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PRIORITIES FOR ALLEVIATING

INTERNATIONAL RICE RESEARCH INSTITUTE AND
NEW YORK STATE COLLEGE OF AGRICULTURE AND LIFE
SCIENCES, CORNELL UNIVERSITY

PRIORITIES FOR ALLEVIATING SOIL-RELATED CONSTRAINTS TO FOOD PRODUCTION IN THE TROPICS

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Foreword

The green revolution has failed to fulfill expectations in most areas of the world. Yields and production levels are only a fraction of those predicted when the new high yielding cereal varieties were first released in the 1960s. There is a growing recognition that environmental factors are largely responsible for this failure of new crop varieties to live up to expectations.

Soil-related factors are among the most significant environmental constraints on crop production in the developing countries. Through practical experience farmers have favored areas with naturally highly productive soils and have shunned those with the less productive soils. Ignorance of improved technology and lack of inputs have constrained them from improving crop performance in areas with poor soils.

Attempts to identify soil constraints and to develop or adopt technologies to remove them are largely location specific. But other factors such as research methodologies and the need for communication and cooperation among soil and crop scientists from the different locations suggest the wisdom of a well-organized international approach to the identification and removal of soil constraints.

To review knowledge of soil constraints in developing countries and to explore ways scientists can use to help remove these constraints, an international symposium was convened. Cosponsored by Cornell University and the International Rice Research Institute (IRRI), the symposium was held at IRRI headquarters in the Philippines, 4–8 June 1979. It was also supported by universities and research agencies from both the developing and more developed countries and by the agricultural research centers funded by the Consultative Group on International Agricultural Research. Direct financial support was provided by the Federal Ministry for Economic Cooperation of the Federal Republic of Germany and the U.S. Agency for International Development.

The papers in this volume summarize what is known about major soil constraints on both geographic and subject matter bases. Also presented are approaches that might be used to increase the efficiency and effectiveness of research on soils and their management. Special attention is given to international cooperation and to mechanisms to encourage such cooperation.

Thanks are extended to the cochairmen of the Symposium Planning Committee, Armand Van Wambeke of Cornell and Hubert Zandstra of IRRI, and to Matthew Drosdoff, Hubert Zandstra, and W. G. Rockwood who edited the papers published in this volume. Likewise, appreciation is expressed to the authors who prepared and presented these papers.

J. F. Metz
Cornell University

N. C. Brady
The International Rice Research Institute

Welcome address

N. C. BRADY

IT IS WITH GREAT PLEASURE that I join the representatives of the cosponsor of this conference, Cornell University, in welcoming you to the International Rice Research Institute and to this conference on the priorities for alleviating soil-related constraints to food production in the tropics.

A series of cooperative efforts has made this conference possible. The two cosponsoring organizations, IRRI and Cornell University, each are associated with groups of comparable institutions concerned with soil constraints to crop production. Scientists at Cornell have served as part of a consortium of U.S. universities concerned with tropical soils. The group includes North Carolina State University and Prairie View University and the Universities of Hawaii and of Puerto Rico. The latter two also planned and are implementing a Benchmark Soils Project in cooperation with scientists in Africa, Latin America, and Asia, and with FAO and USDA.

IRRI, in turn, is associated with a number of similar international agricultural research centers with special concern for soil constraints. Sponsored by the Consultative Group on International Agricultural Research, these centers include the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India, the International Institute of Tropical Agriculture (IITA) in Nigeria, the International Centre for Agricultural Research in the Dry Areas (ICARDA) in the Middle East, and Centro Internacional de la Papa (CIP) in Peru. The centers have sponsored or cosponsored soils conferences of international interest and provide travel and living expenses for their staff who participate in these conferences.

In addition to these organizations, other institutions have a keen interest in soil constraints to crop production. Many of you are from universities or research centers in the developing countries where not only you and your colleagues but national food production experts have a deep interest in soils. Those of you from universities and research centers in Europe, Japan, Canada, and Australia have demonstrated your keen interest in soil constraints, especially in the tropics. Likewise, scientists in the Food and Agriculture Organization of the United Nations (FAO), the United States Department of Agriculture (USDA), Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), and Institut de Recherches Agronomiques Tropicales et des Cultures Vivrières (IRAT) have taken the leadership in identifying and removing soil constraints.

We are very pleased that two donors have very generously provided support to partially cover the expenses of this conference. They are the USAID Devel-

Director general, International Rice Research Institute, P.O. Box 933, Manila, Philippines.

opment Support Bureau and the Federal Ministry for Economic Cooperation of the Federal Republic of Germany. We express appreciation for their inputs into this conference.

In the international research effort to help people produce more food, the first breakthrough has been the development of new wheat, rice, and corn varieties. Great expectations rose with the early findings – expectations based on the concept that plants with good genetic potential would automatically greatly increase the world's food production. We now know that this is not true. The genetic potential of new varieties is necessary, but by itself does not automatically guarantee additional food. We now recognize that the environment in which plants grow and with which the farmer works determines whether the genetic potential is to be realized. While we recognize the importance of the sociopolitical environments that determine whether a farmer will adopt new technology, our primary interest in this conference is with the physical environment and, specifically, with the soil environment.

Most scientists recognize the seriousness of soil-related constraints to crop production. But there is no well-coordinated research program to systematically delineate major soil constraints to crop production in developing countries, and to find practical means of removing these constraints. The major purpose of this conference is to take the first step toward planning and implementing such coordinated research.

