than 100 kg organic N/ha by culturing azolla more than once. Yield tests show that the application of azolla increased rice yield by 0.4-1.5 t/ha over control plots.

The economic potential of azolla is also great. The economic return from azolla adoption, including cost savings in chemical fertilizers and weed control, is more than 10% of the total nonland cost for rice production in areas where environmental conditions favor azolla growth.

However, many natural and social environmental constraints must be overcome before the biological and economical potentials of azolla can be realized. Among these constraints are the P content of the soil, insect and pest control, and labor requirements. In less favorable conditions, the application of P fertilizer is necessary to produce organic N by culturing azolla. However, the need for additional P fertilizer may not be a problem in the adoption of azolla.

The possible susceptibility of azolla to insects and pests may create a setback for its adoption in some regions. If more than 200 g a.i. carbofuran/ha is necessary to control insects and pests, the economic benefits gained from the reduction of inorganic N fertilizer are eliminated.

The economic potential of azolla is greatest in countries where the opportunity cost of labor is low. Labor cost increases of azolla application become critical in countries where agricultural wage rates (or the real opportunity cost of labor) approach $2/day.

The introduction of modern cultivars of rice since the late 1960s has contributed significantly to increased land productivity and thereby to total food production in

---

Associate economist, soil microbiologist, and crop production specialist, International Rice Research Institute, Los Baños, Laguna, Philippines.

the developing countries of Asia. This new technology, often referred to as seed-fertilizer technology, requires heavy application of inorganic fertilizer for the attainment of high yields. Fertilizer subsidies have been implemented in many developing countries to facilitate farmers' use of fertilizer with modern cultivars.

Fertilizer subsidies put a burden on government budgets. Moreover, because the cost of foreign components in chemical fertilizers, even of those domestically manufactured, is high, the increasing utilization of inorganic fertilizers uses scarce foreign exchange reserves. Scarcity of foreign exchange reserves and international trade deficits are common in the developing countries. As long as food production must be increased through improvement of land productivity, the demand for chemical fertilizers will also increase. This will place strong constraints on government resource allocation, on foreign exchange reserves, and on economic development in general.

In this context, organic fertilizers, which can be substituted for chemical fertilizers, can play an important economic role. The use of organic fertilizers could facilitate mobilization of cheap resources for productive purposes, replacing high-cost chemical fertilizers. Azolla, which has recently attracted the attention of biological scientists, is considered to have a high potential for replacing inorganic N fertilizers because it can fix N from the atmosphere.

Although intensive research on azolla started only recently, the fern's practical use as a source of organic N fertilizer for rice production has been recognized in Asia, particularly in China and Vietnam, for quite a while. This suggests that the use of azolla in rice farming has been economically viable in these places, However, it is still not known if the transfer of this technology to new areas, especially the tropical countries, is economically feasible.

This paper examines some of the critical factors determining the feasibility of using azolla practically as a green manure for rice production in developing tropical countries in Asia. In this paper, economic evaluation of azolla is limited to its use in rice farming. Other potential uses, such as feeds (Buckingham 1978, Edwards 1974, Subudhi and Singh 1978), vegetable food (Singh 1979, Rains and Talley 1979), and a means of improving water quality (Rains and Talley 1979), are disregarded.

Reflecting the scarcity of information on actual farming practices with azolla, the economic evaluation made in this paper is but the first step toward better understanding of the technology. The paper also presents some basic information for future studies.

## NITROGEN FIXATION AND YIELD RESPONSE: BIOLOGICAL POTENTIAL OF AZOLLA FOR RICE FARMING

*Azolla* is the genus of a small aquatic fern that grows in ponds, canals, and rice paddies; it floats freely on the surface of the water. It has a worldwide distribution in temperate and tropical regions. Six azolla species are known, of which only one, *A. pinnata,* has so far been cultivated for agricultural purposes, specifically in northern Vietnam, China, and Thailand (Becking 1979). Its capacity to fix molecular N from the atmosphere is due to symbiosis with a heterocystous N-fixing blue-green alga,

**Table 1. N content and average N-fixing rate of azolla.**[a]

| Species/condition[b] | Maximum biomass | | | Av N-fixing rate (kg N/ha per day) | Source |
|---|---|---|---|---|---|
| | Dry matter (t/ha) | N content (kg/ha) | Days | | |
| *A. filliculoides:* | | | | | |
| Fallow paddy, USA | 1.7 | 52 | 35 | 1.5 | Talley and Rains (1980a) |
| Shallow pond, USA | 1.8 | 105 | – | – | Talley et al (1977) |
| Fallow paddy, USA | 2.3 | 93 | 46 | 2.0 | Talley and Rains (1980b) |
| Paddy soil in pot, Japan | 5.2 | 128 | 50 | 2.6 | Tuzimura et al (1957) |
| 26°(d)/18°(n), phytotron | 3.2 | 126 | 51 | 2.5 | Watanabe (1981) |
| *A. mexicana:* | | | | | |
| Pond, USA | 0.8 | 39 | 39 | 1.0 | Talley and Rains (1980b) |
| Fallow paddy, USA | 1.1 | 38 | – | – | Talley and Rains (1980a) |
| *A. caroliniana:* | | | | | |
| 26°(d)/18°(n), phytotron | 3.2 | 146 | 41 | 3.6 | Watanabe (1981) |
| *A. pinnata:* | | | | | |
| Fallow paddy, India | 2.3 | 104 | 30 | 3.4 | Singh (1979) |
| Fallow paddy, IRRI | 1.1 | 48 | 30 | 1.6 | Watanabe (1981) |
| 26°(d)/18°(n), phytotron | 2.2 | 96 | 37 | 2.6 | Watanabe (1981) |
| 33°(d)/25°(n), phytotron | 1.5 | 33 | 22 | 1.5 | Watanabe (1981) |
| 37°(d)/29°(n), phytotron | 1.1 | 30 | 23 | 1.3 | Watanabe (1981) |
| Paddy with rice, IRRI | – | 73 | 91 | 0.8 | Watanabe et al (1981) |
| Paddy with rice, South Cotabato | – | 20 | 7 | 2.9 | RPTR[c] observation |
| Paddy with rice, Vietnam | – | 25 | 60 | 0.4 | Tuan and Thuyet (1979) |
| Paddy with rice, China | – | 41 | 18 | 2.3 | Liu (1979) |

[a] If the figures are reported as ranges, the center figures of the ranges are shown. Readers who wish to know the exact figures should refer to the original sources. (-) = data not available. [b] d = day, n = night. [c] Rice Production Training and Research Department, IRRI.

*Anabaena azollae,* found within the cavities of the upper or dorsal lobes of azolla fronds (Moore 1969).

The growth rate, minimum biomass, and N-fixing activity in optimum conditions provide the estimate of the potentials of *Azolla-Anabaena* symbiosis for agriculture.

Becking (1979) summarized experimental results on the growth rates of azolla. He showed that the doubling time is 2-10 days for all azolla species except *A. filiculoides,* whose doubling time is as long as 20 days. The growth curve of azolla approximately follows a logistic curve until the maximum biomass is reached. The growth rate is retarded as the plant density increases ( Ashton 1974).

The maximum biomass accumulation and average N-fixing rate per day reported by scientists are summarized in Table 1. In the open paddy, pond, or phytotron, the N contents of azolla range from 30 to 146 kg N/ha and the average N-fixing rate ranges from 1.0 to 3.6 kg N/ ha per day. The studies show that under favorable experimental conditions azolla can fix as much as 40-60 kg N ha within 30 days. In open field conditions, a layer of azolla covering a 1 -ha field contains about 10 t green matter and ensures about 25-30 kg N/ha (Singh 1979). This amount of organic matter can be doubled and tripled by growing a second or a third azolla layer after the first crop (layer) has been incorporated or gathered. The annual N production of azolla thus cultivated throughout the year reaches 450 kg N/ ha (Watanabe et al 1980), or even more than 1 t N/ ha (Li 1983).

The average N-fixing rate per day varies from 0.4 kg N/ ha to as much as 2.9 kg N/ ha when azolla is cultured in dual cropping with rice in paddy fields (Table 1). Even at the minimum rate, however, azolla can fix 25 kg N/ ha within a 60-day period in a form usable for rice (Tuan and Thuyet 1979). Under good growing conditions, azolla can fix as much as 130-170 kg N ha in 60 days — an amount that may exceed the N requirement of rice.

These figures indicate that azolla, whose N-fixing rate is almost comparable to that of forage legumes (Nutman 1976), has a high biological potential as a green manure. Indeed, azolla rapidly decomposes in soil after incorporation, and its N efficiency is almost comparable to or only slightly less than that of urea or $(NH_4)_2SO_4$ (Singh 1979, Watanabe et al 1977). As a result, the yield response to azolla in rice production is as good as that to inorganic N (Table 2).

The application of azolla increased yields by 0.4- 1.5 t/ ha, with a mean of 0.7 t/ ha, over the control plots in most of the experimental sites (Table 2) regardless of the absolute yield level, which differed from site to site. The comparison of yields between azolla plots and plots treated with chemical fertilizers indicates that the application of azolla has an effect on rice yields equivalent to the effect of the application of N fertilizers at rates about 30-40 kg N/ha or higher. Although a surface application of azolla without incorporation may still increase yields, there seems to be a positive correlation between yield and incorporation of azolla into soil; the more times azolla is incorporated, the higher the rice yield, presumably through the accumulation of N by the azolla incorporated in the soil.

The biological potential of azolla as a green manure is clear. Because of its high capacity to fix N from the air, azolla can be a complete or partial substitute for chemical N fertilizers in rice cultivation, at least biologically.

Table 2. **Effects of azolla on rice yield.**

| | Yield [a] (t/ha) | | | | |
|---|---|---|---|---|---|
| | Control plot [b] | N fertilizer plot [c] | Azolla plot [d] | Increase due to azolla | Source |
| Chekiang, China, 1964 | 3.7 | – | 4.4 w/o I, T | 0.7 | Liu (1979) |
| | | | 4.4 I 1 time, T | 0.7 | |
| | | | 4.9 I 2 times, T | 1.2 | |
| | | | 5.0 I 3 times, T | 1.3 | |
| 7 Southern Chinese provinces, 1975 | – | – | – – | 0.7 | Liu (1979) |
| Vietnam, 1958-67 | 2.4 | – | 2.8 I, BT | 0.4 | Dao and Do (1970) |
| India, 1976 (kharif) | 4.9 | 5.5 (40 N) | 5.6 I, BT | 0.7 | Singh (1979) |
| 1977 (rabi) | 1.7 | 2.2 (20 N), 3.2 (40 N) | 2.6 I, BT | 0.9 | |
| Thailand, 1977 | 2.6 | 2.9 (37.5 N) | 3.5 I, BT | 1.5 | Sawatdee et al (1978) |
| USA, 1978 | 1.3 | 2.8 (40 N) | 2.8 I, AT | 1.5 | Rains and Talley (1979) |
| IRRI, 1979-80 | 4.2 | 5.2 (77 N) | 5.4 I, BT | 1.2 | Watanabe et al (1981) |
| 4 Asian countries 1979-80 [e] | 2.9 | 3.5 (30 N), 4.0 (60 N) | 3.6 w/o I, AT | 0.7 | INSFFER (1980, 1981) |
| | | | 3.6 I, BT | 0.7 | |
| | | | 3.5 I, AT | 0.6 | |
| | | | 4.0 1, BT & AT | 1.1 | |

[a] (–) = data not available. [b] No azolla and no chemical N. [c] Figures in parentheses are levels of chemical N applied (kg/ha). [d] I, w/o I = incorporated, without incorporation, respectively. T = applied at transplanting time, BT = before transplanting, AT = after transplanting. [e] Thailand, India, China, and Nepal, av of all sites for 2 years.

## AZOLLA AS USED BY FARMERS: A CASE STUDY OF AZOLLA ADOPTERS IN SOUTH COTABATO

In the Philippines, use of azolla is new to most rice farmers. Until 1979 when a MA-IRRI-PCARR[1] cooperative project, Azolla Applied Research Trial, was begun in South Cotabato, few Filipino farmers had reported using azolla as a green manure.

Scientists inoculated a Bangkok strain of *A. pinnata* in the rice-growing area in South Cotabato in 1979 and found that it grew very well there. After the scientists had shown the effect on rice yields in several demonstration plots, azolla was propagated quickly in the area by technicians or farmers who had an interest in it. By the time the 1981 second crop was planted, azolla was growing in a few thousand hectares of rice fields in this area.

A field survey to assess the performance of azolla on farmers' fields was conducted in the area in July 1982. Unfortunately, the study area experienced heavy tungro infestations in the 1981 first and second crops, so that rice yield was very low (or even nil) for many farmers. To avoid disturbances by the infestation, the field survey was conducted in two villages in the area where the rice fields had not been heavily attacked by tungro. Thirty-two farmers, most of them azolla adopters, were interviewed using a questionnaire that included questions on changes in rice farming practices before and after the adoption of azolla, rice yields, and production inputs. A random sampling of respondent farmers in the strict sense was impossible, because the total population of azolla adopters in the study area could not be ascertained within the limited time span for the survey. The sample, however, was drawn randomly in the sense that whatever farmers were available in the study area were interviewed randomly. Some basic characteristics of sample farmers and of the study area are summarized in Table 3.

The study area was a site of the government homestead programs in Mindanao under which farmers who migrated to the area were given a 5-ha farm. As a result, most of the sample farmers were owners or part-owner operators, cultivating relatively large farms (3.2 ha, average).

The irrigation systems in the study area enable farmers to grow two rice crops a year; the first crop is grown from June to October and the second from November to April. The soil conditions in the study area are very favorable to rapid azolla growth. Once azolla is inoculated or flows into a rice field, it can totally cover a 1-ha field within 5-7 days. One layer of azolla covering a 1-ha rice field yields about 10-20 t/fresh weight azolla.

### Farmers' practice with azolla

Azolla was introduced in the study villages in early 1981. Some farmers applied it in the 1981 first crop, and many followed in the 1981 second crop (Table 4). As in the other villages in South Cotabato where azolla was introduced, there are many ponds scattered among rice fields for raising ducks or fish, and there is water throughout the year in these ponds. In Tantangan village, one farmer grew for multiplication in his pond 3 t fresh azolla brought from a village where an azolla demonstration was

---

[1] Ministry of Agriculture-IRRI-Philippine Council for Agriculture and Resources Research.

**Table 3. Basic characteristics of sample farmers and study area, South Cotabato, Philippines.**

| | |
|---|---|
| Farmers interviewed (no.) | 32 |
| Location | |
| Barangay Cabuling, Tantangan, South Cotabato | 28 |
| Barangay No. 9, Banga, South Cotabato | 4 |
| Land tenure | |
| Owner operator | 13 |
| Part-owner | 5 |
| Tenant | 14 |
| Cultivating size | |
| 5 ha or more | 8 |
| 3 - 5 ha | 5 |
| 1 - 3 ha | 16 |
| Less than 1 ha | 3 |
| (Av size) | (3.2 ha) |

| | Tantangan | Banga |
|---|---|---|
| Irrigation system | NIA[a] (Marbel) | Communal (Malaya) |
| Type of soil | Clay loam | Sandy loam |
| pH | 7.2 | 5.7 |
| Available P; Olsen P (ppm) | 57.0 | 41.0 |
| P-absorption capacity (mg $P_2O_5$/100 g) | 1,175.0 | 690.0 |

[a] National Irrigation Administration.

held. The azolla adopters in the village picked up the azolla from this pond for culturing in their ponds or for inoculating directly into their rice fields, free of charge. Twenty-seven or about 80% of the total sample of farmers adopted azolla in the 1981 second crop in 50% (1.6 ha) of their cultivated paddy fields.

Broadcasting was the major method of applying azolla. Eighty-five percent of the azolla adopters in the 1981 second crop used this method, and 80% of them applied azolla once. On the average, about 38 kg fresh weight azolla/ha were inoculated into the rice fields in this way, although the quantity varied considerably from farmer to farmer, ranging from 10 to 100 kg/ha.

One farmer reported that azolla had entered his field from an irrigation canal and established itself. Azolla grows and propagates rapidly in this area. Three azolla adopters in the 1981 second season reported that they utilized the azolla that had survived in their fields from the previous season. This suggests that temperature and soil moisture conditions allow azolla to survive during a fallow season.

The additional labor required for applying azolla by the broadcasting method was 2.8 hours/ha, on the average. In some cases, no labor was required.

Fifteen of the 27 farmers applied azolla before transplanting and 12 after transplanting. Since rotary weeders are not used in the study area, there was no major incorporation of azolla with soil for the cases in which it was applied after transplanting. If inoculated before transplanting, azolla was incorporated with soil by plowing and harrowing. There was no major change in the method of land preparation before and after azolla introduction, except the intentional extension by some farmers of the intervals between each plowing and harrowing and between the

**Table 4. Azolla practices in the study area, South Cotabato, Philippines. 1981.**

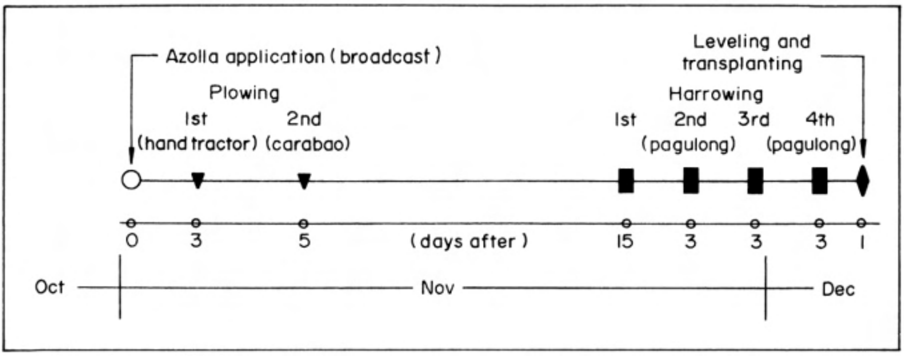
| | |
|---|---|
| Farmers who applied azolla[a] (no.): | |
| 1981 1st crop | 4 |
| 1981 2nd crop | 27 |
| 1981 second crop | |
| Av azolla area (ha/farmer applying) | 1.6 |
| Place where azolla was grown or cultured | Fish pond or water pond |
| Method of application[a] (no.) | |
| Broadcast | 23 |
| From previous season | 3 |
| By water current | 1 |
| Total | 27 |
| Timing of application[a] (no.) | |
| Before plowing | 12 |
| Before harrowing | 3 |
| After transplanting | 12 |
| Total | 27 |
| Frequency of application[a] (no.) | |
| 1 time | 20 |
| 2 times | 1 |
| 3 times | 2 |
| Total | 23 |
| Quantity of azolla applied[b] (kg fresh wt/ha) | 38 |
| Av labor requirement for applying (hours/ha) | 2.8 |
| Method of incorporation with soil | Plowing, harrowing |
| Frequency of incorporation:[a] | |
| 4 times | 4 |
| 5 times | 3 |
| 6 times | 2 |
| 7 times | 2 |
| 8 times | 2 |
| 9 times | 2 |
| Total | 15 |
| (Av) | (6 times) |

[a] Number of farmers reporting. [b] Av from farmers who applied azolla by broadcasting. Azolla that was carried by irrigation water into fields is not included.

last plowing and the first harrowing to allow azolla to grow in the fields (Fig. 1). Counting each plowing and harrowing after azolla inoculation as one incorporation, those who applied before transplanting incorporated six times, on the average (Table 4).

## Changes in rice yield and production inputs before and after azolla use

Average rice yields did not differ significantly between plots with and without azolla, or between crop seasons, except in the 1981 second-crop non-azolla plots, for which some recorded yields were low because of partial infestation of tungro (Table 5). In a normal crop season, the farmers in the study area obtain about 4.5 t/ha, regardless of the season or the use of azolla.



**1.** Typical method of azolla application and incorporation. 1981 2d crop, South Cotabato, Philippines.

By contrast, the levels of some production inputs and costs showed distinct differences among plots, especially between azolla-incorporated plots and non-azolla plots (Table 6). The most important difference was, as expected, the level of inorganic N and fertilizer cost. The farmers could reduce the use of inorganic N more than 18 kg/ha and save about $16/ha in the total cost of fertilizer. Two azolla adopters who did not apply chemical fertilizer at all in part of their fields in the 1981 second crop produced as much as 5.5 t/ha. These farmers were not exceptions in South Cotabato. This reduction in chemical fertilizer application resulted in labor reduction, which almost cancelled out the increased labor requirement for azolla applications.

Aside from a saving in N fertilizer, all azolla-adopting farmers mentioned that

**Table 5. Average rice yield for plots with and without azolla application, by season, South Cotabato, Philippines, 1980 and 1981.**

| Year/crop | Observations (no.) | Rice yield | | |
|---|---|---|---|---|
| | | Yield[a] (t/ha) | S.D. (t/ha) | C.V. (%) |
| | *Without azolla* | | | |
| 1980 | | | | |
| 1st crop | 26 | 4.50 a | 1.06 | 23.6 |
| 2nd crop | 27 | 4.29 a | 1.23 | 28.7 |
| 1981 | | | | |
| 1st crop | 31 | 4.20 a | 1.14 | 27.1 |
| 2nd crop | 18 | 3.47 b | 1.16 | 33.4 |
| | *With azolla* | | | |
| 1981 | | | | |
| 1st crop (incorporated)[b] | 2 | 5.92 a | 1.56 | 26.4 |
| 2nd crop (not incorporated)[c] | 12 | 4.54 a | 1.42 | 31.3 |
| 2nd crop (incorporated)[b] | 15 | 4.59 a | 1.17 | 25.5 |

[a] Yields followed by a common letter are not significantly different at the 5% probability level. [b] For plots to which azolla was applied and incorporated. [c] For plots to which azolla was applied after transplanting without major incorporation with soil.

**Table 6. Average levels of inputs and costs[a] per hectare for the second crop rice production plots with and without azolla, South Cotabato, Philippines.**

| | 1981 2nd crop | | 1980 2nd crop | Difference[b] | | |
|---|---|---|---|---|---|---|
| | Azolla incorporated (1) | Azolla not incorporated (2) | No azolla (3) | (1)–(3) | (2)–(3) | (1)–(2) |
| Observations (no.) | 15 | 12 | 26 | | | |
| Current input (kg) | | | | | | |
| N | 24.0 | 35.7 | 42.5 | –18.5*** | –6.8 | –11.7* |
| P | 6.6 | 14.3 | 11.7 | –5.1** | 2.6 | –7.7* |
| K | 3.1 | 7.8 | 7.2 | –4.1* | 0.6 | –4.7* |
| Total fertilizer cost (₱) | 225 | 348 | 362 | –137*** | –14 | –123** |
| Herbicide cost (₱) | 56 | 75 | 81 | –25* | –6 | –19** |
| Total chemical cost (₱) | 359 | 421 | 390 | –31 | 31 | –62 |
| Total current input cost[c] (₱) | 713 | 918 | 887 | –174** | 31 | –205* |
| Total capital cost[d] (₱) | 726 | 787 | 727 | –1 | 60 | –61 |
| Labor input (labor hours) | | | | | | |
| Weeding | 45 | 65 | 78 | –33** | –13 | –20* |
| Fertilizer application | 5 | 5 | 7 | –2* | –2 | 0 |
| Azolla application | 3 | 3 | 0 | 3*** | 3*** | 0 |
| Total labor hours[e] | 588 | 613 | 601 | –13 | 12 | –25 |
| Total labor cost[e] (₱) | 1571 | 1616 | 1564 | 7 | 52 | –45 |

[a] Costs are at 1981 constant prices. Self-supplied inputs are included; market prices have been imputed. US$1 = ₱8.50. [b] *, **, and *** = statistically significant at the 10%, 5%, and 1% levels, respectively. [c] Sum of seed, fertilizer, and chemicals. [d] Capital service cost of carabao, tractor, and threshing machine. [e] Includes all labor activities from land preparation to threshing.

azolla, besides reducing N fertilizer costs, suppresses weeds because it covers the water surface in rice fields. The effect of azolla as a weed suppressor has been reported in many studies (Rains and Talley 1979, Braemer 1927, Nguyen 1930, Ngo 1973). Consequently, the labor requirement for hand weeding was significantly less for the azolla-incorporated plots than for the no-azolla plots, and so was the herbicide cost, though to a lesser extent.

The cost reductions associated with azolla use were not clear for the azolla plots without incorporation. As in rice yield, they were no different from the no-azolla plots in input levels.

In addition to the significant changes mentioned, there were some changes in farming practices that were associated with azolla use but, on the average, did not affect production costs appreciably. First, some farmers found a problem when they used azolla with dry seedbed preparation *(dapog)* or with direct seeding. They claimed that azolla, covering the water surface like a mat, hinders the growth of short *dapog* seedlings or directly broadcasted rice seeds. Some farmers who had adopted one of these methods shifted back to the traditional method of wet seedbed preparation *(punla)* with the introduction of azolla. The increase in labor use due to the shift back from either *dapog* or direct seeding to *punla* was obscured in the data (the difference in labor hours for crop establishment between azolla plots and no-azolla plots was not significant statistically), simply because some other azolla-adopting farmers switched their crop establishment method in the opposite direction (*punla* to *dapog*) in the 1981 second crop without realizing the problem. Second, some farmers used a wider planting space than the traditional spacing of 18 × 15 cm to 25 × 25 cm. A wider planting space is better for azolla growth because more sunlight can reach it on the water surface (Watanabe 1981). It is not clear, however, how far this change in planting space affected azolla growth. No major change was reported for other farming practices in relation to azolla introduction.

The azolla-incorporated plots and the no-azolla plots, were not significantly different in rice yield but were significantly different in level of inorganic N applied. The opposite was true when the variations within the azolla-incorporated plots were examined in relation to the frequency of azolla incorporation (Table 7). Rice yields were significantly higher in the plots with higher frequency of incorporation, whereas the levels of inorganic N applied did not differ significantly across the frequency classes. This suggests that the more azolla is incorporated into the soil, the more N is fixed.

## Effect of azolla as a green manure: a statistical test

These observations suggest that by applying and incorporating azolla farmers can significantly reduce the quantity of inorganic N fertilizer and still maintain almost the same level of rice production. The frequency of azolla incorporation into the soil may have a positive correlation with rice yield.

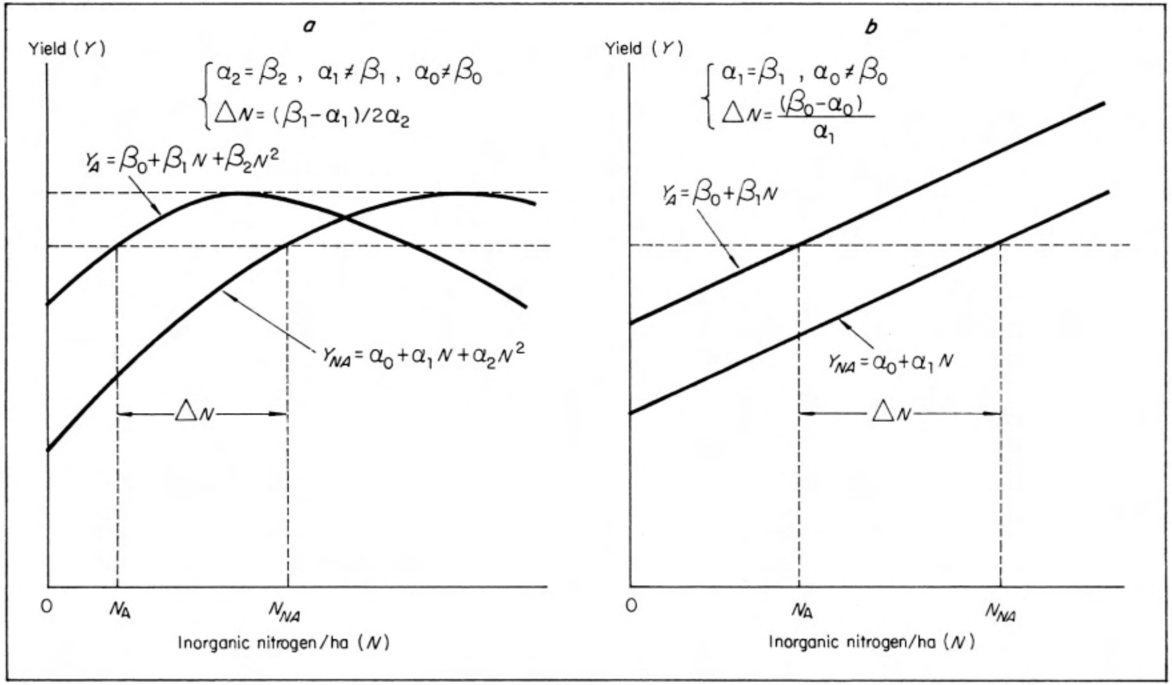
However, unlike in biological experiments, these results were obtained by using uncontrolled farm survey data. Farmers' rice yields depend not only on N applied, either inorganic or organic supplied by azolla, but on other inputs applied. In this section, the effect of azolla as a green manure is confirmed by estimating a production function.

If azolla is indeed a N-fixing green manure, its effect can be demonstrated as

**Table 7. Association between frequency of azolla incorporation and levels of yield and chemical N, 1981 second crop, South Cotabato, Philippines.**

| Frequency of incorporation | Observations (no.) | Yield[a] (t/ha) | N fertilizer[a] (kg/ha) | Difference[b] | | |
|---|---|---|---|---|---|---|
| | | | | 4-5 times | 6-7 times | 8-9 times |
| 4-5 times | 7 | 3.60<br>(0.75) | 29.3<br>(17.4) | | 1.32t***<br>–11.3 kg | 2.40t***<br>–8.6 kg |
| 6-7 times | 4 | 4.92<br>(0.17) | 18.0<br>( 7.3) | | | 1.08 t***<br>2.08 kg |
| 8-9 times | 4 | 6.00<br>(0.39) | 20.8<br>(21.7) | | | |
| Total or av | 15 | 4.59<br>(1.17) | 24.0<br>(16.4) | | | |

[a]Figures within parentheses are standard deviations. [b]The upper figures are the differences in yield and the lower of chemical N levels between associated frequency classes. Figures with 3 asterisks are statistically significant at the 1% probability level and those without asterisks are not significant at any conventional significance level.



**2.** Effect of organic nitrogen on fertilizer response function.

shown in Figure 2. $Y$ stands for rice yield per hectare and $N$ for inorganic N per hectare. All other inputs except N are assumed to be controlled at certain levels. Graph (a) assumes the conventional quadratic form for a response function. If azolla fixes a certain amount of N, its application will cause a shift in the response function without azolla ($Y_{NA}$) toward the left. The shift may or may not be a parallel shift, leaving the shape and maximum of $Y_{NA}$ the same, which can be tested statistically by estimating response functions before and after azolla application. If the shift is parallel, the quantity of organic N that is substituted for or added to inorganic N can be estimated easily from the estimated parameters.

Farmers may be applying much less inorganic N than the amount needed to attain maximum yield. If that is so, the response function may well be described by a linear form (graph b). In this case, too, the effect of azolla in shifting the response function and the quantity of N supplied by azolla can be assessed by a statistical estimation similar to that in the quadratic case.

Results of the estimation are summarized in Table 8. The response functions are estimated for a data set combining both azolla and no-azolla plots instead of separate estimations for each. A general model for estimation is as follows:

$$Y = \alpha_0 + \gamma_0 D + \gamma_0 I + (\alpha_1 + \gamma_1 I)\, N + (\alpha_2 + \gamma_2 I) N^2 + \alpha_3 C + u$$

where $Y$ = rice yield (kg/ha), $N$ = inorganic N (kg/ha), $C$ = total production cost (paid and unpaid) excluding fertilizer cost (₱/ha), $D$ = dummy for azolla plots, $I$ = frequency of azolla incorporation, $u$ = disturbance, and $\alpha_i$ and $\gamma_i$ = parameters to

**Table 8. Estimation of a linear production function for the farm survey data.**[a]

| | $n$ = 53[b] | | | $n$ = 43[c] |
|---|---|---|---|---|
| | Regression I | Regression II | Regression III | Regression IV |
| Nitrogen ($N$) | 49.1***<br>(3.01) | 9.32<br>(0.62) | 15.2***<br>(2.62) | 13.0**<br>(2.16) |
| $N^2$ | –0.153<br>(–0.75) | 0.112<br>(0.17) | | |
| Dummy for azolla plot ($D$) | 676**<br>(2.03) | 195<br>(0.69) | 181<br>(0.65) | |
| Frequency of incorporation ($I$) | 346***<br>(3.61) | 151**<br>(1.77) | 122**<br>(1.90) | 135**<br>(2.10) |
| $N \bullet I$ | –30.2***<br>(4.05) | –5.47<br>(0.72) | –1.33<br>(0.57) | –1.06<br>(0.46) |
| $N^2 \bullet I$ | 0.563***<br>(3.90) | 0.101<br>(0.70) | | |
| Total cost excluding fertilizer ($C$) | | 1.03***<br>(5.21) | 1.14***<br>(7.21) | 1.09***<br>(6.78) |
| Intercept | 2738 | 838 | 546 | 773 |
| $R^2$ | 0.539 | 0.712 | 0.699 | 0.688 |
| $F$-statistic | 8.96 | 15.9 | 21.8 | 21.0 |

[a] *, **, and *** = statistically significant at 10%, 5%, and 1% levels, respectively. Figures within parentheses are $t$-ratios. [b] No-azolla plots + azolla plots without incorporation + azolla plots with incorporation. [c] No-azolla plots + azolla plots with incorporation.

be estimated. Some observations which recorded extraordinarily low yields due to tungro infestation are excluded from the data set in order to estimate an ordinary relationship. Other fertilizer nutrients, i.e., P, K, and Zn and their cross-products with *D* and *I,* e.g., P . *I,* do not give any significant coefficient in all the regression equations, and therefore they are omitted from the equations. Regression I gives siginificant coefficients for all the variables included except $N^2$, indicating that the original response function with azolla ($Y_{NA}$) of the linear form was shifted by azolla use toward the left with a transformation in the shape of the function. However, this relation is false. Once the level of the other inputs is taken into account (regression II), all coefficients are not significantly different from zero except for *I* and *C,* which suggests that the null hypothesis of linearity in response function is to be accepted. The division of the total cost excluding fertilizer into labor cost, capital cost, and current input cost excluding fertilizer gives almost the same results.

Regression III with *N* in a linear form improves the *F*-value substantially. A regression equation of the same form fitted to the data set in which the no-azolla plots and the azolla-incorporated plots are combined gives essentially the same result (regression IV). From these estimates, we can safely conclude that the original response function with azolla is well described by a linear response function, and that the application of azolla results in a leftward-parallel shift of the original function. The insignificant coefficient of the dummy variable for the azolla plots in regression III supports our finding that the application of azolla after transplanting without incorporation has no appreciable effect on rice yield.

The average quantity of N supplied by azolla in the form usable by rice plants is estimated at 48 kg/ha or 8 kg/ha per azolla incorporation, based on regression III.

This estimate of N fixed by azolla is consistent with the results of greenhouse experiments conducted by Watanabe (unpublished). In the experiments, 1.3 g/m$^2$ of azolla inoculated in the South Cotabato soil (from Barangay Magsaysay, Koronadal) propagated within a 28-day period up to 500-870 g/m$^2$, which corresponds to 3.25-2.97 doubling days. The survey data indicate that on the average 38 kg/ ha of azolla inoculum increased to 25 t/ha (converted from 50 kg N/ ha assuming 0.2% N content of fresh azolla) within about a 30-day period. From these data, the doubling day in the study area was estimated at 3.2 days, which falls well within the small range obtained from the experiments. This suggests that, although the farmers reduced the quantity of inorganic N by only 18.5 kg/ha for the azolla-incorporated plots compared with that for the no-azolla plots, they could have saved all the inorganic N of 42.5 kg/ ha and attained the same rice yield as that of the no-azolla plots (Table 6). The rice yield per hectare with no inorganic N, but with azolla incorporated six times is projected at 4.47 t/ha, assuming about P2,800/ha ($330/ha) — the sampling average — of nonfertilizer cost and disregarding the insignificant coefficients of variables *D* and *I.* Instead, the average azolla-incorporating farmers obtained 4.83 t rice/ha using 24 kg N/ha. This high capability of azolla in supplying organic N explains well the fact that some farmers in the study area attained rice yields as high as 5-6 t/ha by applying only azolla to their fields.

## Economic return of azolla use

Based on the data in the previous sections, the economic return of azolla used in the study area was evaluated. Two different estimates on the return are presented in Table 9. The maximum return estimate is based on the assumption that azolla can supply 50 kg N/ha and substitute this amount for inorganic N fertilizer, as estimated by the response function. It is also assumed that cost reductions for herbicide and for labor for weeding and fertilizer application occur in association with azolla use (Table 6). The minimum return estimate assumes only the actual inorganic N saved by the farmers. An additional cost of 3 man-hours labor for azolla application is assumed commonly for both cases.

Evaluating at the 1981 prices in the study area, the maximum estimate shows a cost reduction of about ₱380/ ha ($44 ha), which accounts for more than 10% of the total nonland cost for rice production in the 1980 second crop without azolla. The contribution of azolla in reducing current input cost is large. More than 30% of current inputs, which otherwise flows out, could be left in the rice-farming sector by the use of azolla, thus increasing the income to be shared in the sector. Even if the minimum estimate is assumed, the cost reduction is about ₱100/ha ($12/ha) or more than 10% of current input cost without azolla.

If azolla could be adopted for rice production in all irrigated rice fields in the Philippines, the total economic returns could range from ₱150 to ₱560 million ($17.6 to $64.2 million) annually, which is equal to or greater than the annual government fertilizer subsidy.

## AZOLLA UNDER DIFFERENT GROWING CONDITIONS

The case study of farmers using azolla in South Cotabato shows clearly that the biological potential of azolla as a green manure in rice production can be realized with a significant net economic return. If azolla could be introduced by rice farmers in other rice-growing areas in the Philippines and other Asian countries as easily as in South Cotabato, its total economic return would be enormous.