At the 1978 meetings of the International Soil Science Society held in Edmonton, Canada, a number of soil scientists met with Dr. A. Van Wambeke of Cornell and Dr. H. G. Zandstra of IRRI to advise on the specific objectives of the symposium and on ways to make it most effective. The general outline developed by Drs. Van Wambeke and Zandstra was later circulated among those who had contributed to the Edmonton discussions and provided the general focus for the conference program that was finally developed.

Assembled here today are soil scientists from the developing and more developed countries. Some are scientists whose work is to characterize and classify soils. Likewise, among us are scientists who ascertain soil performance and who want to relate that performance to soil characterization and classification. We hope we will have the wisdom to identify what should be done and how we can best organize ourselves to get the job done.

To help us achieve our task, the organizers of this conference have given us two major assignments. First, we are to summarize what we consider are the major soil constraints in the different ecological regions of the world. And then we are to develop mechanisms and approaches for further identifying these constraints, and technologies to remove them. After listening to a series of papers on these topics, we will have group discussions about the constraints as they occur in different ecological situations in the world. Then, we are to identify who might best perform the research and how it could best be coordinated. Specific attention must be given to the inputs from national research institutes and universities in both the developing and more developed countries, and from international organizations.

Those are our assignments. The week ahead is of tremendous importance. I wish you success.

GENERAL SESSION

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Toward an internationally coordinated program for research on soil factors constraining food production in the tropics

L. D. SWINDALE

Soil-related constraints to food production in the tropics must be overcome mainly by national research. International efforts needed include strengthening national institutions; creating government awareness of needs for research; developing methods and more systematic experimental designs; gap-filling research, particularly in soil physics, biology, mineralogy, and soil-survey interpretation; multidisciplinary research; research on problems that supersede national boundaries; and creating conditions for international communications and the transfer of agrotechnology among countries.

An international, scientifically based coordinated program will assure that resources are obtained and are used efficiently and that soils are used wisely in meeting the demands for increased food production. Its elements include an international coordinating center, an international benchmark soils network, and national and international cooperating centers. The international agricultural research centers (IARC) can provide much of the international effort within their crop-improvement and farming-systems mandates, but at least one specialist international soils research institute may be needed to investigate problems that supersede national boundaries or lie outside the mandates of the IARC.

"Possibly as many as 450 million to a billion people in the world do not receive enough food. Most of the hungry people live in the poor countries . . . If the developing countries are to increase per capita

International Crops Research Institute for the Semi-Arid Tropics, Patanchern P.O., Andhra Pradesh, India 502 324.

> food availability by at least 1% per year, they need to expand their food production over the next 25 years by an average rate of about 3–4% per year . . . increases in yield need to average about 2.5% per year."

This quotation, taken from the Report of the World Food and Nutrition study published in 1977 by the United States National Research Council, serves as an appropriate introduction to this paper.

There is no fundamental reason for people to go hungry, or for the targets not to be met. The world can feed its people and many more. A recent, and optimistic, estimate of the carrying capacity of the world is 40 billion people (Revelle 1976). Unfortunately the performance so far has been less than reassuring. Dudal (1978) gives figures to show that in the 20-year period 1957–1977, the area of arable land in the world increased by 135 million hectares, which is about 10% or less of the land still available to be brought into cultivation and an increase of only about 9% of land already in agricultural use. The world's population increased by 40% during the same period.

Food production from the increased arable land is enough to feed only one-third of the increased population. The food required to feed the other two-thirds has come from more intensive use of existing lands. Most of the increase occurred in the developed world and not in the countries where most of the additional people live. According to Dudal (1978), the additional production resulting from extension of cultivated lands in developing countries is lagging far behind that required by the increase in population.

In addition to the concern about food needs, there has been in recent years an increasing awareness of the need to be concerned about who produces it. The so-called *Green Revolution* has been criticized because, the critics claim, the rich farmers became richer and the poor farmers poorer. The *revolution's* staunch defenders refute this criticism. The truth lies somewhere between – that is, the small farmers are benefiting from the gains in wheat and rice, but the benefits are distributed unevenly, with more accruing to the better endowed producers.

Neither party to the debate on the *Green Revolution* disputes the claim of the small farmer to share in the production and its benefits. Equity, as much as efficiency, is now part of the equation. Indeed it is the declared policy of governments sponsoring this conference that their aid programs will be directed towards the small and resource-poor farmer. For this to happen, the staple foods needed to relieve hunger and malnutrition must be produced by the rural people where they live, and not on empty lands somewhere else.

The need to produce more food from existing or new lands means more efficient use of soils. Roads, dams, canals, fertilizer plants, distribution centers, and market towns must also be built, and all of these put demands on the soil. Soils can be destroyed if not wisely used. A conference of soil scientists considering how research can relieve the soil-related constraints to food production

must also consider constraints to the wise use, management, and conservation of soils.

SOIL-RELATED CONSTRAINTS TO DEVELOPMENT

"The soil is a living body." Norman H. Taylor, late director of the New Zealand Soil Bureau, would make this statement solemnly at the beginning of virtually every conference or workshop held by soil scientists in New Zealand. His intent was to remind scientists of the biological and dynamic nature of soil, and the likelihood of its misuse if treated only as an inorganic mixture of sand, silt, and clay. The recent United Nations Conference on Desertification gave many examples of soil misuse and stressed the need to consider the long-term effects of development upon soil. In this sense, all soil characteristics are potential constraints in that intensified use of soil may lead eventually to deterioration in soil quality.