Unfortunately, however, it is not as easy and cheap to grow azolla under certain

**Table 9. Economic return (cost-saving) of azolla use per hectare per season, South Cotobato, Philippines.** [a]

| | Maximum | | Minimum | |
|---|---|---|---|---|
| | Quantity | Value ($) | Quantity | Value ($) |
| 1. N fertilizer saved [b] | 50 kg | 82.35 | 19 kg | 12.35 |
| 2. Herbicide cost saved | – | 2.94 | | |
| 3. Weeding labor cost saved [c] | 33 h | 7.41 | | |
| 4. Fertilizer application labor saved [c] | 7 h | 1.52 | | |
| 5. Azolla application labor added [c] | 3 h | 0.70 | 3 h | 0.70 |
| 6. Net return (cost-saved) | | 43.52 | | 11.64 |
| (#1 + #2)/current input [d] (%) | | 33.8 | | 11.8 |
| #6/nonland cost [e] (%) | | 11.6 | | 3.1 |
| #6/output [f] (%) | | 5.4 | | 1.5 |

[a] For assumptions on maximum and minimum, see the text. US$1 = P8.50. [b] Nitrogen price = $0.65/kg N. [c] wage rate = $0.22/hour. [d] From Table 6. For the 1980 2nd crop. [e] Sum of current input, capital, and labor. From Table 6. [f] A projected rice yield of 4.47 t/ha for no-azolla plots and a price of $0.18/kg unhusked rice are assumed.

environmental conditions as in South Cotabato. In this section, the limiting factors in growing azolla for rice production are reviewed, and the rosy picture is adjusted to a more realistic one.

### Environmental conditions for azolla

The natural environmental conditions under which azolla grows well are summarized in Table 10. These environmental factors not only work independently but also have complex interactions (Tuan and Thuyet 1979).

*Temperature.* The optimum temperature for azolla grown at constant temperature is about 30° C except for *A. filiculoides,* which requires 25° C (Peters et al 1980). In field conditions, *A. pinnata* can grow at 14-40° C (Singh 1979) with an optimum range of 16-30° C, depending on other environmental conditions. At temperatures lower or higher than the optimum range, the growth of the fern and its N-fixing activity are retarded. The fern dies at temperatures lower than 14° C and higher than 40°C.

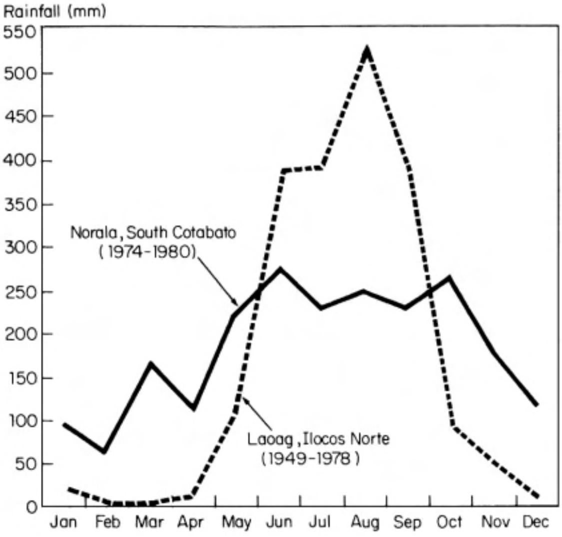
Though found widely in the tropics, *A. pinnata* grows better in the cooler season. In northern Vietnam, it grows best in January, with an average temperature of 17° C. In Varanasi, India, it grows from July to December, but is absent from ponds in the hot summer, April to June (Gopal 1967). In Southern China, growth is best from February to May. In the Philippines, it is poorest in April and May, when monthly average temperatures exceed 32°C (Watanabe et al 1980). This characteristic of azolla could be a problem for its use in the hot seasons and for its year-round cultivation.

*Light.* Scientists disagree regarding the effect of light intensity on azolla growth. However, it seems that too high a light intensity works against azolla growth, and shading helps it during the dry season (Watanabe 1981).

*Humidity.* As an aquatic fern, azolla requires high relative humidity; at a relative humidity lower than 60%, it becomes dry, fragile, and more susceptible to adverse conditions. This requirement for humidity creates a practical problem if azolla is grown throughout the year. In South Cotabato, the monthly rainfall is 50 mm or higher (Fig. 3). As a result, the farmers there can culture azolla in ponds throughout

**Table 10. Environmental conditions under which *Azolla pinnata* grows well.**

| Environmental condition | Optimum level or range | Source |
|---|---|---|
| Temperature | | |
| India | 24-35°C (day)/17-28°C (night) | Rice Research News (1978) |
| China | 20°C optimum | Liu (1979) |
| Vietnam | 16-17°C optimum | Becking (1979) |
| IRRI | 23-30°C (27°C Optimum) | Watanabe et al (1981) |
| Solar radiation | 50% of full sunlight | Watanabe (1978) |
| Ambient relative humidity | >75% | Zhejiang Academy Agricultural Science (1975) |
| Soil pH | 5.5-8 | Singh (1979), Rice Research News (1978) |
| Soil P status | | |
| Olsen P | >50 mg soil/kg | Watanabe (unpublished) |
| P-absorbing capacity | <1,000 mg $P_2O_5$/100 g soil | Watanabe (unpublished) |



**3.** Rainfall patterns in South Cotabato and Ilocos Norte. Philippines.

the year, and the fern can survive in paddy fields even during a 1- to 2-month fallow season. In areas where the rainfall pattern is very skewed, such as in northern Luzon, where there is almost no rainfall for a 5-month period, it may be difficult to keep azolla alive for use the following season.

*Soil pH.* Singh (1977) reported that azolla grows better in soils of pH 5.5-7, although Ashton and Walmsley (1976) showed that it grew at pH 10. Acidic soils of pH 3-3.5 did not support growth, and the inoculum died (Singh 1979).

*Mineral requirements.* The optimum macronutrient contents of azolla expressed in percent of dry weight are, approximately: N, 4-5: P, 0.5; K, 1.0-2.0: Ca, 0.5: Mg. 0.5; and Fe, 0.1. In aquatic habitats, azolla absorbs nutrients mainly from the water. In shallow water, the plant root attaches to the soil and the plant absorbs nutrients from the soil.

The P content of soil solution or of paddy water is generally too low to meet azolla requirements. When the soil P status is such that both the Olsen P and P-absorbing capacity are out of the optimum range, P fertilizer must be added for good azolla growth (Watanabe et al 1980). In this regard, again, the soil conditions of South Cotabato are suitable for azolla growth (Table 3). The use of arolla gave good results even with lower amounts of P (Table 6), and the level of P had no significant effect on rice yields, directly or indirectly.

*Insects and pests.* Insect damage to azolla can be serious. Because the generation time of insects decreases at higher temperatures, it could be more serious during hot summer temperatures above 30°C. Thuyet and Tuan (1973) identified the main insect pests of arolla as the larvae of *Pyralis, Nymphula,* and *Chironomus* spp. In hot climates, fungus damage is also serious, but generally the fungus appears after damage of insects or desiccation. It may be necessary to apply insecticides to control insects and pests during or before an outbreak. In this regard, South Cotabato had ideal conditions: there was no insect attack on azolla, so no insecticide was necessary during the 1981 second season. Recent observations (20 August 1982), however, have shown that azolla in the study area in South Cotabato is now under attack by insects.

*Water control.* Good water control is critical for azolla multiplication. Water depth should be kept at about 3-5 cm. When mineral deficiency occurs, it helps to reduce the water depth to less than 3 cm so that the roots touch and absorb nutrients from the soil. When azolla is incorporated, fields should be drained so that it is easily and effectively turned under by rake or weeder.

## Economic return of azolla use under constraints

The potential of azolla as a green manure is great, but the constraining factors to its use are also significant. Some limiting factors, such as temperature and solar radiation, are totally beyond control under ordinary circumstances. Others, such as nutrient deficiencies or insects, can be controlled by farmers with management practices. Some may require public actions to overcome, such as land infrastructure development to improve water control or soil quality.

The economic return of using azolla varies much from one rice-growing area to another, depending on local limiting factors. It is therefore rather difficult to evaluate the economic return for a general condition without having precise specifications on these factors. In this section, the economic return of azolla use is estimated, assuming that azolla can be grown within the perspective of farmers' management. This means that other conditions such as temperature, soil pH, and water control are satisfied. In addition, it is assumed that azolla is already available to farmers for culturing and inoculation. This means that the initial investments in azolla propagation, including research and its distribution to certain areas, are not included in the analysis. An estimation of the economic return of azolla under such restrictive assumptions may not be much beyond an illustration. The estimate, however, will still give an idea of what the problems can be in realizing the potential of azolla as an economically feasible green manure.

Before estimating the economic return, the levels of P fertilizer, insecticide, and labor — the necessary inputs for azolla — must be determined.

*P fertilizer.* The need for P fertilizer is well recognized. Recommended levels in several countries are summarized in Table 11, though some of them are not for farmers' application but for scientists' experiments. The recommended levels vary considerably from 1.8-11 kg P/ ha. Fortunately, Watanabe et al (1980) intensively studied the effect of P fertilizer on azolla growth. Their results showed a clear quadratic relation between the level of P fertilizer applied and total N fixed by azolla ($N$). The following equation is estimated from data reported in their paper:

$$
\begin{aligned}
N = 14.3 + {} & 1.82\,P - 0.0389P^2 \\
& (7.28) \quad (-5.14) \\
& \qquad\qquad R^2 = 0.930,\ n = 9
\end{aligned}
$$

where $N$ and $P$ are both in kg/ ha, and figures in parentheses are $t$-ratios. Although the degree of freedom is small, the coefficients of $P$ and $P^2$ are highly significant. The intercept term is estimated as 14.3 kg/ ha, indicating that azolla can fix this amount of N without P fertilizer. The level of intercept term varies from place to place,

**Table 11. Levels of phosphorus fertilizer and chemical for growing azolla recommended by biological scientists.**

| Fertilizer | Rate | Recommended by |
|---|---|---|
| *Phosphorus* | (kg P/ha) | |
| India | 1.8 - 11.0 | Singh (1979) |
| China | 10 | Liu (1979) |
| Vietnam | 2.2 - 4.4 | Tuan and Thuyet (1979) |
| USA | 2.2 - 6.6 | Rains and Talley (1979) |
| *Chemical* (carbofuran) | | |
| India | 2.25 kg a.i./ha or<br>3.15 g a.i./inoculum for 1 ha | Singh (1979) |
| | 2.13 kg a.i./ha or<br>0.1-1 g a.i./kg azolla | Rice Research News (1978) |
| IRRI | 3-4 kg a.i./ha | Watanabe (1981) |

depending on the soil P status. In the analysis in this section, the above equation is assumed to be a general case. The optimum P level is then estimated as 12 kg/ha under world price conditions and 5 kg/ha under Philippine price conditions.

*Chemicals (insecticides).* It is rather difficult to determine the optimum level of insecticides for azolla because a chemical spray may or may not be necessary, depending on local insect conditions. Some scientists recommend carbofuran at 2-4 kg a.i./ha upon outbreak or 3-15 g a.i./azolla inoculum for 1 ha (Table 11). Depending on these recommendations, two cases may be assumed: in case 1, 15 g a.i. carbofuran mixed with azolla inoculum for 1 ha can control insects and pests of azolla; in case 2, 2 kg a.i. carbofuran/ha are necessary for controlling insects and pests.

*Labor.* Besides the survey data in South Cotabato, which seems to be an extreme case involving negligible labor, there are no available data on the labor requirement for azolla culture and application. The labor requirement would vary greatly according to the application methods and conditions. For instance, the recommended level of inoculum density is 1-5 t/ha (Tuan and Thuyet 1979, Singh 1979). If this amount of inoculum is carried from an inoculum production plot to a rice field located far away, the labor would be enormous. However, if the same amount is applied by adopting the half saturation method recommended in Vietnam (Watanabe 1981) or by using water currents along irrigation canals, the labor is much less.

Labor has a dual aspect in evaluating the economic return of azolla use (or of any other self-supplied organic fertilizer). On one hand, the labor needs form an additional cost in private management. On the other hand, the labor demand opens up new employment and income-earning opportunities. There can be cases where azolla is not adopted by farmers because of net negative private return, even though the net return to the society or to the rice sector is positive.

It is also difficult to evaluate the cost of additional labor required. The opportunity cost of labor varies from place to place and from busy season to slack season in agricultural production. If azolla is applied in a place where work opportunities are scarce or at a time when farm labor remains primarily idle, the additional labor cost would be negligible even if the increments in labor due to azolla use are substantial.

In this analysis, it is assumed that 5 days of labor are required for azolla production and application. Two cases are assumed to identify the effects of different levels of opportunity cost of labor; case 3 has low opportunity cost and case 4 high opportunity costs.

The estimated economic returns of azolla under two different price situations, 1980 world prices and 1981 Philippine prices, are in Table 12. The return due to N fertilizer savings after subtracting the cost of P fertilizer applied for azolla is about $10/ha for both price structures (row 3). These estimates are almost comparable to the minimum estimate in South Cotabato.

If insects and pests of azolla can be controlled well by low use of chemicals (case 1), the net return for the rice sector is still around $9/ha (row 5). But, if farmers have to apply at the high-use level (case 2), they will realize a huge loss (row 6). The amount of carbofuran that can be bought by the net return due to N saving is only 263 g a.i./ha (9 kg Furadan 3 G) for the world price case (row 8). Chemicals beyond this amount incur an economic loss. This clearly suggests the importance of developing more effective insect and pest control methods for azolla. Unless more effective methods of insect and pest control are developed, or chemical prices decline drastically, azolla will never be economically feasible in areas of frequent insect outbreaks.

With the assumption of no opportunity cost of labor the estimates of rows 3,5, and 7 in Table 12 are the economic returns of azolla use for the whole rice economy as well as for individual farmers. Even if the opportunity cost is positive, the economic return for farmers may not be reduced much in places such as India where the opportunity cost, as measured by the average agricultural wage rate, is low (row 10). However, the economic incentive to adopt azolla is eliminated in places such as Taiwan Province, China, where the opportunity cost is high (row 12). Under such an economic environment, farmers would never adopt azolla. The break-even wage rate, computed in the same way as the chemical case, assuming a 5-day labor requirement, is about $1.90/day (row 13). The wage rate in the Philippines is approaching this.

These results suggest that azolla has a great economic potential in countries such as India, Bangladesh, and Indonesia where the wage rates in agriculture are still low and there is a stringent need to increase rural employment. Both the social and private returns would be high in these countries. It is also clear that azolla has no economic potentials as long as it requires substantial labor in places such as Taiwan Province, China, and Korea where the rural wage rate is already high and rising. Both the social and private returns of azolla use can be negative in this case. The situation in countries such as the Philippines where the rural wage rate is approaching the break-even rate makes it difficult to assess the economic potential of azolla. The social return may be positive, though its level depends critically on accurate estimates of the opportunity cost of labor for the society. If there is a discrepancy between the opportunity cost of labor for the society and farmers' subjective evaluation of labor, azolla may not be adopted despite the positive return to the society. For adopting azolla in these countries, it will be important to design technology for utilizing farm labor during idle times.

**Table 12. Economic return of azolla use under different price structures and different assumptions of cultural practices.**

| | 1980 world prices[a] | | | 1981 Philippine prices[b] | | |
|---|---|---|---|---|---|---|
| | Quantity/ha | Unit price ($) | Total value ($) | Quantity/ha | Unit price ($) | Total value ($) |
| 1. N fertilizer saved[c] | 30 kg | 0.50/kg | 15.00 | 22 kg | 0.64/kg | 14.08 |
| 2. $P_2O_5$ fertilizer for azolla[d] | 12 kg | 0.42/kg | 5.04 | 5 kg | 0.89/kg | 4.45 |
| 3. Return of azolla use (1-2) | | | 9.96 | | | 9.63 |
| 4. Chemical for azolla: case 1, low use[e] | 15 g a.i. | 37/kg a.i. | 0.56 | 15 g a.i. | 46/kg a.i. | 0.69 |
| 5. Return of azolla use (3-4) | | | 9.4 | | | 8.94 |
| 6. Chemical for azolla: case 2, high use[f] | 2 kg a.i. | 37/kg a.i. | 74.00 | 2 kg a.i. | 46/kg a.i. | 92.00 |
| 7. Return of azolla use (3-6) | | | –64.04 | | | –83.37 |
| 8. Break even quantity of chemical for azolla[g] | 263 g a.i. | | | 209 g a.i. | | |
| 9. Labor use for azolla: case 3, low wage[h] | 5 days | 0.63/day | 3.15 | 5 days | 1.87/day[k] | 9.35 |
| 10. Return of azolla use for farmer (3-9) | | | 6.81 | | | 0.28 |
| 11. Labor use for azolla: case 4, high wage[i] | 5 days | 14.58/day | 72.90 | | | |
| 12. Return of azolla use for farmer (3-11) | | | –62.94 | | | |
| 13. Break-even wage rate[j] | | 1.94/day | | | 1.93/day | |

[a] F. O. B. prices at port of origin nearest to Asia are assumed. Data are from Palacpac (1982) except for carbofuran, for which price data are given by O. Mochida, IRRI entomologist. [b] Prices paid by farmers. Data are from same sources as in [a]. [c] Quantity of chemical N (urea) that could be replaced by use of azolla with optimum use of $P_2O_5$ fertilizer for azolla. [d] Optimum level of $P_2O_5$ (superphosphate) for azolla growth with given relative prices of N and $P_2O_5$. [e] Assume that 15 g a.i. carbofuran mixed with azolla inoculum for 1 ha can control insects and pests for azolla. [f] Assume that 2 kg a.i. carbofuran/ha is necessary for controlling insects and pests. [g] #3/price of carbofuran. [h] Assume 5 days of labor requirement for azolla application net of labor saved due to azolla (labor for chemical fertilizer application and weeding), and assume a low wage rate that prevails in India. [i] Assume the same labor requirement above, but assume a high wage rate that prevails in Taiwan. [j] #3/5 days. [k] Philippine wage rate in agriculture.

The economic returns of azolla use, as shown in Table 12, must be adjusted when the price structure changes. If the price of N fertilizer increases in the future relative to other prices, the returns would increase, and *vice versa.*

## RESEARCH AND POLICY IMPLICATIONS

The following research and policy implications for realizing the potentials of azolla in rice farming are derived from our findings.

- The search for improving cultural techniques to grow azolla under less favorable conditions should be strengthened. New azolla strains that are tolerant of adverse growing conditions need to be found.
- Specifically, tolerance of insects and pests is critical for azolla to be an economically viable green manure.
- Azolla strains should also be able to absorb scarce P from water and soil efficiently.
- With the present strains of azolla, it is imperative to study effective and efficient methods of insect and pest control. In dual cropping with rice, the possibility of integrating insect and pest control for azolla with rice should be studied.
- Efficient P fertilizing methods for azolla should be established for different locations with different types of soil.
- Cultural methods for azolla production should be sought by which off-season labor of low opportunity cost can be mobilized.
- Public efforts for improving land infrastructure would help overcome constraints to growing azolla. At the same time, the returns to public investments for infrastructure development would be increased by the introduction of azolla into a rice farming system.

## REFERENCES CITED

Ashton, P. J. 1974. Effect of some environmental factors on the growth of *Azolla filiculoides* LAM. Pages 124-138 *in* Orange River Progress Report (Institute for Environmental Sciences) Univ. O.F.S. Bloemfontein, South Africa.

Ashton, P. J., and R. D. Walmsley. 1976. The aquatic fern Azolla and its Anabaena symbiont. Endeavour 35:39-43.

Becking, J. H. 1979. Environmental requirements of Azolla for use in tropical rice production. Pages 345-373 *in* International Rice Research Institute, Nitrogen and rice. Los Baños, Philippines.

Braemer, P. 1927. La culture des *Azolla* an Tonkin. Rev. de Botanique applique et d' agriculture coloniale 7:815-819.

Buckingham, K., S. W. Ela, J. G. Morris, and C. R. Goldman. 1978. Nutritive value of nitrogen-fixing aquatic fern *Azolla filiculoides.* J. Agric. Food Chem. 26: 1230-1234.

Dao, T. T., and A. Do. 1970. A few ideas on equating different kinds of nitrogenous fertilizer with pure nitrogen [in Vietnamese]. Agric. Sci. Technol. Vietnam 93:168-174.

Edwards, D. J. 1974. Weed preference and growth of young grass carp in New Zealand. N. Z. J. Mar. Freshwater Res. 8:341-350.

Gopal, B. 1967. Contribution of *Azolla pinnata* R. Br. to the productivity of temporary ponds at Varanasi. Trop. Ecol. 8:126-129.

INSFFER. 1980. Report on the first trials of Azolla use to rice: 1979. International Rice Research Institute. Los Baños, Philippines.

INSFFER. 1981, Report on the second trials of Azolla use to rice: 1980. International Rice Research Institute, Los Baños, Philippines.

Li, S. Y. 1983. Azolla in the paddy fields of eastern China. Pages 171-180 *in* International Rice Research Institute. Organic matter and rice. Los Baños, Philippines.

Liu, C. C. 1979. Use of Azolla in rice production in China. Pages 375-394 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Moore, A. W. 1969. *Azolla:* biology and agronomic significance. Bot. Rev. 35:17-34.

Ngo, G. D. 1973. The effect of *Azolla pinnata* R. Br. on rice growth. BIOTROP Report. 2d Indonesian Weed Sci. Conf.

Nguyen Cong Tieu. 1930. The *Azolla* plant cultivated for use as a green fertilizer [in French]. Bull. Econ. Indochine 33:335-350.

Nutman, P. S. 1976. IBP field experiments on nitrogen fixation by nodulated legumes. Pages 211-237 *in* P. S. Nutman, ed. Symbiotic nitrogen fixation in plants. Cambridge University Press. Cambridge.

Palacpac, A. C. 1982. World rice statistics. Department of Agricultural Economics, International Rice Research Institute. Los Baños, Philippines.

Peters, G. A., R. E. Toia, Jr., W. R. Evans, D. K. Christ, B. C. Mayne, and R. E. Poole. 1980. Characterization and comparisons of five N2-fixing Azolla-Anabaena associations. I. Optimization on growth conditions for biomass increase and N content in a controlled environment. Plant Cell Env. 3:261-269.

Rains, D. W., and S. N. Talley. 1979. Use of Azolla in North America. Pages 419-433 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Rice Research News. 1978. Vol. 4, No. 2 (June). Central Rice Research Institute, Cuttack, India.

Sawatdee, P., W. Seetanum, C. Chermsiri, C. Kanareugsa, and J. Takahashi. 1978. Effect of *Azolla* as a green manure crop on rice yield in northeastern Thailand. Int. Rice Res. Newsl. 2(3):10.

Singh, P. K. 1977. Multiplication and utilization of fern *Azolla* containing nitrogen-fixing algae symbiont as green manure in rice cultivation. Proc. Indian Acad. Sci. 2:175-200.

Singh, P. K. 1979. Use of *Azolla* in rice production in India. Pages 407-418 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Subudhi, B. P. R., and P. K. Singh. 1978. Nutritive value of the water fern *Azolla pinnata* for chicks. Poult. Sci. 57:378-380.

Talley, S. N., B. J. Talley, and D. W. Rains. 1977. Nitrogen fixation by *Azolla* in rice fields. Pages 259-282 *in* A. Hollander, ed. Genetic engineering for nitrogen fixation. Plenum Publishing Co. New York.

Talley, S. N., and D. W. Rains. 1980a. Azolla as a nitrogen source for temperate rice. Pages 311-320 *in* W. E. Newton and W. H. Orme-Johnson, eds. Nitrogen fixation. Vol. 2. Univ. Park Press. Baltimore.

Talley, S. N., and D. W. Rains. 1980b. *Azolla filiculoides* LAM as a fallow season green manure for rice in a temperate climate. Agron. J. 72:11-18.

Thuyet, T. Q., and D. T. Tuan. 1973. Azolla — a green compost. Vietnamese studies, Agric. Probl. 38:119-127.

Tuan, D. T., and T. Q. Thuyet. 1979. The use of *Azolla* in rice production in Vietnam. Pages 395-405 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Tuzimura, K., F. Ikeda, and K. Tukamoto. 1957. *Azolla imbricata* as a green manure for rice [in Japanese]. Nippon Dojo Hiryo Gaku Zasshi (J. Sci. Soil Manure) 28:275-278.

Watanabe, I., C. R. Espinas, N. S. Berja, and B. V. Alimagno. 1977. Utilization of the *Azolla-Anabaena* complex as nitrogen fertilizer for rice. IRRI Res. Pap. Ser. 11.

Watanabe, I. 1978. *Azolla* and its use in lowland rice culture. Tsuchi to Biseibutsu (Soil and Microbes), Tokyo 20:1-10.

Watanabe, I., N. S. Berja, and D. C. del Rosario. 1980. Growth of *Azolla* in paddy field as affected by phosphorus fertilizer. Soil Sci. Plant Nutr. 26:301-307.

Watanabe, I. 1981. Biological nitrogen fixation by *Azolla-Anabaena* symbiosis and its utilization [in Japanese]. J. Sci. Soil Manure. Jpn. 52(5):455-464.

Watanabe, I., K. Z. BAi, N. S. Berja, C. R. Espinas, O. Ito, and B. P. R. Subudhi. 1981. The *Azolla-Anabaena* complex and its use in rice culture. IRRI Res. Pap. Ser. 69.

Zhejiang Academy Agricultural Sciences. 1975. Cultivation, propagation and utilization of Azolla [in Chinese]. Agriculture Publishing, Beijing. 127 p.

## DISCUSSION

BUNOAN: What is the efficiency of azolla N in terms of kilograms rough rice per kilogram of azolla N per crop of azolla in a hectare as: 1) green manure before transplanting and 2) intercrop after transplanting when incorporated into the soil and when not incorporated?

*KIKUCHI:* The results of the response function estimation indicate that azolla incorporated in the soil six times can supply about 50 kg N/ha in a form usable by rice plants, producing about 4.5 t rice/ha with no inorganic N. From these data, an average efficiency of azolla N is estimated as 90 kg rough rice/kg azolla N where azolla is applied before transplanting and incorporated in the soil. Where azolla is applied after transplanting, no incorporation is done, and azolla application does not have any significant effect on rice yield.

MORACHAN: Did you take into account the cost of production of azolla in your calculations?

*KIKUCHI:* No, we did not, because 1) virtually no cost for producing azolla was incurred in the case of South Cotabato — azolla was available to farmers free of charge; and 2) we limited our study to the economic performance of azolla on farmers' fields in the case of general assessment; if azolla does not generate a positive return on farmers' fields, the inclusion of additional costs, such as initial investments for azolla research and making the azolla inoculum pond, is necessary.

# RICE STRAW AND STUBBLE MANAGEMENT

J. C. Flinn and V. P. Marciano

The agronomic benefits of incorporating rice straw have been analyzed in detail. However, there is little farm management or economic analysis of the practice. Such analysis should recognize that rice straw frequently has an opportunity cost. Thus, the labor and land preparation costs and resulting savings should be identified in the analysis of straw as a source of plant nutrients.

Straw use, and its opportunity cost, is highest in South Asia, where farming systems are crop-livestock based. High labor costs in East Asia make composting a less attractive proposition than inorganic fertilizers. Innovations in straw incorporation may have the greatest chance of success in the Southeast Asian countries.

Philippine rice farmers adopt straw management practices that require little labor. They do recognize that ash and decomposed straw contribute to soil fertility and reduce fertilizer inputs to fields where these have been incorporated. Incorporating undecomposed straw is labor and power demanding during land preparation.

The benefits of straw incorporation need to be studied at the farm level to identify the benefits and costs, from the farmer's viewpoint, of the technology.

An important agronomic benefit of incorporating rice straw is improved soil fertility, which leads to higher rice yields. Regrettably, there is little analysis of the farm management and economic aspects of rice straw as a nutrient source in rice production.

Ponnamperuma (1983) places the yield benefit of incorporated straw in excess of 0.4 t/ha per crop. Composted straw frequently results in yields more than twice this amount (Tanaka 1978). Rice straw may also be used as a substitute for or as a complement to inorganic fertilizers. Various options for incorporating rice straw must be pursued in the quest to develop rice production systems that are more energy and cost efficient than they are at present.

In certain circumstances (particularly in cool climates and in poorly drained fields), incorporating straw may reduce rice yields (Tanaka 1978). However, in the tropics or where straw is rotted or composted (as is usually the case in Japan and China), these adverse effects do not seem to be a major problem, and thus are not of direct interest here. The main "penalties" considered in this paper are the costs of

---

Department of Agricultural Economics, International Rice Research Institute.

alternative straw management practices. One of these costs is the value of straw for other uses; another is the labor cost of handling and incorporating this low-analysis fertilizer into the soil.

The net economic benefit of straw incorporation depends on the balance between benefits and costs. The change in benefits consists of two components: 1) the added benefits of adopting the new practice, and 2) the reduced costs of changing from the existing to the proposed practice. From the farmer's viewpoint, the added benefits may be higher rice yields as well as reduced costs, including reduced fertilizer outlay if less inorganic fertilizer is used. Another benefit to society is reduced air pollution when straw is incorporated and not burned.

New straw management practices may result in higher yields but may also result in cost changes to farmers. These may be either reduced benefits or added costs. In many areas, straw has alternative uses, such as livestock feed or as a source of industrial raw material. Unfortunately, straw prices which reflect the value in these uses are rarely reported in official statistics. However, lines of straw-loaded wagons seen in Dhaka, Hyderabad, or Lahore and some farmers' preference for long-strawed rice cultivars over short-strawed (but higher yielding) ones attest to the value of rice straw in many rice-based farming systems in Asia. Such alternative uses of straw mean a reduced benefit to farmers. Added costs involved in increasing straw use in rice culture include the labor necessary to handle this bulky material, and costs of incorporating it into the soil.

The technical performance and profitability of alternative straw management practices vary country by country, and by farming systems within countries. The economic merit of incorporating rice straw is therefore location specific: it will be dependent on prices, some of which (e.g., rice and fertilizer prices) are frequently a function of government policy; on the nature of farming systems found in the area, which determines the opportunity cost of straw; and on the biological relationships between crop response to straw and to inorganic fertilizers.

This paper begins by reviewing existing methods of straw management and some relevant price relationships that exist in Asia. The tentative conclusion drawn is that, given technological innovation, there may be the greatest opportunities to increase the efficiency of straw use in the rice-based farming systems of Southeast Asia. The paper explores farmers' straw management in two different Philippine rice production systems. It concludes that the "problem" is not farmer awareness of the benefits of straw utilization, but the fact that alternative technologies which would make it attractive to increase the efficiency of straw use in rice production do not exist. Finally, we suggest some areas of research in rice straw management that may be timely.

## RICE STRAW MANAGEMENT IN ASIA

The dominant methods of rice disposal in Asia are depicted in Figure 1. Straw use in Asia tends to fall into three categories. In East Asia (Korea, Japan, and China) and in the hills of Nepal rice has until recently been harvested at ground level, and most of the threshed straw was combined with manure and returned to the field as compost.

| Country | Incorporation into soil | Compost | Burning | Feed or animal bedding | Mushroom culture | Mulching for orchard or vegetable | Fuel of household | Straw products or roofing | Manufacture of paper |
|---|---|---|---|---|---|---|---|---|---|
| Korea |  | ●← | ------ | –● | ○ | ○ |  | ○ |  |
| Japan | ○ | ● | ○ |  |  |  |  |  |  |
| China |  | ●← | ------ | –● | ○ | ○ |  | ○ |  |
| Nepal |  | ●← | ------ | –○ |  |  | ○ |  |  |
| Philippines | ● |  | ● | ○ | ○ |  |  | ○ | ○ |
| Thailand |  |  | ● | ○S |  |  |  |  |  |
| Indonesia | ○ |  | ● |  | ○ |  |  |  | ○ |
| Malaysia | ○S |  | ● |  |  |  |  |  |  |
| Burma |  |  | ● (North) | ● (South) |  |  |  | ○ |  |
| Bangladesh |  |  | ○S | ● |  |  | ○ |  |  |
| India |  |  | ○ | ● |  |  | ○ | ○ |  |
| Pakistan |  |  |  | ● |  | ○ |  |  | ○ |
| Sri Lanka |  |  | ○ | ● |  |  |  | ○ |  |

● = Major ○ = Minor S = Stubble

**1.** Methods of handling rice straw in various countries. (Source: Tanaka 1973)

In Southeast Asia (e.g., Vietnam, Philippines, Indonesia, Malaysia) rice straw tends to be harvested higher from the ground, and the stubble (or the remnants after weathering or grazing) incorporated into the soil; the threshed straw is either burned or partially decomposed before being spread back in the rice fields. In South Asia rice is usually harvested at ground level and the straw used for cattle feed and household uses; in many cases little of the straw is returned to the field, either as straw or compost.

What are the opportunities for increasing straw use in rice production in these three groups of countries?

## Traditional compost-producing countries

Wen (1983) and Wiens (1983) discussed the use of organic materials (including rice straw) in cereal crop production in China. In existing systems of crop management, there seems to be little loss of plant nutrients. However, China cannot reach its desired levels of foodcrop production using only organic fertilizers. Thus, increased use is being made of inorganic fertilizers to increase the productivity of rice lands and labor. It seems unlikely that this trend will be reversed in the near future. More likely, inorganic and organic sources of fertilizer will be used in combination more frequently (Liu and Lin 1982).

In Japan the per-hectare use of compost in rice production is falling, while that of inorganic fertilizer is increasing (Table 1). Korean data would show similar trends. Composting is labor intensive, and rural wages are increasing in these countries.

**Table 1. Yield of rice, input of nitrogenous fertilizer, and relative price, Japan, 1883-1970.**[a]

| Period | Yield of rice (t/ha) | Input of nitrogenous fertilizer (kg/ha) | | | Relative price[b] | |
|---|---|---|---|---|---|---|
| | | Total | Homemade | Commercial | (A) | (B) |
| 1883-1887 | 2.0 | 49 | 44 | 5.2 | 323 | 100 |
| 1888-1892 | 2.2 | 50 | 45 | 5.0 | 375 | |
| 1893-1897 | 2.1 | 52 | 46 | 6.0 | 292 | 88 |
| 1898-1902 | 2.3 | 45 | 46 | 7.3 | 245 | 77 |
| 1903-1907 | 2.5 | 57 | 47 | 10 | 234 | 68 |
| 1908-1912 | 2.6 | 65 | 47 | 18 | 181 | 54 |
| 1913-1917 | 2.8 | 71 | 48 | 23 | 189 | 58 |
| 1918-1922 | 2.9 | 78 | 47 | 31 | 149 | 42 |
| 1923-1927 | 2.8 | 87 | 49 | 38 | 124 | 35 |
| 1928–1932 | 2.9 | 99 | 52 | 47 | 105 | 21 |
| 1933-1937 | 3.02 | 108 | 59 | 49 | 109 | 26 |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |
| . | . | . | . | . | . | . |
| 1951-1955 | 3.3 | 118 | 40 | 78 | 73 | 20 |
| 1956-1960 | 3.8 | 144 | 39 | 105 | 62 | 22 |
| 1961-1965 | 4.0 | 150 | 34 | 117 | 43 | 17 |
| 1966-1970 | 4.4 | 179 | 30 | 149 | 35 | 14 |

[a] Source: Tsuchiya 1974.

[b] Relative price (A) = $\dfrac{\text{Price of commercial nitrogeneous nutrient}}{\text{Price of homemade nitrogenous nutrient}} \times 100$

(B) = $\dfrac{\text{Price of commercial nitrogenous nutrient}}{\text{Price of rice}} \times 100.$

Thus, the cost of compost has risen compared to that of commercial fertilizers. As a result, in Japan, inorganic fertilizers are replacing organic sources of N and other plant nutrients in rice production (Tsuchiya 1974).

It is unlikely that in Japan there will be a material shift back to compost and away from inorganic fertilizers. Not only have relative prices prompted a shift toward inorganic fertilizers, but recent changes in harvesting techniques have resulted in more straw being left in the field than previously. In 1965, 95% of the rice crop was harvested by sickle and the crop threshed in a central place; assembling the straw for composting presented little difficulty. Now 56% of the crop is harvested by combine and the straw left in the field (Ezaki 1982). Direct incorporation of this straw under cooler Japanese conditions may delay plant growth and reduce rice yields, so straw may not be an effective substitute for composting (Tanaka 1978). A larger proportion of the rice straw is now burned in the field than was historically the case, leading to pollution and consequent legislation to control the burning. An emerging problem for Japanese rice scientists, therefore, is to develop practical and economic methods of utilizing or disposing of rice straw, which has declining value as a source of organic fertilizer.

### Cereal-livestock-based farming systems

Farming systems in South Asia and northern Burma tend to be crop-livestock based. Over 60% of Asia’s large ruminants (cattle and buffalo) are found in India, Nepal, Pakistan, and Bangladesh (FAO 1975). These animals are kept as a source of power, for milking, as a form of income and wealth, and in some cases for religious purposes. The animals normally consume 3-5 kg of dry fodder each day. Massive cattle and water buffalo populations therefore require huge quantities of low-cost roughage to sustain them (McDowell 1972).

Virtually all the straw produced in South Asia is conserved for livestock feed. Some of the straw nutrients are subsequently returned to the ground as animal excreta. This and bedding straw become sources of compost or are used as inputs into other production processes. The Indian Council of Agricultural Research (ICAR 1971) estimated that about a third of the livestock dung produced in India is used as fuel and about another third as fertilizer. Other competing demands for these composting materials are as stock for bio-gas plants to produce fuel gas and as straw for paper and board manufacture. Nitrogen and other nutrients can be recovered from the slurry of these plants and used as a source of plant nutrients (Srinivasan 1977). Indeed, Jackson (1979) argued that the efficiency of straw use is probably higher in South Asia than in Southeast or East Asia because nearly all straw is utilized in a two-stage process: Feeding straw to animals utilizes energy embodied in the straw, while plant nutrients contained in the feed are recycled back to the land either directly or as compost.