The purpose of this conference is to determine the main soil-related constraints to food production in the tropics. It is necessary, for purposes of this paper, to anticipate the results of the conference. Fortunately there are some impressive guides in the soils literature. Sanchez (1976) recently summarized and codified current knowledge of soils in the tropics. Greenland (1978) has made an up-to-date analysis of research needs in soil science. Much of his analysis applies to the tropics. He cites the need for better understanding of the chemistry of humic materials, soil nitrogen balance sheets, and the ecologies of soil organisms, and the failure of soil physicists to provide solutions to field problems. He lists among future challenges the need to increase soil productivity in developing countries, to develop new lands for agriculture, to prevent soil degradation, and to stop the alienation of prime agricultural lands.

The Technical Advisory Committee (TAC) to the Consultative Group on International Agricultural Research (CGIAR) recently suggested (TAC 1979) that several aspects of soil science warrant international support:

- soil and water management research within the programs of the international agricultural research centers (IARC) as relevant to the centers' programs in crop improvement and farming systems;
- correlation of national soil inventories to overcome the site-specificity problems of soils research;
- use of benchmark soil sites and the need for soil, plant, and water studies on them;
- improving and maintaining, with low inputs, the potential of infertile tropical soils;
- principles and methods of soil conservation, particularly in semiarid and arid zones;
- soils research closely related to improved water management, particularly for major irrigation schemes or for irrigating problem soils; and
- in Africa south of the Sahara and in much of Latin America where irrigated areas are relatively small, concentration also within the context of farming

systems research on rainfed farming in semiarid and semihumid savanna areas, where seasonal water deficit and seasonal waterlogging are both problems.

Obvious constraints

Soil fertility and plant nutrition. Intensification of food production in the tropics will need large inputs and more efficient use of nitrogen, phosphorus, and potassium fertilizers. Much research is needed, but most of it should be done through national efforts. Methodologies are well understood, governments are aware of the need, and the fertilizer producers are able and willing to help. Substantial work at the international level is already under way or planned by the Food and Agriculture Organization of the United Nations, the International Fertilizers Development Center, and the IARC.

Strengthening national programs, training scientists, and improving research quality and methods are the best uses for bilateral and multilateral assistance. Still needed are methods to investigate efficient use of nitrogen in flooded soils and the dynamics of nutrient movement in the semiarid tropics. There is scope for internationally coordinated trials and need for more research on the relationships between fertilizer response and soil variability.

Although the current research effort on micronutrients is small, it is probably in balance with the current need in relation to soil use. Exceptions may be for research on microelements that are widely deficient in tropical soils or that significantly influence biological nitrogen fixation. Micronutrient research should also be through national programs.

Soil survey and classification. Survey and classification is the essential basis for the wise use and management of soils. About one-fifth of the world's soils have been surveyed, with the highest percentage in Europe and the lowest in Africa (Dudal 19[illegible]). There is a substantial need for more large-scale surveys, particularly of first and second order, and for greater use of remote-sensing techniques for higher order, smaller-scale surveys where these do not already exist.

Much of this work can, indeed must, be done through national efforts. Methods are well known and essentially standardized throughout the developing world through effective assistance by FAO. Governments are generally aware of the needs, and some provide sufficient and substantial resources for the work. Development agencies usually require soil or land surveys as part of area development projects, and are willing to pay for them. International assistance is mainly needed to strengthen national efforts, to train staff, and to assist in the improvement of staff quality.

An adequate international soil classification, *Soil Taxonomy* (USDA 1975), now exists as a result of an impressive 20-year effort by the United States Soil Conservation Service and cooperators throughout the world. Improvements in soil correlation to ensure accuracy in soil survey and classification require international effort and funding. Research is needed to improve the usefulness and accuracy of *Soil Taxonomy* with respect to tropical soils. The research is best

done in the tropical countries where the problems exist, but it will need international support. Changes in *Soil Taxonomy* will require international effort and agreement. International soil-data banks are required to store information on correlated and classified soils.

Soil amendments. Much research is needed on the use of lime, farmyard manure, and silicates as soil amendments in the tropics. The World Food and Nutrition Study (U.S. National Research Council 1977) states that 70% of the unused arable land has acidic soils. Application of lime to correct soil acidity in the tropics according to procedures used in temperate zones has often ended in failure (Kamprath 1972). Newer knowledge of the importance of exchangeable aluminum in soils has been helpful, but substantial improvement is needed in methods to estimate lime requirements and the incorporation of lime at depth in the soil.

Phosphorus plays a double role as nutrient and amendment. It is an essential nutrient deficient in most tropical soils, but is needed in such vast quantities to overcome high fixation in a few of them, particularly Dystrandepts and Hydrandepts and some Udults and Oxisols, that it must be classed and financed as a soil amendment.

The work must be done largely through national efforts, but international support is probably needed to improve methodology and the exploration of the principles involved. Much research, including long-term availability studies, should be done to improve the efficiency of phosphorus use in high phosphorus fixing soils.

Soil erosion and conservation. The tendencies for soils to erode and the need for their conservation are obvious constraints to all-out food production. There has been in recent years substantial emphasis on the seriousness of soil erosion in the tropics, but not much sound and useful research has been done (Greenland and Lal 1977) and the work is expensive, complex, and multidisciplinary in nature. A significant international and internationally funded research effort is required to supplement the effort that nations can make for themselves. Furthermore, there are often international implications to soil erosion, i.e. the effects of soil erosion or conservation in one country may have direct effects upon soil productivity in another.