Straw, being bulky, is usually fed to animals and applied to crops on the farm where it is produced. Thus, while this by-product of the rice crop has value to farmers, it may not have a clearly established market price in the normal sense. This may partly explain why rice straw prices are rarely quoted in official statistics, and why economists often neglect this important output when analyzing the farmer relevance of alternative systems of rice management.

The value of straw as livestock feed seems to range from $6 to $14/t in South Asia (Table 2). The value of straw to the cultivator may represent a substantial part of his net earnings from the crop, particularly if he is a tenant who may share grain output with a landlord but retain most of the straw — a common practice in much of the Indian subcontinent. For example, Rustagi (1982, pers. comm., International Rice Research Institute) places the value of cereal fodder in an Indian cereal-pulse intercrop system at 25% of the net output value of the pattern; values ranging from 15 to 20% have been reported in the Sind region of Pakistan (Bhatti et al 1981) and in the Eastern Tarai of Nepal (Sah and Flinn 1981). The lower price of rice straw reported for Nepal (Table 2) is consistent with the observation that Nepalese farmers often have a distinct preference for long-strawed cultivars (e.g., Masuli), partly because of their superior palatability as animal feed. Indeed, this preference for long straw for feed, fuel, or construction may constrain the adoption of modern cultivars (Briscoe 1980).

Ponnamperuma (1983) suggested that the value of nutrients in straw is about $7/t at current world fertilizer prices, recognizing that such estimates are rough because no account is taken of comparative nutrient availability, crop-use efficiency, or yield

Table 2. Impressionistic values of rice straw in South Asia.[a]

| Location | Value per ton | |
|---|---|---|
| | Local currency | US$ equivalent[b] |
| Pakistan | | |
| Punjab | Rs 100 | 10.10 |
| Sind | Rs 110 | 11.11 |
| India | | |
| Punjab | Rs 50 | 5.62 |
| Eastern India | Rs 100 | 11.24 |
| Southern India | Rs 60 | 6.74 |
| Bangladesh | | |
| Joy de bpur | Tk 260 | 14.28 |
| Nepal (Tarai) | | |
| IR cultivars | Rs 70 | 5.80 |
| Long-strawed cultivars | Rs 110 | 9.17 |

[a] Sources: Punjab Pakistan: Mubarik Ali (pers. comm.); Sind, Palistan: Bhatti et al 1981; India: Rajagopalan et al 1978, author's field notes, M. S. Srinivasan (pers. comm.); Bangladesh: Jabber (pers. comm.); Nepal: Sah and Flinn 1981. [b] At rates prevailing in early 1982.

response between organic and inorganic nutrient sources, or of comparative labor costs involved in using them. Despite these caveats, it still appears that the opportunity cost of rice straw as fodder for animal feed in South Asian farming systems may exceed its direct value as a plant nutrient for rice.

There may be few opportunities or little incentive for farmers to increase direct straw utilization as a source of nutrients for rice in crop-livestock based farming systems in South Asia. Rather, increased benefits may come primarily in the form of a source of livestock feed and secondly as an input to compost. Thus, the real benefits of straw-related research in these locations may emerge from that which focuses on increasing productivity in its primary use in animal production.

### Crop-based farming systems

Rice-based farms generally have lower ruminant populations in Southeast Asia than in South Asia. However, this does not imply that livestock should or can be ignored when studying the alternatives for using rice straw in these systems. Unlike in East or South Asia, the rice in Southeast Asia is frequently harvested high above the ground. This results in considerable rice straw left standing in the field. This stubble, or its remnants, are usually plowed in or grazed by livestock. The straw harvested with the crop is often burned (if dry enough), fed to livestock, or allowed to decompose before being spread on rice fields. Rarely is undecomposed straw directly incorporated into the rice field. Tanaka (1973) argued that the main objective of straw management in these locations is to dispose of the straw as cheaply as possible; any beneficial effects of incorporated straw on soil fertility are not important considerations.

In summary, the characteristics of existing farming systems are important determinants of the options open for increasing the efficiency of straw use in rice production. Described in general terms, the profitability of alternative straw management practices is poorly documented from the farmer's viewpoint.

## RELATIVE PRICES AND STRAW USE

The short-term potential for increasing rice straw use (either in addition to or as a substitute for inorganic fertilizer) may be considered by comparing the prices of fertilizer, labor, and rice in various Asian countries (Table 3). To provide a standard base across countries, these comparisons are couched in terms of rice grain equivalents. Straw and compost prices are not reported for most countries and hence are not included.

In Korea, Malaysia, Japan, Thailand, and Taiwan, China, over 10 kg of rice can be bought with the equivalent of a day's labor, i.e., rice is "cheap" compared to labor. A characteristic of an attractive innovation, therefore, will be one with a high rice output per day of labor input. In these circumstances, other things being equal, labor-intensive methods of plant-nutrient management will be less attractive to farmers than low labor-using technology; thus, comparatively high-analysis inorganic fertilizers should have an advantage over more bulky organic forms.

Inorganic fertilizers are more expensive in Vietnam, China, India, the Philippines, Pakistan, and Thailand than in other Asian rice-producing countries. In these countries, increased use of rice straw as a nutrient source may be attractive, provided wage rates and the value of straw for alternative uses are low. In China straw is already fully utilized as compost; in India and Pakistan the opportunity cost of straw as livestock feed is high; in Thailand relative wage rates are high. Thus, the greatest opportunities for increasing rice straw use may be in countries such as Vietnam and the Philippines.

**Table 3. Prices (in US$ equivalent) and relative prices of labor and fertilizer, Asian countries, late 1981.**[a]

| | Price ($) | | | Price ratio[b] | |
|---|---|---|---|---|---|
| | Rice (1 kg) | Labor (1 day) | Urea (1 kg) | Fertilizer/ rice price | kg rice purchased with day's wage |
| *South Asia* | | | | | |
| India | 0.23 | 1.12 | 0.61 | 2.65 | 1.72 |
| Pakistan | 0.08 | 1.00 | 0.29 | 3.63 | 2.63 |
| Sri Lanka | 0.13 | 0.87 | 0.14 | 1.08 | 2.70 |
| Bangladesh | 0.21 | 1.06 | 0.37 | 1.76 | 3.97 |
| Nepal | 0.20 | 0.79 | 0.45 | 2.25 | 2.86 |
| *Southeast Asia* | | | | | |
| Malaysia | 0.18 | 5.95 | 0.33 | 1.83 | 17.41 |
| Thailand | 0.11 | 2.46 | 0.38 | 3.45 | 11.90 |
| Philippines | 0.18 | 1.95 | 0.66 | 3.67 | 5.96 |
| Indonesia | 0.17 | 0.79 | 0.28 | 1.64 | 2.50 |
| Burma | 0.07 | 0.97 | 0.12 | 1.71 | 7.30 |
| Vietnam | – | – | – | 17.39 | 2.70 |
| *East Asia* | | | | | |
| Japan | 1.47 | 22.20 | 0.66 | 0.45 | 14.39 |
| Taiwan, China | 0.39 | 17.36 | 0.52 | 1.33 | 30.05 |
| Korea | 0.60 | 10.97 | 0.71 | 1.18 | 10.92 |
| China[c] | 0.13 | – | 0.67 | 5.15 | – |

[a] Palacpac 1982. [b] Price ratio based on the price of urea and ordinary quality rice. Milled rice, farm wage rates for preharvest activities. [c] Includes all provinces except Taiwan.

These impressions, of course, will be tempered on a country-by-country basis. Where inorganic fertilizer is in short supply (still a problem in many parts of Asia), the real value of plant nutrients to the farmer will exceed official prices quoted in Table 3. Alternatively, the price of organic fertilizer may be artificially low due to abundant supply (e.g., near a livestock plant). In these cases organic fertilizers may provide a comparative advantage over inorganic sources. Provided labor costs are acceptable or other cost-efficient means of material handling exist, there are many opportunities to expand the use of organic fertilizers in rice production.

Price expectations also provide an impression of whether future technology should by design be labor or capital intensive. In the present context, should the research bias be toward innovations to increase productivity of inorganic or organic fertilizers, or both? The scenario in many South and Southeast Asia countries remains one of growing rural population, a limited if not shrinking land base, and limited foreign exchange reserves (Hsieh et al 1981). Man-land ratios are increasing which, with other things being equal, tend to decrease the price of labor compared to land or capital inputs. As export prices fall relative to rising costs of imports, the terms of trade of several of these countries are also deteriorating (ADB 1977). Thus, the price of capital- and energy-intensive inputs (such as inorganic fertilizers) may rise compared to the price of labor or rice (ADB 1978).

Development practitioners faced with these realities, may recommend policies that seek to increase land productivity using human energy and other domestically available resources, rather than using inputs that impose net demands on foreign exchange (Nurkse 1953). Greater use of straw residues as an organic fertilizer source for rice may therefore have an important economic role in the future of these countries.

How realistic, however, is this argument as a case to promote research into rice straw as a plant nutrient source for rice?

Some experts do not believe that livestock numbers will fall appreciably in South Asia (Crotty 1980). Further, the demand for straw and manures for fuel, household, or industrial uses may result in increased opportunity cost of straw. Thus, even if labor is cheap and inorganic fertilizers become more expensive, they may remain the most cost-effective source of fertilizer for rice. Under such circumstances, research leading to increased efficiency of inorganic fertilizers (De Datta and Gomez 1981) may have a greater short-run payoff than focusing on organic sources such as rice straw.

Southeast Asia’s rice lands are typified by increasing rural populations and expanding areas of double-cropped rice. The demand for animals is declining (Crotty 1980) because of the increasing cost of maintaining draft animals and the fact that milk is not an important source of farm income. This, coupled with the expanding urban demand for meat, implies that livestock populations may well decrease in rice-growing areas of Southeast Asia. Thus, the opportunity cost of straw may remain low, increasing its attractiveness as a potential source of inorganic fertilizer.

Whether or not this potential will be realized will depend on labor being cheap enough to make straw incorporation a productive use of this labor. With the current methods of straw handling, the authors are not overly optimistic that this will be the case. If innovative straw management techniques that will materially improve the value-cost ratio of straw to labor are developed, then this by-product may become a more significant plant nutrient source in rice farming than it is now. In the meantime, and recognizing that it is unlikely that organic plant nutrient sources will materially substitute for inorganic forms, it is critical that farmer effective methods of increasing the efficiency of inorganic fertilizers continue to be pursued.

## FARMER’S RICE STRAW MANAGEMENT

There may be opportunities for increasing efficiency of straw use in rice production in countries such as the Philippines where the opportunity cost of straw is low. Farmers' current straw management practices were examined in two Philippine locations: a rainfed site in Tarlac Province (some 150 km north of Manila) and an irrigated site in Laguna Province (east of Los Baños). Forty farmers were interviewed at each site.

These sites represent extremes in Philippine rice production. With irrigation, farmers in Laguna grow two rice crops a year. In Tarlac, the 5-month wet season (June to November) restricts farmers to one rainfed rice crop (Table 4). Laguna soils are in general more fertile than Tarlac soils.

Laguna farms are larger on the average than Tarlac farms. Three quarters of the Tarlac households and one quarter of the Laguna farmers own carabaos. In Tarlac, land preparation by carabao (86%) dominates; in Laguna over 90% of cultivation is with power tillers. Prices also differ markedly between the two locations: the daily wage in Laguna is nearly twice that in Tarlac; hiring a carabao is ₱10-15/day more expensive in Laguna than in Tarlac; and hiring a power tiller is ₱20-30 more expensive per day in Laguna.

**Table 4. Characteristics of farms surveyed in Tarlac and Laguna, Philippines.**

| | Tarlac | Laguna |
|---|---|---|
| Water source | Rainfed | Irrigated |
| Crops/yr | 1 | 2 |
| Soil characteristics | | |
| CEC (meq/100 g) | 20 | 27.9 |
| Olsen P (ppm) | 11 | 24 |
| K (meq/100 g) | 0.13 | 1.35 |
| Total N (%) | 0.09 | 0.23 |
| Organic C (%) | 0.73 | 2.23 |
| C/N ratio | 8.25 | 9.6 |
| Rice area (ha) | 1.9 | 2.4 |
| Livestock | | |
| Households owning carabao (%) | 78 | 25 |
| No. per household | 2 | 2 |
| Prices[a] | | |
| Hired labor (₱/day) | 8-10 | 16-18 |
| Carabao (₱/day) | 30 | 40-45 |
| Power tiller (₱/day) | 140-150 | 160-170 |

[a] US$1 = about ₱8.10.

Rice production methods are sketched in Table 5. Two cultivars (IR36 and IR50) accounted for over 80% of those grown in Tarlac, while in Laguna three cultivars (IR36, IR42, and IR50) accounted for over 80% of those grown. Due to their shorter duration, IR36 and IR50 are preferred by Tarlac farmers to IR42, which has a longer field duration.

Laguna farmers apply higher input levels than Tarlac farmers (Table 5). All the Laguna farmers applied N, and at a higher rate in the dry season than in the wet. Half (21 of 40) also applied P and K, usually as 14-14-14. Four farmers in Tarlac did not use fertilizer, and those who did applied on the average 31 kg N/ha; less than half the farmers applied P or K. Twenty-seven percent of the Tarlac farmers applied a portion of their fertilizer basally. Laguna farmers did not follow this practice, although it was recommended. The first application of fertilizer in Laguna was usually 15 or more days after transplanting, the second application around panicle initiation. The farmers' practice is inefficient from a N-efficiency viewpoint (Craswell et al 1981). However, farmers in Laguna do not apply basal fertilizer in an effort to avoid early rapid vegetative growth, which they feel leads to higher incidence of crop disease and lodging.

Laguna farmers reported higher wet-season yields than Tarlac farmers, and dry-season yields in Laguna were higher than wet-season yields, although several farmers in the sample reported lower-than-anticipated dry-season yields because of problems with irrigation water deliveries.

Rice in both locations was harvested some 20-25 cm from the ground. In Tarlac, 65% of the farmers claimed they rotated threshing sites around fields to spread straw nutrients over the farm; 28% threshed in a particular field, either for thresher accessibility or ease of hauling rice to the house after harvest; and 7% made random choices of threshing sites. Forty-two percent of Laguna farmers claimed they rotated

**Table 5. Rice production practices, Tarlac and Laguna, Philippines.**

| | Tarlac | Laguna |
|---|---|---|
| Dominant cultivars | | |
| IR36 (%) | 54 | 23 |
| IR42 (%) | 4 | 25 |
| IR50 (%) | 27 | 33 |
| Fertilizer[a] – wet season | | |
| N (kg/ha) | 31 | 67 |
| P (kg/ha) | 8.4 | 7 |
| K (kg/ha) | 11 | 12 |
| – dry season | | |
| N (kg/ha) | – | 83 |
| P (kg/ha) | – | 7 |
| K (kg/ha) | – | 13 |
| Insecticide[b] (₱/ha) | 81 | 194 |
| Herbicides[b] (₱/ha) | [c] | 105 |
| Yields | | |
| Wet season (t/ha) | 3.3 | 4.1 |
| Dry season (t/ha) | – | 4.5 |

[a] Of those who applied the nutrient. [b] US$1 = about ₱8.10. [c] Less than 10% of Tarlac farmers used herbicides.

**Table 6. Current methods of straw management in Tarlac and Laguna, Philippines.**

| | Tarlac wet season | Laguna | |
|---|---|---|---|
| | | Wet season | Dry season |
| Straw supply[a] (t/ha) | 5.0 | 6.2 | 6.8 |
| (t/farm) | 9.4 | 14.8 | 16.2 |
| Straw management | | | |
| Burn (%) | 0 | 5 | 80 |
| Stack/decompose (%) | 95 | 85 | 0 |
| Burn/stack (%) | 5 | 10 | 20 |

[a] Potential straw supply, assuming 1.5 t of straw for each ton of harvested rice.

threshing sites to spread straw nutrients; 33% chose the driest paddies to make threshing easier; and 25% made random choices.

The potential supply of rice straw may be about 5 t/ ha in Tarlac and more than 6 t/ ha per crop for Laguna farmers (Table 6). However, as the crop is not harvested close to the ground, the actual current quantity of straw is more than two-thirds of this amount.

Tarlac farmers stack straw in the field at the threshing site. Over 87% of the sample regarded rice stubble as an important source of nutrients for the next rice crop; it was an equally important source of animal feed and rice nutrients for the remaining farmers. Farmers who owned carabaos (78% of the sample) regarded stacked straw as more important as livestock feed than as a plant nutrient source for the next rice crop. Straw is also used for mushroom culture, roof thatching, and as a mulch for vegetables.

Tarlac farmers estimated that 60% of the straw and 12% of the stubble are consumed by livestock during the dry season. The remnants of the stacks are usually spread at the start of the rains. When cultivation commences some 3-4 weeks later, this straw is decomposed and does not hinder land preparation. The value of the remaining straw and stubble provides less than 14-4-43 NPK on a per-hectare basis — assuming it were spread over the whole farm.

Rice straw is not an important source of animal feed among Laguna farmers. Most farmers stack straw from the wet-season crop at the threshing site (it is too wet to burn) and allow it to decompose. This decomposed straw is spread before the next wet-season crop is transplanted. Most straw from the dry-season crop is burned; the ash and remaining straw are also spread before the following wet-season crop. The wet-season rice crop thus receives decomposed straw from the previous wet-season crop plus ash and any nutrients present in the stubble from the previous dry-season crop. For the reported crop yields this represents an upper level of nutrient supply of 40-12-166 NPK/ha. The nutrient contribution of stubble to the dry-season rice crop would not exceed 12-3-30 NPK/ha. Farmers recognize the nutritive value of the straw and in general apply less fertilizer on plots where straw has been incorporated (Table 7).

Analysis at this point deviates from reporting figures on a per-hectare basis; rather, a per-farm basis is used. The reason for this approach is that farmers found it easier to relate input use and output to the whole farm than to individual fields.

**Table 7. Differences in fertilizer management between fields with and without decomposed straw or ash incorporated, Tarlac and Laguna, Philippines.**

| | Tarlac, Decomposed straw | | Laguna | | | |
|---|---|---|---|---|---|---|
| | | | Ash | | Decomposed straw | |
| | no. | % | no. | % | no. | % |
| Apply more fertilizer | 4 | 10 | 5 | 13 | 0 | 0 |
| No change in practice | 7 | 18 | 15 | 37 | 14 | 35 |
| Apply less fertilizer | 29 | 12 | 20 | 50 | 26 | 65 |

Multiplying up from one field to the farm level can result in unacceptable results because of rounding errors and errors of measurement.

Ash and straw are spread on less than 20% of the total rice area. Labor inputs used to spread ash in Laguna and straw in Tarlac were both 2.2 days/farm; for decomposed straw in Laguna the labor requirement was 4.5 days. In neither location did farmers consider that land preparation took longer when decomposed ash or straw was incorporated than when fields were free of these materials.