Soil management. The term *soil management* is used to cover many types of activities aimed at improving soil productivity or increasing crop production on specific soils. It includes the management of special types of soils, such as soils for rice or soils with special problems such as waterlogging or salinity.

A substantial research effort is being made by national institutes, often with bilateral or multilateral assistance. International effort is needed to devise more efficient multidisciplinary methodologies, to train national research workers, and to devise techniques to reduce the site specificity of the research.

Dudal (1978) concludes that the lack of knowledge of soil requirements for specific crops is seriously limiting interpretation of soil surveys. Not enough is being done to relate crop performance to permanent soil characteristics. Some

of the IARC are pioneering in soil management research within larger farming systems frameworks. The work is attracting national interest and is currently being subjected to intensive review and study.

Less obvious constraints

Soil physical conditions. Several authors, from Aubert (1962) to Greenland (1978), have stressed the importance of soil physical constraints to the use of tropical soils. There has been little response by scientists. A major international effort is needed to close the gap between what is known and what needs to be known, and to create national programs of research.

Water in the soil, either too much or too little for adequate plant growth, is often a major limiting factor. But there are few soil physicists in the tropics doing field work on dynamic water balances or hydrological profiles. Let me give a simple illustration by quoting a statement by Antoine (1977) at the Soil Resources Inventory Workshop at Cornell University in 1977. He said, "The USDA's *Soil Taxonomy* offers some serious disadvantages. As in most countries of Africa, Asia, and South America, available soil moisture data are very scarce in Northern and Western Africa." And yet these measurements are not difficult to make.

Other soil physical constraints such as surface and subsurface impedance, tilth, and structural conditions are either difficult to measure accurately (and therefore to study effectively) or expensive to overcome. Much research is needed because they are likely to be major economic soil constraints in the tropics.

Soil-survey interpretations and land classification. Although an adequate national input is being, or can be, made into soil survey and classification, this is not so for soil survey interpretation and land classification. An understanding of soil potentials and limitations is essential to good land use planning for food production and economic development and for the wise use of soils. Soil-survey interpretation and land classification, like soil management, are approaches toward a holistic understanding of soils.

The requirements for effective soil survey interpretation for agricultural development are known (Swindale 1977), but there is virtually little research in the tropics on the methodology and validity of soil survey interpretation and government awareness of its importance is insufficient. The soil fertility capability classification by Buol et al (1975) and the interpretations for rubber in peninsular Malaysia by Chan (1978) are noteworthy exceptions. A major international effort is needed and is possible. The Benchmark Soils Projects of the University of Hawaii and the University of Puerto Rico are pioneering efforts that demonstrate what needs to be done.

Soil biology and reactions of organic compounds. Concern about the costs and deleterious effects of nitrogen fertilizers has led in recent years to greater interest in, and research on, biological nitrogen fixation. The work in the tropics has been mainly done at international levels by the IARC, with a few major

exceptions (see, for example, Dobereiner and Day 1975). A somewhat similar situation exists with respect to research on the influence of mycorrhiza on phosphorus utilization. The efficiency of nitrogen fertilization is closely related to the reactivity and nature of soil organic matter.

Pesticide use is increasing in the tropics. Research on retention and fate of these chemicals in the soil will be needed.

Soil scientists study soil microflora primarily because of an interest in organisms that improve the supply of nutrients and oxygen to plants, but many plant diseases are caused by soil-borne organisms. Root and stem rots are prevalent in the tropics and pose serious constraints to food production. The study of the ecology of these organisms is a soil research need.

Soil mineralogy and surface chemistry. The significance of soil mineralogy in the tropics has long been recognized. Laterites, soil hardening, and the low permanent charge characteristics of many tropical soils are well described in the literature. The importance of soil mineralogy to food production and economic development has not been given the same degree of study. We are beginning to understand the significance of variable charge and surface phenomena to fertilizer use and efficiency. It is possible, if rather speculative, to believe that more fundamental research on the surface reactions of soil minerals may lead to important improvements in the productivity of soils in the tropics. The effort, at least initially, must be at international levels.

THE NEED FOR COORDINATED RESEARCH

This analysis of soil-related constraints has identified much need for national research in soil science and the following needs for international efforts:

- strengthening of national programs, including training and improving research quality;
- creating government awareness;
- more accurate identification of constraints;
- developing new methods and more systematic research;
- conducting international trials;
- storing data;
- filling major gaps in neglected areas;
- multidisciplinary, holistic research;
- research on problems that supersede national boundaries;
- creating conditions for the transfer of technology among countries; and
- developing communications networks.

Coordination is needed a) because agricultural research is costly and the creation of a sufficiently large national effort is often beyond the resources of developing countries; b) so that knowledge building can proceed at widely different locations; and c) to help harness the substantial reservoir of talents and facilities for soils research that exists in the developed countries (Kelley 1974).

Coordination in international soils research will also focus attention on the need to use and manage soils wisely in meeting demands for increased food production.

If there are advantages to coordination there are also disadvantages. Coordinated international research may frustrate the efforts of national scientists and interfere with their ability to perceive what is most needed in their own countries. It can reduce funds and jobs available to national scientists; it can reduce their influence and importance in their home countries. It can reduce the value of individual initiative and exploitation of chance observations in research. Coordinated multilocational trials may divert scarce resources of time and funds of national scientists, and their institutions, away from more important national concerns. It is important in developing an internationally coordinated system of soils research to be aware of these potential problems. It is not necessary, possible, or even wise to coordinate all soils research in the tropics.

A RATIONAL SCIENTIFIC BASIS FOR COORDINATION

A soil is part of the landscape; unlike the seed of a plant it cannot be moved physically from place to place. Soils are variable, and soils of the tropics are more variable than soils in temperate regions (Moormann 1972). An international center in a single location cannot conduct all the international level soil research required; even a network of cooperating institutions cannot cover the needs adequately unless there is some rational scientific basis to their efforts.

An agreement to utilize common methodologies would provide a first basis for coordination. It would also lead to comparative studies of methods and eventual improvement in their accuracy. A valuable side benefit would be the training in methodology provided to staffs of cooperating centers and other researchers.

An emphasis on process-oriented rather than practice-oriented research would provide another basis for coordination. That is easier said than done. Research to elucidate principles and cause and effect relationships requires good understanding of theory, careful design of experiments, and the use of the scientific method. It may also require greater emphasis on basic research than most donors or governments may be able to understand or willing to accept.

The *Benchmark Soils* concept provides a third basis for coordination. A benchmark soil is one occupying a key interpretative position in a soil classification framework, or covering a large area of a region or nation or both. Research undertaken on benchmark soils can be used to estimate probable results for soils not otherwise investigated. The Benchmark Soils concept, combined with *Soil Taxonomy* and established methods of soil interpretation will provide, in fact, the elements of a systematic methodology for agrotechnology transfer in the world and is potentially the most effective basis for a coordinated network for research on soil-related constraints to food production.

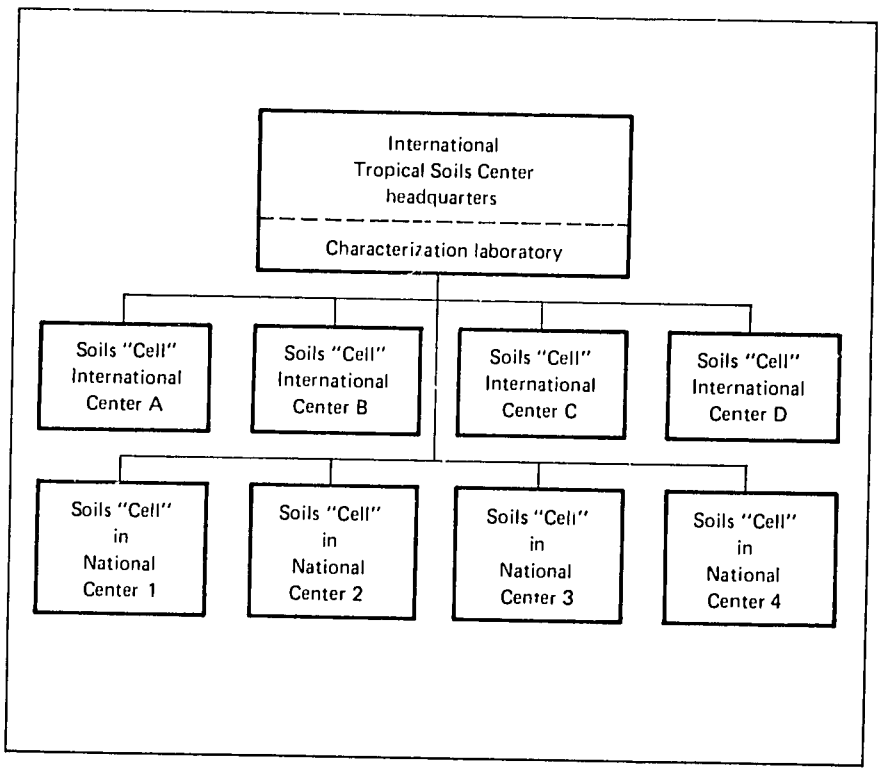
COORDINATING MODELS

Several models have been proposed for coordinating international soils research.

The Brady model

One of the earliest was proposed by Brady (1972). He envisaged a "decentralized" center with a director, a small administrative staff, and a basic soil characterization laboratory at one headquarters location. Its scientists would work at satellite sites – in international or national research centers – carefully selected to provide a range of soil conditions characteristic of the tropics. A schematic illustration of the concept is presented in Figure 1. Soil scientists would work for the soils center and the crop-oriented center or field station at which they were located. The staff would work closely with staff from other disciplines in the crop-oriented center but would, at the same time, implement research planned and coordinated within programs from the soils center.

Brady saw the tropical soils center as serving several purposes. First, it would provide an international focus on soils of the tropics and their management. Second, it would provide a mechanism for coordination, planning, and annual