## Benefits of straw and ash incorporation

Farmers agreed that incorporating decomposed straw or ash improved soil fertility (Table 8). All but one of the Tarlac farmers indicated that incorporating decomposed straw increased rice yields; a smaller proportion (63%) of Laguna farmers were of a similar opinion. Over a third of Laguna farmers (38%) considered that ash incorporation increased yields, while 27% felt that yields were lower on ash-incorporated plots. In most cases farmers felt that yield changes would be small and that yield increments would be larger with decomposed straw than with ash.

## Problems of straw and ash incorporation

Farmers recognized the beneficial effects of incorporating ash and decomposed straw, but they also recognized problems that may be associated with this practice (Table 9). Most did not believe incorporating ash or decomposed straw materially

**Table 8. Farmers' perception of benefits of incorporating ash and straw into rice fields.**

| Effect | Tarlac - straw | | Laguna | | | |
|---|---|---|---|---|---|---|
| | | | Ash | | Decomposed straw | |
| | no. | % | no. | % | no. | % |
| Soil fertility | | | | | | |
| Improves fertility | 39 | 97 | 28 | 70 | 25 | 63 |
| No change | 1 | 3 | 21 | 53 | 3 | 8 |
| Decreases fertility | 0 | 0 | I | 17 | 12 | 29 |
| Rice yields | | | | | | |
| Improves yields | 39 | 97 | 15 | 38 | 25 | 62 |
| No change | 1 | 3 | 14 | 35 | 10 | 25 |
| Decreases yields | 0 | 0 | 11 | 27 | 5 | 13 |

**Table 9. Problems perceived by farmers in fields where straw or decomposed straw has been incorporated versus those without these materials, Tarlac and Laguna, Philippines.**

| Nature of problem | Farmer perception[a] | Tarlac – straw | | Laguna | | | |
|---|---|---|---|---|---|---|---|
| | | | | Ash | | Decomposed straw | |
| | | no.[b] | % | no.[b] | % | no. | % |
| Insects | a | 15 | 38 | 11 | 28 | 13 | 33 |
| | b | 23 | 57 | 26 | 65 | 24 | 60 |
| | c | 2 | 5 | 3 | 7 | 3 | 7 |
| Diseases | a | 14 | 35 | 10 | 25 | 12 | 30 |
| | b | 24 | 60 | 27 | 68 | 25 | 64 |
| | c | 2 | 5 | 3 | 7 | 3 | 6 |
| Rats | a | 15 | 38 | 15 | 38 | 17 | 43 |
| | b | 23 | 57 | 24 | 60 | 21 | 52 |
| | c | 2 | 5 | 1 | 2 | 3 | 6 |
| Weeds | a | 12 | 30 | 18 | 45 | 18 | 45 |
| | b | 28 | 70 | 21 | 53 | 20 | 50 |
| | c | 0 | 0 | 1 | 2 | 2 | 5 |
| Lodging | a | 32 | 80 | 23 | 58 | 24 | 60 |
| | b | 8 | 20 | 16 | 40 | 14 | 35 |
| | c | 0 | | 1 | 2 | 2 | 5 |
| Space | a | na | | na | | 33 | 82 |
| | b | na | | na | | 5 | 13 |
| | c | na | | na | | 2 | 5 |

[a] a implies anticipation that the problem will become worse; b implies no anticipated change; c implies don't know. [b] na = not applicable.

increased the incidence of insects, diseases. rats, or weeds. However, more than half considered lodging more of a problem in fields that had received ash or decomposed straw. Farmers attributed this lodging problem to excessively vigorous early growth of the rice crop.

Straw piles occupy rice land and thus reduce the area of dry-season rice. Ponnamperuma (1983) placed this reduced area at about 5%. In Tarlac this is not a problem, as the land is fallow during the dry season and has no opportunity cost in another crop.

## Incorporation of undecomposed straw

The benefits of incorporating undecomposed straw are recognized in tropical environments. Why, then, is this procedure not followed?

In South Asia, where straw has an oppportunity cost in other uses, it is often more profitable for farmers to buy inorganic fertilizers and use straw in other ways. In Southeast Asia, some of the rice stover is directly incorporated in the sense that 20 cm or more of rice stubble may remain in the field. The issue, therefore, is: why is harvested straw not incorporated?

Incorporating undecomposed rice straw in the rainfed Tarlac site is not relevant. This straw is used for animal feed, and after 7-8 months in the stack it has already decomposed before the next rice crop is planted. But in Laguna the opportunity cost of straw is low. In this situation how do farmers view this practice?

Laguna farmers do not generally incorporate undecomposed rice straw. They responded to hypothetical questions, so their responses are at best impressions. Nonetheless, they indicated the type of problems farmers may encounter if the practice is recommended to them.

*Costs of straw incorporation.* Farmers identified two cost categories that would increase if undecomposed straw were incorporated into rice fields. First was the cost of spreading straw; second was the extra time necessary for land preparation (Table 10).

On a per-farm basis, farmers estimated it would take 7 extra labor-days to spread undecomposed straw compared to spreading ash. In the wet season they estimated 12.5 labor-days would be necessary to spread undecomposed straw versus 4.5 days for the present practice of spreading decomposed straw.

The timing of this operation was also seen as a problem. Currently, decomposed straw is spread during the comparatively slack labor period between dry- and wet-season crops. The practice of spreading straw between the first-season harvest and dry-season plantings increases the demand for labor during a period that is already a labor bottleneck. Farmers also estimated that land preparation with power tillers would increase by 2 days (1 day each for plowing and harrowing) and by 4 days (2 days each for plowing and harrowing) if animals were used to incorporate undecomposed straw. As machine tillage is dominant in Laguna, analysis is developed assuming this technology for land preparation.

Another "cost" farmers perceived was the delay necessary to allow straw to decompose before transplanting. Eighty-eight percent of the sample estimated that the presence of undecomposed straw would increase turnaround time by 21 days. With an adequate water supply, though, this could be reduced to 14 days.

The main constraints to incorporating undecomposed straw were labor costs to spread straw and extra power necessary for land preparation. Pest-related problems were not an important issue.

*Incremental benefits of straw incorporation.* One saving from incorporating undecomposed straw may be reduced fertilizer costs; another may be higher rice yields. Half of the farmers thought their current fertilizer practice would have to

**Table 10. Laguna farmers' estimates of labor and land preparation time on a per-farm basis if undecomposed straw were incorporated in rice fields.**

| | Labor-days | | | |
|---|---|---|---|---|
| | Wet season | | Dry season | |
| *Spread undecomposed straw* | 12.5 | | 8.7 | |
| Ash | – | | 2.2 | |
| Decomposed straw | 4.5 | | – | |
| Difference | 8.0 | | 6.5 | |
| *Land preparation* | plow | harrow | plow | harrow |
| Mechanical, with straw | 4.9 | 4.5 | 4.9 | 4.5 |
| Mechanical, no straw | 3.9 | 3.5 | 3.9 | 3.5 |
| Difference | 1.0 | 1.0 | 1.0 | 1.0 |
| Animal, with straw | 9.5 | 10.1 | 9.5 | 10.1 |
| Animal, no straw | 7.4 | 8.0 | 7.4 | 8.0 |
| Difference | 2.1 | 2.1 | 2.1 | 2.1 |

**Table 11. Farmers' expectations of changes in fertilizer rates and rice yields if decomposed rice straw were incorporated into fields.**

| Expectation | Farmers responding | |
|---|---|---|
| | no. | % |
| *Fertilizer practice* | | |
| No change | 21 | 52 |
| Change fertilizer: | | |
| use more | 7 | 18 |
| use less | 10 | 25 |
| Unsure | 2 | 5 |
| | Wet season | |
| *Anticipated yield effect* | | |
| Higher yields | 15 | 37 |
| No change in yield | 9 | 23 |
| Lower yields | 12 | 30 |
| Unsure | 4 | 10 |
| | Dry season | |
| Higher yields | 17 | 43 |
| No change in yield | 8 | 20 |
| Lower yields | 11 | 27 |
| Unsure | 4 | 10 |

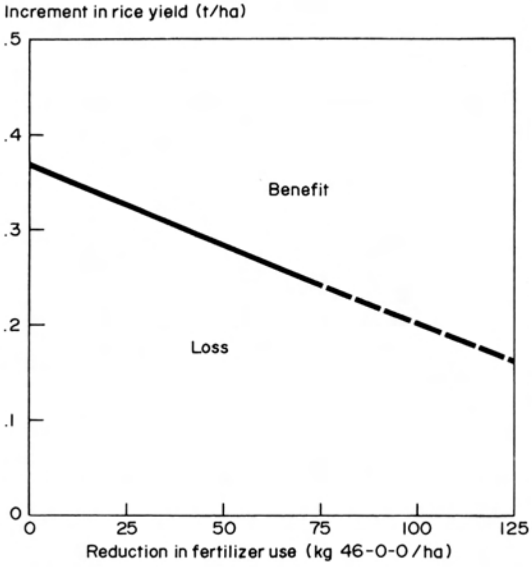
continue if they incorporated undecomposed straw (Table 11). Of the half who felt their fertilizer use would change, seven (18%) indicated they would need to increase fertilizer use to compensate for retarded early rice growth. Unlike with decomposed straw and ash, there is no clear indication that farmers would use less fertilizer on straw-incorporated fields than on fields with no straw incorporation.

Nearly 40% of the respondents felt that rice yields would increase if undecomposed straw were incorporated (Table 11). A smaller proportion (30%) considered that yields would decline. The remainder, about 20%, felt that yields would not change. Thus, about 60% of the Laguna farmers considered yields would increase or remain the same if this practice were followed.

*Net benefits of straw incorporation.* The combination of reduced fertilizer inputs and higher rice yields which would provide farmers a 2:1 benefit-cost ratio for the technology are sketched in Figure 2. The yield increment, nearly 0.4 t/ha, necessary to pay for the practice (even if there were no reduction in fertilizer use) is similar to the 0.4-t/ha yield advantage from straw incorporation estimated by Ponnamperuma (1983). This, of course, may be a long-term advantage and may not be reproducible under farm conditions. Another issue is whether adequate short-term advantages could be realized to make investment in such a high-labor input attractive. On-farm trials would be necessary to determine if these combinations of benefits can be achieved and whether there are hidden costs (or benefits) that should be considered when evaluating this technology from the farmers' viewpoint.

## RESEARCH IN STRAW UTILIZATION

A vast literature exists on the long-run benefits on soil fertility and rice yields of incorporating rice straw. However, this knowledge does not imply the existence of



**2.** Breakeven combinations of yield advantage and reduced fertilizer inputs necessary to provide a 2:1 benefit for incorporating rice straw. Data drawn from Laguna, Philippines. Assumptions:rice price = ₱1.30/kg. urea price = ₱2.30/kg, incremental cost = ₱480/ha. $1 = about ₱8.10

technologies that make this information applicable to farmers. For example, are farmers willing to allocate sufficient quantities of their rice straw to obtain the benefits predicted by the researcher? If not, what are the opportunities for the joint use of organicand inorganic fertilizers? Given the farmer’s value of family and hired labor, are proposed methods of straw management profitable? Basically, there has been little discriminating analysis of the technical and economic relevance of straw management experiments.

Researchers should be encouraged to take the next step and test their most practical alternatives in farm conditions where the constraints they face are consistent with opportunities and choices that influence the farmer’s own straw management practices. [A methodology for this research approach was presented by Zandstra et al (198l).] This would provide more realistic insights into alternative uses and values of straw; into supply, losses, and wastage, and thus availability, of straw in a practical setting; and into the labor and power costs of implementing these alternatives. In this way, true costs and benefits of alternative straw management practices may be better understood. Such information would provide an opportunity to design and interpret subsequent research more effectively.

Economists must document straw values in alternative uses and the effective prices and costs embedded in these alternatives. Duncan (1975) outlined the challenges faced by economists. For example, as straw management is an integral component of most farming systems, any change in its use (especially if it is labor demanding) may entail unexpected additional costs or reduced profits in other farm activities. Thus, analysis in most cases needs to be at the farm, not the crop level. Further, many costs and benefits of alternative uses of straw may not be accorded market values by the farmer or his household. Imputed prices, therefore, may not provide accurate guides to the real values farmers use when deciding on straw management. In summary, economists need better evaluation of the benefits and costs of proposed straw management practices from the point of view of the farmer and his family.

Though Luzon farmers have not been overwhelmingly convinced, the technical benefits of incorporating straw in rice fields have been demonstrated. Thus, what important areas of adaptive research may lead to technical innovations in straw management that may be of particular interest to farmers?

First, in most situations labor and power costs deter more intensive use of straw. Can cost-effective methods of straw handling be developed that will increase labor productivity in these uses to the point of making it competitive with inorganic fertilizers? As this is essentially a materials-handling problem, agricultural engineering has a role to play. However, if the professional consensus is that such innovations are unlikely, straw will probably remain a low-analysis and low-value form of plant nutrient.

Second, integrated fertility management implies the conjunctive use of rice straw, possibly other organic fertilizers, and inorganic fertilizers. From a farm viewpoint, what are the opportunities for combining straw and green manures (e.g., *Leucaena* spp., *Crotalaria* spp., *Sesbania* spp., or *Azolla* spp.) to synthesize organic fertilizer with better properties than straw alone? What other ways of integrating rice straw management and inorganic fertilizers (timing, placement, N source, etc.) need evaluation to generate these as more productive plant nutrient sources? The INSFFER Network is tackling a number of these issues and should be encouraged to continue to do so.

Third, rice straw has other uses — fodder, fuel, or industrial material. In some cases, advances in alternative uses of straw may exceed its value as organic fertilizer in benefits to farmers. In the light of expected payoff, these alternatives must be examined and research priorities set.

Fourth, an enormous quantity of nutrients and energy is embodied in the mass of rice straw produced each year in Asia. If this low-cost source of nutrients and energy is to be more efficiently used, it is critical that constraints on its better use — whether labor costs, productivity as an input to animal or crop production, prices, transport, or a combination of these — be identified. This information may provide insights into broader researchable issues that must be resolved before more efficient straw use by farmers can be anticipated.

## REFERENCES CITED

ADB (Asian Development Bank). 1977. Rural Asia: challenge and opportunity. Praeger Publishers, Tokyo.

ADB (Asian Development Bank). 1978. Second Asian agricultural survey. Manila.

Bhatti, I. M., et al. 1981. On-farm constraints to rice yields in Larkana district, Pakistan. Paper presented at On-Farm Yield Constraints Workshop, Pakistan. Agricultural Research Council, 1-2 July, Islamabad.

Briscoe, J. 1980. Energy use and social structure in a Bangladesh village. Popul. Dev. Rev. 5(4):615-641.

Craswell, E. T., S. K. De Datta, W. N. Obcemea, and M. Hartantyo. 1981. Time and mode of nitrogen fertilizer application in tropical wetland rice. Fert. Res. 2:247-259.

Crotty, R. 1980. Cattle, economics and development. Commonwealth Agricultural Bureau, Slough.

De Datta, S. K., and K. A. Gomez. 1981. Interpretative analysis of the international trials on nitrogen fertilizer efficiency in rice. Fert. Int. May 1-5.

Duncan, A. 1975. Economic aspects of the use of organic materials as fertilizers. *In* Organic material as fertilizers. FAO Soils Bull, 41, Rome.

Ezaki, H. 1982. Rice harvesting machines. Chapter III *in* Paddy Rice Production Machinery (in press).

FAO (Food and Agriculture Organization). 1975. Statistical directory, Asia and the Far East. FAO, Rome.

Hsieh, S. C., J. C. Flinn, and N. Amerasinghe. 1982. The role of rice in meeting future needs. Pages 27-49 *in* International Rice Research Institute. Rice research strategies for the future. Los Baños, Philippines.

ICAR (Indian Council of Agricultural Research). 1971. Organic manures. Tech. Bull. (Agriculture) No. 32, New Delhi.

Jackson, M. G. 1979. Indian experience with treated straw as feed. Pages 60-67 *in* Bioconversion of organic residues for rural communities. Tokyo.

Liu, Chung-chu, and Zeng-quan Lin. 1982. The integrated management of organic and inorganic fertilizers in multi-cropping systems in some areas in China. International Rice Research Conference, 19-23 April, IRRI, Los Baños, Philippines.

McDowell, R. E. 1972. Improvement of livestock production in warm climates. Freeman and Co., San Francisco.

Nurske, R. 1953. Problems of capital formation in underdeveloped countries. Oxford University Press, New York.

Palacpac, A. C. 1982. World rice statistics. The International Rice Research Institute, Los Baños, Philippines.

Ponnamperuma, F. N. 1983. Straw as a source of nutrients for wetland rice. Pages 117-136 *in.* International Rice Research Institute. Organic matter and rice. Los Baños, Philippines.

Rajagopalen, V., P. K. Aiyasamy, R. Srinivasan, and V. Subramanian. 1978. Studies of cost of production of major crops in Tamil Nadu. Tamil Nadu Agricultural University, Coimbatore, India.

Sah, R. N., and J. C. Flinn. 1981. Considerations when estimating profitable fertilizer levels for rice. Nepalese J. Agric. Sci. (in press)

Srinivasan, M. R. 1977. Biogas (Gobar gas) and manure from the waste of farm animals. UNEP/ FAO Seminar on Residue Management — The Management of Agricultural and Agro-Industrial Wastes. 18-21 January, Rome.

Tanaka, A. 1973. Methods of handling the straw in various countries. Int. Rice Comm. Newsl. 22(2):1-20.

Tanaka, A. 1978. Role of organic matter. Pages 605-622 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

Tsuchiya, K. 1974. An economic analysis of fertilizer use in Japanese agriculture — the relevance of Japan’s experience to East Asian countries. Proceedings of Planning Meeting, Fertilizer I.N.P.U.T.s Project, 21-25 October, East-West Center, Honolulu, Hawaii.

Wen, Qi-xiao. 1983. Utilization of organic materials in rice production in China. Pages 45-56 *in* International Rice Research Institute. Organic matter and rice. Los Baños, Laguna, Philippines.

Wiens, T. 1983. Microeconomic study of organic fertilizer use in intensive farming in Jiangsu Province, China. Pages 541-564 *in* International Rice Research Institute. Organic matter and rice. Los Baños, Laguna, Philippines.

Zandstra, H. G., E. C. Price, J. A. Litsinger, and R. A. Morris. 1981. A methodology for on-farm cropping systems research. The International Rice Research Institute, Los Baños, Philippines.

# A NEW STRATEGY FOR THE UTILIZATION OF ORGANIC MATERIALS AS FERTILIZERS FOR RICE PRODUCTION

B. R. Nagar

This paper indicates the need for determining the availability of organic matter for fertilizer in rice production and suggests methods for increasing its production. The paper mentions the methods of converting organic matter into useful organic fertilizers, emphasizes the importance of use of biofertilizers and green manuring for rice production, and refers to the significance of agronomical trials, short-term research, long-term research, education, extension, and international cooperation for this purpose. It also discusses the economic, social, and psychological issues involved in the large-scale use of organic fertilizers for rice production. The paper suggests that an integrated systems approach, especially for the small marginal farmer, is absolutely essential for the large-scale use of organic matter for rice production.