1. The concept of a "decentralized" International Center for Research on Tropical Soils.

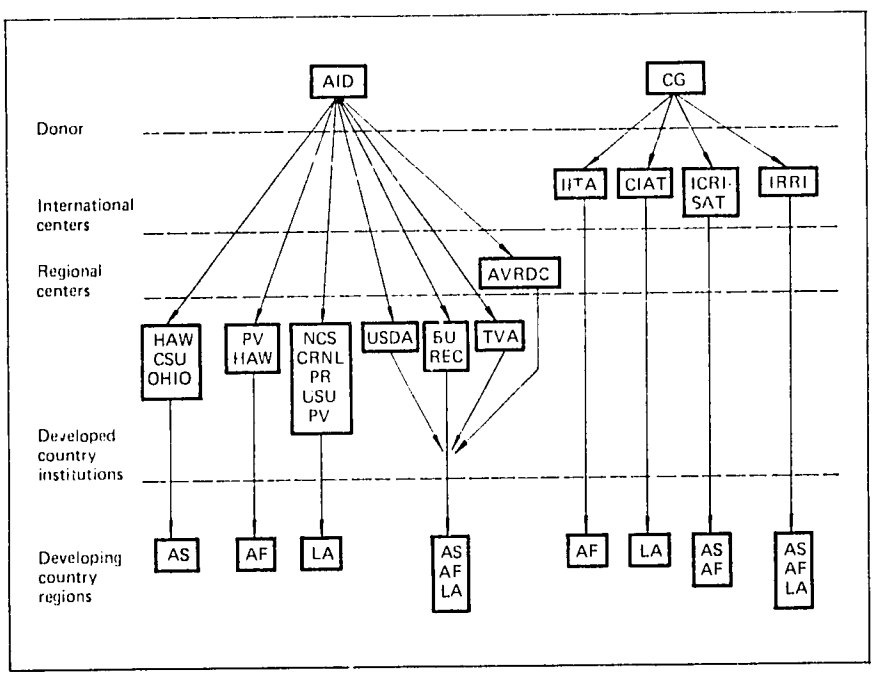
reporting. Annual workshops, proposed as part of the center's work, would be held in different places and would be coordinated with regional research conferences. Thirdly, the center would provide managed funding for badly needed research on tropical soils. It was hoped that the development of such an institutional framework would lead to the creation of additional sources of support for tropical soils research.

The training of scientists and educators concerned with tropical soils work would be an important objective of the center. The use of postdoctoral trainees was stressed as a means of providing experience in working in the tropical countries for scientists from developing countries who had gained their academic qualifications overseas.

The Kelley model

A more elaborate structure for a coordinating network for tropical soil science was proposed by Kelley in 1972, and enlarged in a subsequent paper (Kelley 1974). The model (Fig. 2) paralleled as nearly as possible the commodity network of the existing international agricultural research centers. Baird (1978) supported the general idea of the Kelley model.

Emphasis in the Kelley model is on developing a network to achieve *critical massing* of resources required to gain breakthroughs on important soil-related constraints. Kelley stressed the importance of focusing the outputs of the network on farmers in the developing countries, and the need for effective internal linkages between national research institutions and the farmers. He also stressed



2. Proposed international soil-research network.

the importance of coordination and communication and mentioned the need for a *nerve center* to carry out and facilitate many of the functions currently being handled by commodity-related IARC. The Kelley model, however, did not provide for such a nerve center; coordination at international levels presumably would be developed at a later stage and be dependent on the IARC soil science programs and the AID-supported Consortium on Tropical Soils and U.S. universities.

The Swindale-Uehara model

Swindale (1978) and Uehara (1978) proposed a model based on the Benchmark Soils projects of the universities of Hawaii and Puerto Rico. Their model stresses scientific coordination through the benchmark soils concept and particularly through the soil family of *Soil Taxonomy*.

The soil family is the fifth level of subdivision in the taxonomy. To quote from the definition in the taxonomy,

> "... the intent has been to group (in a soil family) the soils within the subgroup having similar physical and chemical properties that affect their responses to management and manipulation for use. The responses of comparable phases of all soils in a family are nearly enough the same to meet most of our needs for practical interpretations of such responses."

Benchmark soil families, therefore, provide in principle the basis for agrotechnology transfer.

Swindale and Uehara proposed expanding the Benchmark Soils project into a global network of benchmark soil families. Existing agricultural research stations would be incorporated into the network by determining which soil families were represented to a significant extent among them. They considered that the soils research network would:

- improve communication between researchers and planners in different countries working under similar soil and environmental conditions;
- increase the value of published data, reports, and regional development plans;
- provide the basis for cooperative research on soil and water management and crop responses to manufactured inputs;
- be useful in designing experiments to ascertain crop responses to the variables that constitute soil family criteria;
- provide in-country type locations for soil classification; and
- aid in refining soil-family criteria for the tropics and in testing the general usefulness of the soil-family concept for land-use planning and development.

The University of Hawaii-University of Puerto Rico Benchmark Soils projects would provide coordination by assisting in:

- classifying soils at the family level;
- publishing and distributing compilations of soil-family data;

- storing the data in soil data banks and making the information available to all contributors;
- establishing contacts between countries with similar soils;
- making arrangements to incorporate published reports of research available in the data banks and making them available through bibliographic retrieval services; and
- providing training and organizing seminars and workshops for coordinating and planning purposes.

The IBPGR model

Baird (1978) referred to the International Board for Plant Genetic Resources (IBPGR) as a possible model for the coordinating center of a Soils Research Network. IBPGR has been in existence since 1974 and is a member of the CGIAR system. The objectives of the Board are to:

- identify needs and priorities for exploration, collection, and evaluation and conservation of plant genetic resources, and to make the collections available for crop improvement;
- establish standard methods and procedures;
- arrange for regional activities;
- promote technical meetings and training;
- develop a worldwide network of institutions, organizations, and programs able and willing to contribute to the above objectives;
- promote articulation of ongoing programs to avoid unnecessary duplication;
- strengthen national programs;
- promote the dissemination of information and material among centers and institutions;
- develop computerized information storage and retrieval systems; and
- estimate the annual financial requirements of those parts of the program not otherwise adequately covered.