After the advent of the oil crisis in 1973, FAO/SIDA organized an “Expert Consultation on Organic Materials as Fertilizers” in December 1974, at which the writer presented a paper (Nagar 1975) describing a strategy for the large-scale utilization of organic materials as fertilizers. Subsequently, this strategy was revised by the author in a FAO publication (Flaig et al 1978) written jointly with three German scientists. Almost all the points included in these papers are still valid for the large-scale utilization of organic materials for the production of cereal crops, including rice.

According to a very recent UNCTAD (1982) study, there is likely to be a shortfall of 11 million t N, 7 million t P, and 6 million t K by 1989-90, over and above the projected production of these fertilizers by 1984-85. The developing countries may be most hard hit by these likely shortages. In addition, in view of the escalating price of oil, the base material for the production of nitrogenous fertilizers, it has become absolutely essential for us to take a second look at the problem of organic matter and rice production and to prepare a suitable new strategy in this field, especially when the consensus is that rice soils take a considerable amount of N from soil organic

---

Government of India Planning Commission, New Delhi, India.

matter, even in the presence of applied chemical fertilizers (Broadbent 1978, Brady 1982, Central Rice Research Institute 1982).

The salient features of this new strategy should be as follows:

- There should be maximum production of rice with the least possible utilization of oil-based energy.
- Organic materials should be used on a large scale as fertilizers for the production of rice.
- Steps should be taken to produce in huge quantities suitable organic matter from green manures, farm and animal residues, biogas technology, organic industrial wastes, and city and municipal wastes, including sewage sludge. By pursuing suitable research and development (R&D), these organic wastes should be converted into good-quality organic fertilizers by efficient, economically viable, environmentally sound, and socially acceptable processes.
- Special emphasis should be placed on the utilization of biofertilizers for providing plant nutrients as well as, in some cases, organic matter to rice crops, especially on the basis of location-specific research.
- To obtain the maximum possible yield of rice with the minimum possible use of oil-based energy, a strategy of integrated nutrient supply from chemical fertilizers, organic manures, and biofertilizers should be used.
- Extensive R&D should be carried out on the chemical and biochemical considerations for maximizing efficiency of chemical fertilizers, especially in the developing countries.
- A special strategy should be prepared for the use of organic matter for rice for small marginal farmers of the developing countries, taking into consideration their socioeconomic conditions.
- A large-scale extension program should be organized to propagate the use of organic manures and biofertilizers for rice soils.
- International cooperation should be organized for R&D, education, and extension work in the use of organic matter for rice production.
- Investigations should be carried out to establish administrative, psychological, and sociological constraints, proper support services, and public policy for the use of organic matter for rice crops.
- Special studies should also be carried out to establish what packages of services — incentives and disincentives — such as credit or regulations, extension, training, education, public policies, and mode of public participation would promote propagation of organic matter use for rice soils.
- In addition, an integrated systems approach should be used for the propagation of large-scale use of organic materials for rice production.

Very recently Brady (1982) indicated the limitations, potentials, and prospects of rice soils that should be considered in using organic materials as fertilizers for rice soils. In addition, special attention should be given to recent work on various aspects of submerged soils, especially their chemistry, and management of upland and rice soils.

Although organic wastes are very significant sources of organic fertilizers, a number of limiting factors and processing difficulties should be overcome by massive R&D. These problems are:

- low plant nutrient contents;
- high C:N;
- plant materials in unavailable forms;
- trace elements present either in very inadequate amounts or in large amounts harmful to plant growth;
- presence of injurious organic substances; and
- occurrence of heavy metals such as Cd, Mg, etc.

Therefore, these organic wastes must undergo quantitative and qualitative analysis and proper methods of processing before they are used as organic fertilizers. Usually good organic fertilizers can be produced from farm and animal wastes, wood and pulp industries wastes, wastes of food and brewing industries, some industrial organic wastes, and city and municipal wastes, including sewage sludge. Significantly, by producing organic fertilizers from organic wastes, we not only obtain plant nutrients and soil conditioners but in some cases also produce bio-energy and check pollution of the environment. Recently in India, action-oriented planning has been done in this field (Nagar 1981a, b; 1982), and some of these programs are already being implemented on a large scale.

## AVAILABILITY OF ORGANIC MATTER AND THE POTENTIAL OF INCREASING PRODUCTION

To use organic matter for rice production on a large scale, it is absolutely essential to determine its availability (at national, provincial, and district levels) for the production of organic fertilizers, taking into consideration various factors such as different types of wastes, their qualities and quantities, and their present utilization as fuel or manures or both. In this field significant work has been done in the USA (USDA 1978) and India (Nagar 1981c) and by the FAO (1979). The proforma used by the author in India for this purpose are available on request. According to Swaminathan (1979) the available potential in India for production of organic fertilizer is 10.8 million t from urban wastes and 657 million t from rural wastes.

To obtain a major breakthrough in the production of organic matter for producing organic fertilizers and energy, basic research on the following problems is essential:

- increasing the efficiency of photosynthesis;
- producing N-fixation capacity in nonleguminous plants;
- obtaining by genetic engineering varieties of plants that can withstand adverse soil and climatic conditions, especially shortages of water; and
- producing by genetic engineering redistribution of the organic matter components of the plants such as wood, leaves, and roots according to location-specific needs.

Significantly, efforts are under way to increase the production of biomass (organic matter) for obtaining energy. This research may also be utilized for the production of organic fertilizers from biomass. Further efforts should be made to screen species to optimize the conditions for maximum growth, to develop proper methods of harvesting (Klass 1982, Biomass Energy 1981), and, above all, to perform net energy and Plant nutrient analysis and to explore the possibility of production of organic fertilizers. Similar attempts should be made for the production of biomass or organic fertilizers from nonwoody herbaceous plants. In these fields considerable success can be obtained by genetic engineering techniques (National Academy of Sciences 1982). While evaluating the potential for increasing the production of terrestrial biomass, the "fuel vs food" controversy should be taken into consideration. The solution of the problem depends on the particular situation, such as availability of land and other inputs. In fact, it is most desirable to produce more terrestrial biomass on marginal wastelands (Swaminathan 1982). The suitable requirements of any terrestrial plant for production of energy and organic manure should be its capacity to grow rapidly, to coppice, to fix N, to produce good-quality manures and fuels, and to be able to grow under widely different conditions and adverse water and plant nutrient contents. Therefore, research work should be carried out in these directions.

Attempts should also be made to use aquatic biomass for the production of organic fertilizers and bioenergy on a large scale. Usually. the growth rate yields of aquatic biomass are high; and, most significantly, the production of aquatic biomass does not suffer from the limitation of land availability as is the case with terrestrial biomass. The aquatic biomass has been classified as follows: microalgae, submerged and floating macrophytes, marsh plants, and marine species. Considerable work has been done on aquatic biomass, especially on water hyacinth (Da Silva 1979, Gopal and Sharma 1981), kelp (Ministry of Agriculture 1979). and seaweeds. The main aim of this work is to produce methane from kelp and seaweeds. Additional R&D is still required in this field, and the economics of the processes should be worked out very carefully.

## BIOFERTILIZERS

Biofertilizers can substantially contribute to the N supply, and in certain cases to the organic matter content of rice, and considerable research work has been carried out on them. Biofertilizers provide N to rice plants through free-living bacteria, blue-green algae, and azolla with its symbiotic *Anabaena azollae.* It is highly desirable that the tremendous potential of biofertilizer for rice production should be further exploited, and further research work should be carried out using $^{15}N$ tracer techniques with already known biofertilizers on different rice cultivars, on the influence of soil conditions (effect of phosphate, pesticide dosages, etc.), on the rate of mineralization, on the dosage of chemical fertilizer and organic materials, etc. Furthermore, fundamental studies should be carried out on the various reactions involved in the process of biological N fixation by using modern computational methods.

In addition, it is essential to perform location-specific research to identify and isolate new biofertilizers, study their characteristics and developmental needs such as growth requirements and multiplication techniques, and study the influence of other factors on their large-scale use under field conditions.

Furthermore, genetic engineering should be used to manipulate microorganisms employed in biofertilizer technology. For example, research work should be carried out in the development of free-living bacteria that can consume less energy and in the development of strains of blue-green algae that can fix N in substantial amounts in the presence of chemical N fertilizers and organic matter.

After organic matter has been produced in large quantities, it is desirable to convert it into organic fertilizer, the process to be used depending on the specific type of raw material available. Planning is also essential for related problems such as storage; pretreatment; production and utilization of byproducts, especially for bioenergy; gross energy analysis; the economics of the process; the impact on the environment; social acceptability; etc. Usually, composting and anaerobic digestion including biogas technology are used for the preparation of organic manures from organic materials. For this purpose recent advances in the fields of composting (USDA 1980, Composting 1981, Tietjen 1977, Gillet 1980) and anaerobic digestion, especially dry fermentation technology (Jewell et al 1981a, b; Wujcik and Jewell 1979), and construction of modern and efficient large-scale digesters (Ghosh and Klass 1981, Goldberg et al 1981, Meynell 1976, De Waart 1982, Rijkens 1981, International Contract and Research Corporation 1980, Golueke 1981) should be taken into consideration. Special attention should be paid to the recent advances in green manuring (Agboola 1982, Krishnamoorthy and Kothandaraman 1982).

## ECONOMIC, SOCIAL, PSYCHOLOGICAL, AND PUBLIC POLICY ISSUES

It is desirable to involve economists and social scientists along with a team of multidisciplinary scientists and extension workers to utilize organic matter for rice production on a large scale. A realistic and practical view of the problem would take into consideration alternative uses of organic matter for fuel, chemicals, and feedstock. In addition, economists must study large systems versus small plants. Investigations also must be carried out to identify administrative, psychological, and sociological constraints and ways to overcome them. Furthermore, as stated previously, studies must be undertaken on public policy issues such as incentives or disincentives and mode of public participation. Above all an integrated systems approach, especially for small and marginal farmers, is absolutely essential for the large-scale use of organic matter for rice production.

## REFERENCES CITED

Agboola, A, A. 1982. Organic manuring and green manuring in tropical agricultural production. Pages 198-222 *in* Transactions of the 12th International Congress of Soil Scienc,. New Delhi, Symposia Papers I.

Biomass Energy. 1981. Report of the Energy Research Advisory Panel on Biomass, USA.

Brady, N. C. 1982. Rice soils of the world: their limitations, potentials, and prospects. Pages 42-66 *in* Transactions of the 12th International Congress of Soil Science, Managing Soil Resources, New Delhi.

Broadbent, F. E. 1978. Mineralization of organic nitrogen in paddy soils. Pages 105-118 *in* International Rice Research Institute. Nitrogen and rice. Los Baños, Philippines.

Central Rice Research Institute, Cuttack. 1982. Pages 98 *in* Annual Report, 1980. Indian Council of Agricultural Research, New Delhi.

Composting, 1981. Theory and practice for city industry and farm. The JG Press, Emmaus, Pennsylvania, USA.

Da Silva, E. J. 1979. Marine microbes and macrobes: a renewable supply. Impact Sci. Soc. 29:163-173.

DeWaart, J. 1982. Recent developments in anaerobic digestion techniques in industrialized countries. Paper presented at the Joint UNIDO/UNESCO Symposium/ Workshop. Biogas Technology in Africa, Tanzania. February.

Flaig, W., B. R. Nagar, H. Sochtig, and C. Tietjen. 1978. Organic materials and soil productivity. Soils Bull. 35 FAO, Rome.

Food and Agriculture Organization. 1979. Agricultural residues: quantitative survey (FAO, Rome).

Ghosh, S., and D. L. Klass. 1981. Advanced digestion process development for methane production from biomass wastes. *In* Klass, D. L., ed. Biomass as a nonfossil fuel source, American Chemical Society, Washington, D.C.

Gillet, R. 1980. Compost from household refuse and aerobic composting process in tropical environment, UNIDO BIOKOM 104/80. Prepared for Conference for “Biogas and City Wastes Composting.” Jakarta, 1-4 July 1980.

Goldberg, T. et al. 1981. An anaerobic digestion for continual high solid loading: the bio-fumal. Pages 451-58 *in* Preprints of the 1981 International Gas Research Conference, sponsored by GRI, A.G.A., and US DOE, Los Angeles, California, 28 Sept-1 Oct 1981.

Golueke, C. G. 1981. Biogasification of wastes. Pages 9-23 *in* Biogas and Alcohol Fuels Production. Vol. II. The J. G. Press, Emmaus, Pennsylvania.

Gopal, B., and K. P. Sharma. 1981. Water hyacinth (*Eichhornia crassipes*). Hind Asia, New Delhi.

International Contract and Research Corporation Ce Tom. 1980. Methane process, Washington, D.C. 16 p.

Jewell, W. J., J. A. Chandler, S. Dellorto, K. J. Fanfoni, S. Fast, D. Jackson, and R. M. Kabrick. 1981a. Dry fermentation of agricultural residues. Report No. XB-0-9038-1-7. The report prepared for the U.S. Department of Energy. Cornel1 University, New York, USA.

Jewell, W. J., S. Dellorto, K. J. Fanfoni, S. Fast, D. Jackson, and R. M. Kabrick. 1981b. Dry anaerobic methane fermentation. Paper presented at the Biogas and Alcohol Fuels Seminar. Chicago, Illinois, 13 March 1981. Cornell University, Ithaca, New York.

Klass, D. L. 1982. 1981 Energy from biomass and wastes: update paper presented at energy from biomass and wastes. VI. Lake Buena Vista, Florida. 25-29 January 1982. Institute of Gas Technology, Chicago, USA.

Krishnamoorthy, K. K., and G. V. Kothandaraman. 1982. Organic manuring and green manuring in tropical soils: Indian experience. Pages 179-188 *in* Transactions of the 12th International Congress of Soil Science, New Delhi, Symposia Papers I.

Meynell, P. J. 1976. Planning a digester. C.T.T. Ser. 2. Prism Press, Dorchester.

Ministry of Agriculture. 1979. Recommendations of the task force on water hyacinth. Government of India, Ministry of Agriculture and Irrigation, New Delhi.

Nagar, B. R. 1975. Proposals for short term research, long term research, extension, education and international cooperation in Report of the FAO/SIDA Expert Consultation on Organic Materials as Fertilizers, Soil Bull. 27 FAO, Rome.

Nagar, B. R. 1981a. Utilization of city garbage and industrial wastes, especially willow waste for bioenergy. Planning Commission Paper, New Delhi.

Nagar, B. R. 1981b. Utilization of sewage sludge on a large scale for bioenergy. Planning Commission Paper, New Delhi.

Nagar, B. R. 1981c. Survey of organic recycling in India. Planning Commission, New Delhi.

Nagar, B. R. 1982. Soil productivity, national planning and biogas research and development. Paper presented at the National Workshop on Agricultural Development in the Context of Prime Minister's New Twenty Point Programme and Productivity Year, New Delhi.

National Academy of Sciences. 1982. Summary report: Symposium on Biomass Substitutes for Liquid Fuels. Compinas, Brazil. 9-12 February 1982. National Academy of Sciences, USA.

Rijkens, B. A. 1981. A novel two-step process for anaerobic digestion of solid wastes. Symposium "Energy from Biomass and Wastes V." Lake Buena Vista, Fla. USA.

Swaminathan, M. S. 1979. Inorganic recycling inagriculture. Fertilizers Division, Ministry of Agriculture and Irrigation, New Delhi. 7 p.

Swaminathan, M. S. 1982. Report of the Fuelwood Study Committee Planning Commission. New Delhi, India.

Tietjen, C. 1977. Feasibility study on organic manure production by Composting City and Industrial Wastes in some selected countries. FAO Report, FAO Rome.

UNCTAD. 1982. Study prepared by the UNCTAD secretariat in cooperation with Mukherjee, S. K. Fertilizer Supplies for Developing Countries: Issues in the Transfer and Development of Technology, TD/B/C. 6/71, 4 June 1982.

USDA (United States Department of Agriculture). 1978. Improving soils with organic wastes.

USDA (United States Department of Agriculture). 1980. Manual for composting sewage sludge by the Beltsville-Aerated Pile Method, EPA 60018-80022. Agricultural Research Science and Education Administration, Washington, D.C.

Wujcik, W. J., and W. L. Jewell. 1979. Dry anaerobic fermentation. Paper presented at the 2nd Symposium on Biotechnology in Energy Production and Conservation, Gatlenburg, TN, 3-5 October.

# RECOMMENDATIONS

## For agronomic evaluation

The group felt that there is a definite need for application of organic matter in rice farming systems for economic reasons. On the basis of detailed discussions, the following recommendations for research were made:

- Determine the level of organic matter to be maintained in rice soils for securing high yields.
- Evaluate the comparative efficacy of different kinds of organic matter on soil health and rice yields.
- Select efficient azolla strains with high biomass production capability, pest resistance, and tolerance to heat and shade through:
  a) screening;
  b) hybridization; and
  c) genetic engineering.
- Evaluate methods of multiplication of azolla through spores, and evaluate management methods such as application of phosphorus for rapid and economic multiplication of azolla.
- Design equipment for incorporation of azolla to save labor cost.
- Evaluate the comparative efficiency of azolla application, green manuring, and dual cropping; determine the time and method of application for different crop systems.
- Concentrate on blue-green algae where they perform better than azolla.
- Study the usage of straw in different parts of the world and evolve methods to use straw in an economic manner.
- Determine the quantity, time, and method of application of straw as organic matter for rice-based cropping systems.
- Evaluate the comparative efficiency of using straw directly or indirectly through aerobic or anaerobic decomposition.
- Design methods of fixing microbes to quickly decompose straw.
- Develop methods to enrich straw compost through application of lime, superphosphate, etc.
- Undertake agronomic experiments to evaluate organic matter in parts of the world other than IRRI, such as locations where INSFFER trials are conducted.
- Standardize and fix parameters for reporting on studies on organic matter at international conferences.

### For management and economics of use of organic materials

The overall conclusion of the 12 delegates was that there is a need for location-specific investigations on the integrated use of organic materials and mineral fertilizers using the most recent known techniques and not historical data. Such investigations would include:

- studies on maintenance of soil matter;
- quantity (e.g., C-N ratios) of organic matter;
- methodology of composting rice straw, especially procedures to enrich its nutrient content, and development of optimum procedures for its application.

For these investigations, IRRI should involve other institutions and universities in the region, including both INSFFER and the Asian Cropping Systems Network.

The FAO/UNDP regional project on organic recycling will inform IRRI of its proposed national programs, preferably at the formulation stage, so that IRRI can become involved. IRRI could, for example, provide details on the latest technology.

On the subject of economics, it is suggested that agroeconomic (not socio-economic) studies be made, especially in areas using and those not using organic materials. Additionally, demonstration sites could be set up using recommended procedures. The studies should include alternate uses of organic materials, not just agricultural, and should investigate the value of the labor necessary for all uses. There is a need for studies on more efficient and economic *handling* of organic manures, including mechanization and how to reduce labor costs and time.

In general, there should be an evaluation of the long-term economic benefits of incorporation of organic materials in soils to determine whether government policies promoting organic fertilizer use are justified.

It was considered that more research is needed on the management of blue-green algae vs azolla. It was felt that we have insufficient knowledge of the functions of blue-green algae — all we know is that it works. As the technology is relatively low cost, we should find out why its use is so limited.