IBPGR cooperates closely with the IARC, several of which have agreed to coordinate the genetic resources activities of the crops in their mandates.

The Board is small, works mainly through committees of experts, and has few operational responsibilities. The Executive Secretary and staff of the Board are provided by and partially financed by FAO, where the Board has its headquarters. The Board has been effective in creating international and national awareness of the need to collect genetic resources, and has catalyzed and stimulated much activity in this field.

The International Soil Science Research Institute (ISSRI)

Bentley (1978), in his presidential address at the 11th Congress of the International Soil Science Society, proposed the establishment of an international soil science research institute, to be a member of the IARC funded by the CGIAR. Although his proposals contain few details, it is clear that ISSRI would be expected to concentrate on the problems of food production on tropical soils.

He envisaged a single center of excellence with resources, recognition, and rewards second to none. Bentley proposed a single institute as essential to ensure for soils research the type of support and prestige that have accrued to the present IARC or, better still, to the centers for excellence in medical research around the world. According to Bentley, some of the site-specific problems of a single institute could be overcome by the use of more modern methodology, e.g. the use of remote sensing techniques for land resource inventories.

TAC took note of the ISSRI proposal at its twenty-first meeting in February 1979, but did not accord soil science research a high priority from the point of view of CGIAR support.

The International Benchmark Soils Network (IBSN)

An International Benchmark Soils Network, closely related to the earlier Swindale-Uehara proposal, was recommended by the AID-sponsored workshop, The Implications of Agrotechnology Transfer Research, at the International Crops Research Institute for Semi-Arid Tropics in October 1978. It was proposed that the Network be based on existing national and international agricultural research centers.

The Network would be responsible for establishing:

- a global network of benchmark soils;
- a program of coordinated standardized agronomic research to obtain essential production information for important tropical crops;
- a coordinated program to develop relationships between soil characteristics, climatic parameters, and crop performance;
- data banks containing files on soil distribution, soil characteristics, soil classification, and soil use;
- a communications network involving national agricultural research centers, international agricultural research centers, and international governmental agencies; and
- a central unit with a governing board to serve as a clearinghouse, coordinating forum, and training center.

The workshop proposed certain ancillary international activities to internationalize *Soil Taxonomy*, establish a system for international soil correlations, and develop standards for research to collect crop-performance data. The workshop also outlined procedures for establishing national benchmark soils networks and coordinating them with the international system. A logical framework (Fig. 3) was developed to show the Network, its division into crop and soil studies and their recombination into interpretations for increased food production, better land use planning, and accelerated economic development.

CONCLUSIONS

None of the models described in the previous section can serve all requirements for international cooperation and action in soils research that derive from a

consideration of the constraints. A new model, comprising some combination of previous models and new ideas, must be developed by this Conference. The model needs a coordinating center, national and international cooperating centers, and a rationale for coordination based, in my view, on the Benchmark Soils concept.

An international coordinating center

The responsibilities of the coordinating center would be similar to those described for IBPGR and the Brady model. They would be:

- to develop a worldwide network of institutions, organizations, and programs;
- identify needs and priorities for international cooperation in soils research;
- create international and national awareness of needs and priorities;
- obtain funds for soils research and particularly for strengthening national programs;
- promote national and regional activities and their articulation as necessary and appropriate; and
- develop or assist in the development of soil data banks and other clearinghouse activities and communications functions, including the promotion of technical meetings and training.

The center would be most appropriately governed by a Board of Trustees selected to represent constituencies of national programs, donors, contributing centers, and the professional fraternity of soil science.

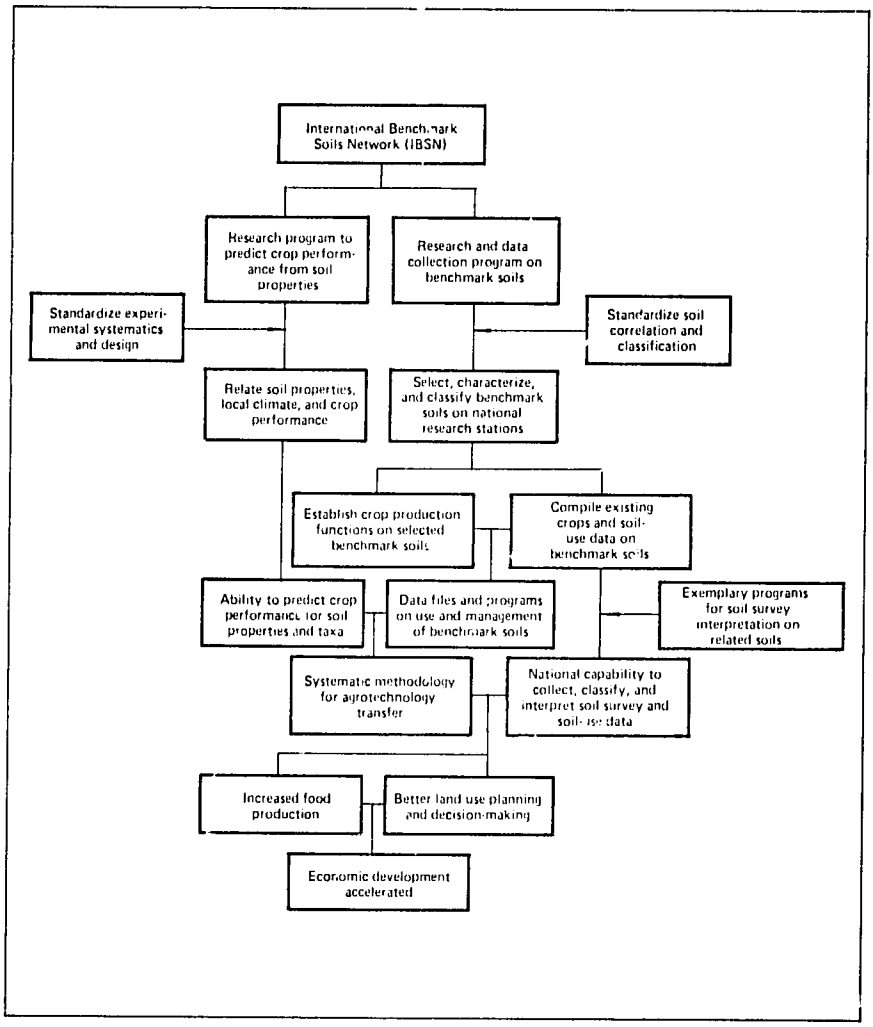
An international benchmark soils network