### For decomposition and transformation processes

The group felt that future work should consist of concerted research to provide basic information on organic matter in paddy soils. Methodology should be developed with the aim of developing a benchmark study on organic matter in submerged rice soils.

An important consideration is the fate of nutrients released in the course of decomposition and transformation processes in high yielding and other rice environments as well as in different climatic regions, on different soils, and in different rice-based cropping systems.

The group felt the need for preparation of rice-derived humic standards. It was suggested that a freeze-dried paddy soil monolith be prepared for delivery to the International Humic Substances Society (IHSS) and inclusion in its standard collection.

The need was felt for expanding our knowledge of the physical and chemical properties of humic substances formed under submerged conditions (size and shape determination, ultra-centrifugation, gel chromatography, cross polarization, CPMASMNR) as well as for making a search for aromatic structures related to plant parent material and for aliphatic compounds and their mode of occurrence in anaerobic rice soil environments. Research is needed on phenolic acids in soil solution, and a search for phototoxic substances derived from the decomposition of paddy-specific organic matter should be made.

Organic matter management requires information about the initial phase of decomposition or transformation of fresh plant material and crop residues. Little is known about this decomposition in the "exponential phase" under tropical environments, and studies with uniformly labeled plant materials typical for rice-based agroecosystems are required to calculate approximate rate constants for the decomposition of different plant residues.

To understand the whole process of organic matter recycling, we need to measure the natural radiocarbon profile — age vs depth — of typical rice soils.

From results of monitoring the exponential phase (uniformly labeled plant material) as well as the steady state phase (conventional $CO_2$ measurements and natural radiocarbon profiles), a unified decomposition conservation model should be produced.

Information on organic matter protection should be obtained from natural $^{14}CO_2$ collection and measurement in the lowest fringes of the epipedon. If the collected $^{14}CO_2$ is young, the hypothesis of "protected carbon" finds support; if $^{14}CO_2$ shows identical age with the humus, organic matter protection is improbable.

The capability of the clay fraction of rice soils to bind and conserve humus should be tested by radiometric precipitation of complexes from the clay suspension in a $^{14}C$ humus solution by monitoring the remaining $^{14}C$ of the supernatant.

Transformation and the fate of nutrients of the organic manures have to be scanned on the basis of available tracers: $^{14}C$, $^{15}N$, $^{32}P$, $^{33}P$, $^{34}S$, and $^{35}S$.

### For nutritional and physiological effects

The group recommended that a research program be considered along the following lines:

- I. Laboratory investigations
  - A. Isolation and identification of specific organic compounds that occur in decomposing organic matter, these compounds to be studied with regard to:
    1. Plant growth-regulating activity
    2. Effects on N fixation, nitrification, and other microbial processes that occur in soils
    3. Capacity to confer disease resistance onto rice seedlings
  - B. Studies on rice plants with synthetic compounds that are known to possess physiological activity in plants. All available sources for the provision of such chemicals should be sought. The experimental work would be shown in A 1, 2, and 3 above.
  - C. Tissue culture investigations that might lead to higher yields, resistance to unfavorable environmental conditions, and resistance to disease.
- II. Model experiments with plants

III. Field experiments

The programs under Sections II and III would be follow-ups of the leads obtained under Section I.

The group recommended that support be provided for the purchase of necessary sophisticated equipment not now available at IRRI, which would be required for undertaking the above program. Furthermore, scientists and technicians should be provided with opportunities to receive training in specialized techniques in laboratories elsewhere.

## For soil physical properties and processes

The following recommendations were made by the group:

- Initiate a study of current practices in tillage and organic matter amendment procedures for both wetland and wetland/dryland systems with the objective of finding simple but effective tillage systems.
- Undertake a monitoring program of the effects of organic matter amendments on soil physical variables (such as temperature, water characteristics, gas concentration, soil strength, and consistency) to study the relation, if any, of these variables to root growth patterns.
- Investigate the links among the physical, chemical, and nutritional effects of organicmatter amendments on the productivity of those wetland and wetland/dryland cropping systems that involve puddling.
- Investigate air-water relationships and root growth in paddy soils as related to soil characteristics and organic matter amendments, researching if necessary the benefits of applications of inorganic chemicals. (The need was identified to make more widely available the pertinent Japanese literature.)
- Establish a small working group to standardize laboratory and field procedures in studies of soil physical properties in the wetland environment.

Wetland repellancy was *not* thought to be a widespread problem in practical farming situations, even for the peats of Indonesia. (The recommendations of previous discussion groups on these topics should be taken into account.)

## For environmental and ecological problems

The group identified the following objectives:

- Identify and survey the availability of different sources of organic matter — which may be in the form of crop residues, animal droppings, urban wastes, and/or factory byproducts — in different countries with a view to exploiting solar energy to its maximum while at the same time maintaining the ecological equilibrium of the watersheds.
- Standardize the methods of composting all available organic matter for the production of organic manures of high quality.
- Popularize the production and use of organic manures among farming communities in the various countries involved.

The group identified the following problems:

- Lack of organic matter due to arid/semi-arid climate methods of increment. Source of organic matter for silted soils, as in the Philippines; Azolla in Pakistan. Organic matter management.

- Peat as a source of organic matter and its improved use for cultivation.
- Wastes and associated problems: identification, modification, and improved use.
  - a. Agriculture wastes:
    - (i) Crop residues (rice husk and straw)
    - (ii) Farm wastes (including garden waste) such as farmyard manure
    - (iii) Plantation wastes
  - b. Industrial wastes:
    - (i) Industrial effluent linked with plantations
    - (ii) Manufactures
    - (iii) Identification of heavy metal toxicity and pathological problems associated with industrial wastes and management for use as organic matter for improving cultivation
  - c. Urban wastes:
    - (i) Domestic refuse: identification and management
    - (ii) Sewage: recognition, management, and improved use
- Green manuring
  - a. Species identification
    - (i) Legumes
    - (ii) Non-legumes, especially weeds
  - b. Improved methods for use and transportation

More research must be conducted on the role of organic matter in improving crop cultivation in the light of advanced understanding of agricultural practices, while at the same remembering not to misuse the forest biomass.

# CONCLUDING ADDRESS

I have promised to keep my final remarks brief, but there are a few things that need to be said — words of thanks — and also a few words of assessment, which may be instrumental in bringing about actions helpful to many poor rice farmers, and which may therefore help increase rice production. That is after all the objective of IRRI, and it has been the underlying objective of this and other meetings we hold here. Our mandate, written in 1960, states that one of IRRI's tasks is:

> "To organize or hold periodic conferences, forums, and seminars, whether international, regional, local, or otherwise, for the purpose of discussing current problems."

In his opening remarks, Dr. Swaminathan mentioned that at the Nanjing Paddy Soils Symposium we had decided that the first priority among the many topics that required further assessment was the role of organic matter in the productivity of paddy soils. He also mentioned that we hoped in this meeting to be able to arrange for a sharing of experiences in the practical use of organic amendments, particularly of Chinese, Japanese, Indian, and Korean experiences. I think you will agree that our friends have been not only generous in sharing their experience with us, but highly skilled in conveying the fruits of their knowledge and experience. The publication from the meeting should benefit not only us, but many others, and we must thank them for their efforts at making this information available.

But our discussions have ranged much wider than a recounting of experiences in the use of organic manures and wastes. They have ranged from detailed discussions of the complex molecular components of humic materials, as determined by the latest ultra-sophisticated physicochemical techniques, to simple methods of allowing human organic wastes to pass easily into fish ponds. Some of you must have been thinking, as I was myself, that our focus was too wide, and our objectives too loosely defined for an effective assessment of the way in which we can develop both practical actions and research programs to see that we make the best use of organic manures.

As the week has progressed 1 believe we have moved toward defining the questions to be asked, the steps we need to take to get the answers, and the actions needed. As I see it the questions are:

- How much can organic wastes contribute to the short-term and long-term productivity of paddy soils?
- How can organic materials of all kinds best be used in rice-based cropping systems?
- How can the most effective and economical management of organic manures best be encouraged to contribute to the prosperity of rice farmers?

You have, I believe, identified many important issues related to these questions, both research issues and administrative and policy issues. I hope it will be possible for action to be taken to deal with the issues.

In formulating IRRI's research programs, meetings of this type make a great contribution, and I would like to express my very real gratitude and that of my IRRI colleagues to all of you who have made the effort to come here, to prepare your papers — in what for many of you is a most illogical and badly organized language —and to give us the benefit of your knowledge and wisdom. I hope we can put your contributions to use, not for our own benefit, but for the advantage of the vast community who are dependent on rice for their food, and for much of their prosperity — or, often, lack of prosperity.

I know you would also like me to thank on your behalf the various Filipino staff who have helped to make the meeting possible — Ado Nora, Gem Alvez, Miss Pascual, and their many associates. We are grateful to them, and to you, for the efforts that have gone into this meeting.

Finally, Dr. Ponnamperuma, who at the start quoted Dr. Brady — "blame the organizing committee for deficiencies, praise the directors for success" — must, I think, be praised for putting the meeting together so effectively; also Dr. Fillery, who handled the poster session effectively, and Dr. Scharpenseel, for his scientific contributions to the meeting — and for his diplomacy and ability to persuade the German AID ministry of the importance of research related to organic matter and its use — and for getting their financial support for the meeting.

Thank you all.

D. J. Greenland
Deputy Director General

# PARTICIPANTS

*Mohd Zahari Abu Bakar,* Soil Science Branch, MARDI, Kuala Lumpur 01-02, Malaysia
*Carol Acuña,* Bureau of Soils, Legazpi City, Philippines
*Akinola A. Agboola,* Agronomy Department, University of Ibadan, Ibadan, Nigeria
*S. Amarasiri,* Central Agricultural Research Institute, Gannoruwa, Peradeniya, Sri Lanka
*Isriqal Amien,* Soils Research Center, Bogor, Indonesia
*Steve Bantu,* IRRI, P.O. Box 933, Manila, Philippines
*Hayat M. Bhatti,* Ayub Agricultural Research Institute, Faisalabad, Pakistan
*Aguinaldo J. Bueno,* Maligaya Rice Research and Training Center, BPI, Muñoz, Nueva Ecija, Philippines
*Juan C. Bunoan. Jr.,* Bureau of Soils, P.O. Box 1848, Manila, Philippines
*R. Q. Cannell,* Agricultural Research Council, Letcombe Laboratory, Wantage Oxon OX12 9JT. United Kingdom
*Yun-sheng Cheng,* The Institute of Soil Science, Academia Sinica. P. O. Box No. 821, Nanjing, China
*Taj Mohammad Choudhary,* Agricultural Research Institute, Tandojam, Pakistan
*S. K. De Datta,* IRRI, P.O. Box 933, Manila, Philippines
*Crisanto R. Escaño,* Philippine Council for Agriculture and Resources Research, Los Baños, Laguna, Philippines
*A. M. Fagi,* Sukamandi Research Institute for Food Crops, Sukamandi, Subang, Indonesia.
*Regino Fernandez,* Ministry of Agriculture, Region 7. BPI Bldg., Arellano Blvd., Pier I, Cebu City, Philippines
*I. R. P. Fillery,* IRRI, P.O. Box 933, Manila, Philippines
*W. Flaig,* Otto-Hahn-Strasse 132, D-8708 Gerbrunn, Federal Republic of Germany
*J. C. Flinn,* IRRI. P.O. Box 933, Manila, Philippines
*A.C. Gaur,* IARI, New Delhi-12, India
*D. J. Greenland,* IRRI, P.O. Box 933, Manila, Philippines
*H. H. Hagerman.* IRRI, P.O. Box 933, Manila, Philippines
*L. D. Haws,* IRRI, P.O. Box 933, Manila, Philippines
*M. H. B. Hayes,* Department of Chemistry, University of Birmingham, P.O. Box 363, Birmingham B15 2TT, England
*R. W. Herdt,* IRRI, P.O. Box 933, Manila, Philippines
*P. R. Hesse,* c/o UNDP, P.O. Box 3059, New Delhi 110003, India
*Dong-mai Huang,* Soil and Fertilizer Institute, Jiangsu Academy of Agricultural Sciences, Nanjing, China
*Shan-ney Huang,* Taichung District Agricultural Improvement Station, Taichung, Taiwan, China
*Sukhdev Singh Hundal,* Department of Soils, Punjab Agricultural University, Ludhiana (Punjab) 141004, India
*EIisa M. Imperial,* Bicol Experiment Station, San Agustin, Pili, Camarines Sur, Philippines
*A. Inoko,* NIAS, Soil Fertility Division, Yatabe-cho, 3-1-1, Ibaraki-ken, Japan
*M. Ismunadji,* Central Research Institute for Food Crops, Jalan Merdeka 99, Bogor, Indonesia
*N. Kanazawa,* Department of Agricultural Economics, Nihon University, 3-34, Shimouma, Setagaya-ku, Tokyo, Japan
*M. Kikuchi,* IRRI, P.O. Box 933, Manila, Philippines
*K. Kumazawa,* Department of Agricultural Chemistry, University of Tokyo, Bunkyo-ku, Tokyo, Japan

*K. Kurihara,* Fukui Agricultural Experiment Station, Ryo-machi, Fukui-shi, Fukui 910, Japan

*W. E. Larson,* Department of Soil Science, University of Minnesota, 1529 Gortner Avenue, St. Paul, Minnesota 55108, USA

*Sang-kyu Lee,* Office of Rural Development, Suweon 170, Republic of Korea

*Shi-ye Li,* Zhejiang Academy of Agricultural Sciences, Hangzhou, China

*Char-fen Lin,* Taiwan Agricultural Research Institute, 189 Chung-cheng Road, Taichung, Taiwan, China

*Xin-xiong Lin,* Nanking Institute of Soil Science, Academia Sinica, P.O. Box 821, Nanjing, China

*Chung-chu Liu,* Soil and Fertilizer Institute, Fujian Academy of Agricultural Sciences, Fuzhou City, Fujian, China

*T. A. Lumpkin,* Department of Agronomy and Soil Science, University of Hawaii at Manoa, 3190 Maile Way, Honolulu, Hawaii 96822, USA

*B. B. Mabbayad,* Department of Agronomy, UPLB, College, Laguna, Philippines

*J. L. Malcolm,* Renewable Natural Resources, Office of Agriculture, Bureau for Science and Technology, USAID, Washington D.C. 20523, USA

*C. P. Mamaril,* IRRI, P.O. Box 933, Manila, Philippines

*B. E. Marges,* Bureau of Plant Industry, Manila, Philippines

*M. R. Martinez,* Department of Botany, UPLB, College, Laguna, Philippines

*T. W. Mew,* IRRI, P.O. Box 933, Manila, Philippines

*Y. B. Morachan,* Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641003, India

*R. A. Morris,* IRRI, P.O. Box 933, Manila, Philippines

*M. L. Nafziger,* IRRI, P.O. Box 933, Manila, Philippines

*B. R. Nagar,* Government of India Planning Commission, Yojana Bhavan, New Delhi, India

*N. Nalampang,* Multiple Cropping Project, Chiang Mai University, Chiang Mai, Thailand

*N. Nakaya,* NIAS, Department of Soils and Fertilizers, Kannondai 3-1–1, Yatabe, Tsukuba, Ibaraki 305, Japan

*H. U. Neue,* IRRI, P.O. Box 933, Manila, Philippines

*W. K. Oh,* Department of Chemical Engineering, The City University of Seoul, 8-3 Jeonnong-dong, Seoul 131, Korea

*V. M. Palaniappan,* Department of Botany, University of Malaya, Kuala Lumpur 22-11, Malaysia

*S. Partohardjono,* Central Research Institute for Food Crops, JI. Merdeka 99, Bogor, Indonesia

*J. W. Pendleton,* IRRI, P.O. Box 933, Manila, Philippines

*F. N. Ponnamperuma,* IRRI, P.O. Box 933, Manila, Philippines

*I. B. Ramat,* MA-NFAC Fertilizer Program, National Food and Agriculture Council, Diliman, Quezon City, Philippines

*B. Rerkasem,* Faculty of Agriculture, Chiang Mai University, Chiang Mai, Thailand

*K. Rerkasem,* Faculty of Agriculture, Chiang Mai University, Chiang Mai, Thailand

*E. D. Reyes,* Soil Science Department, UPLB, College, Laguna, Philippines

*P. A. Roger,* IRRI, P.O. Box 933, Manila, Philippines

*In Soo Ryu,* Office of Rural Development, Suweon 170, Republic of Korea

*H. Saint Macary,* SEARCA, College, Laguna, Philippines

*P. D. Sangatanan,* Ministry of Agriculture, Region 6, Iloilo City, Philippines

*I. E. Santos,* Bureau of Soils, Alabang, Muntinlupa, Rizal, Philippines

*H. W. Scharpenseel,* Ordinariat fur Bodenkunde, Von-Melle-Park 10, 2000 Hamburg 13, Federal Republic of Germany

*N. T. Singh,* Department of Soils, Punjab Agricultural University, Ludhiana 141004, India

*P. Snitwongse,* Division of Agricultural Chemistry, Department of Agriculture, Bangkok 10900, Thailand

*G. Soepardi,* Faculty of Agriculture, Bogor Agricultural University, Jalan Raya, Pajajaran, Bogor, Indonesia

*P. J. Stangel,* IFDC, P.O. Box 2040, Muscle Shoals, Alabama 35660, USA

*M. S. Swaminathan,* IRRI, P.O. Box 933, Manila, Philippines

*M. W. Thenabadu,* Postgraduate Institute of Agriculture, University of Peradeniya, Old Galaha Road, Peradeniya, Sri Lanka

*K. Tsutsuki,* IRRI, P.O. Box 933, Manila, Philippines

*A. Venkataraman,* Tamil Nadu Agricultural University, Coimbatore 641003, India

*H. Wada,* Department of Agricultural Chemistry, The University of Tokyo, Bunkyo-ku, Tokyo, Japan

*R. L. Wain,* Staple Farm, Hastingleigh, Ashford Kent TN 25 5HF, United Kingdom

*Qian-lin Wang,* Institute of Hydrobiology, Academia Sinica, Wuhan, Hubei Province, China

*I. Watanabe,* IRRI, P.O. Box 933, Manila, Philippines

*Qi-xiao Wen,* The Institute of Soil Science, Academia Sinica, P.O. Box 821, Nanjing, China

*T B. Wiens,* The World Bank, 1818 H. Street, N.W., Washington D.C. 20433, USA

*T. Woodhead,* Physics Department, Rothamsted Experimental Station, Harpenden, United Kingdom

*Zhen-bang Xi,* Institute of Soil and Fertilizer, Shanghai Academy of Agricultural Sciences, Shanghai, China

*Ze-hong Xiao,* Hunan Academy of Agricultural Science, Changsha, Hunan, China

*T. Yoshida,* Institute of Applied Biochemistry, The University of Tsukuba, Ibaraki-ken 305, Japan

*Cong-yi Yuan,* Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China

*Zhao-liang Zhu,* Nanking Institute of Soil Science. Academia Sinica, P.O. Box 821, Nanjing, China