The Benchmark Soils concept should be used to provide the rational, scientific basis for cooperation. The soils of all field research stations of cooperating institutions should be considered, at least initially, as benchmark soils, and characterized and classified in terms of *Soil Taxonomy*.

A Benchmark Soils Network would be responsible for scientific activities related to its own establishment, that is, soil characterization (including the standardization of methods), international soil correlation, soil classification, assisting to internationalize *Soil Taxonomy*, and establishing related data banks and communications activities. In addition, the network would promote conditions for agrotechnology transfer by assisting in the establishment of national benchmark soils networks, promoting or engaging in research on soil survey interpretation and land classification, and developing a coordinated program of research on the relationships between soil characteristics, climatic parameters, and crop performance (see Fig. 3). The network could be developed *de novo* or be the responsibility of an existing institution.

National cooperating centers

Most of the research to relieve soil-related constraints to food production and to ensure wise use of soils in the tropics must be done by national institutions.



3. Logical framework for the International Benchmark Soils Network.

They are often well-equipped to do particularly in the fields of soil chemistry and fertility, soil amendments, and soil survey and classification. They would benefit from infusions of funds to supplement their own resources. They could undertake some of the priority research needed at international levels through specific research contracts or regional research activities.

National centers often benefit from international help in convincing governments of the importance of their work, in strengthening their programs, and in training. They usually need outside funds for participation in international workshops and coordination activities.

International agricultural research centers

Several of the IARC undertake soils research within their mandates in crop improvement and farming systems. The work is necessarily of an international character. The Centers could enlarge their activities to undertake gap-filling research related to their mandates, develop new methods, conduct coordinated international trials, provide training facilities and opportunities, and act as regional coordinating centers for international soils research. Particularly within their farming or cropping systems programs, they can take leadership in developing multidisciplinary methods for research on soil management and soil erosion and conservation. It is unlikely, however, that the Centers will be able to provide for all the international needs in soils research, and because of their strong commodity orientation, they are not the best institutions to focus international attention on the wise use of soils.

Specialized international soils research institutes

Some research to fill gaps in such fields as soil physics, soil biology, and soil mineralogy, and some multidisciplinary research may need to be undertaken by a specialized institute or institutes established on an international basis for the purpose. Such institutes could also undertake responsibilities for research on problems that supersede national boundaries and for activities similar to those described for the IARC.

Existing institutions in developed or developing countries could undertake all or part of these research activities and some of the other backup basic and methodology research required, with funds provided by donor governments or agencies. However, the existence of a specialized international soils research institute would help ensure international attention to soils, something which existing national institutes will not be able to do so well. For this reason, it may be wise to ensure that at least one such institute is included in the overall network.

Initiating the system

There are many organizations, institutes, and centers in the world willing to be involved and capable of contributing. Their current activities may form the basis for their contributions, but for the most part they would require additional funds from outside donors to be able to undertake the work required. United Nations organizations (particularly FAO, UNESCO, and UNDP), the IARC, the International Soil Museum, and some centrally funded activities of USAID should, because they are already international in character, be able to contribute directly to the needs.

Furthermore, FAO and particularly the IARC may be able to enlarge their activities using existing funding sources. To this extent, an internationally coordinated network in the immediate future would probably be best initiated through them. FAO might undertake to be the initial headquarters for the coordinating Center. If it is unable or unwilling to do so, one of the IARC might

assume the role. My choice, in that case, would be IRRI, led as it is by a distinguished soil scientist who suggested one of the earliest models for an internationally coordinated program for research on soil factors constraining food production in the tropics.

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Soil-related constraints to agricultural development in the tropics

R. DUDAL

Tropical regions are reputed to have vast potential for increasing agricultural production. This potential is usually attributed to temperatures that favor plant growth throughout the year, and to the availability of large areas of noncultivated land in the tropics. It is recognized, however, that the intensification of agriculture in the tropics presents a number of problems. Soil-related constraints are often listed among those that are most difficult to overcome.

Estimates of the agricultural potential of the tropics have been made in general terms. A more precise evaluation is now needed. Constraints related to soils of the tropics – frequently equated with *problem soils* – require qualification and the concept of tropics itself needs to be more clearly defined and to be stratified in terms that have interpretation value.

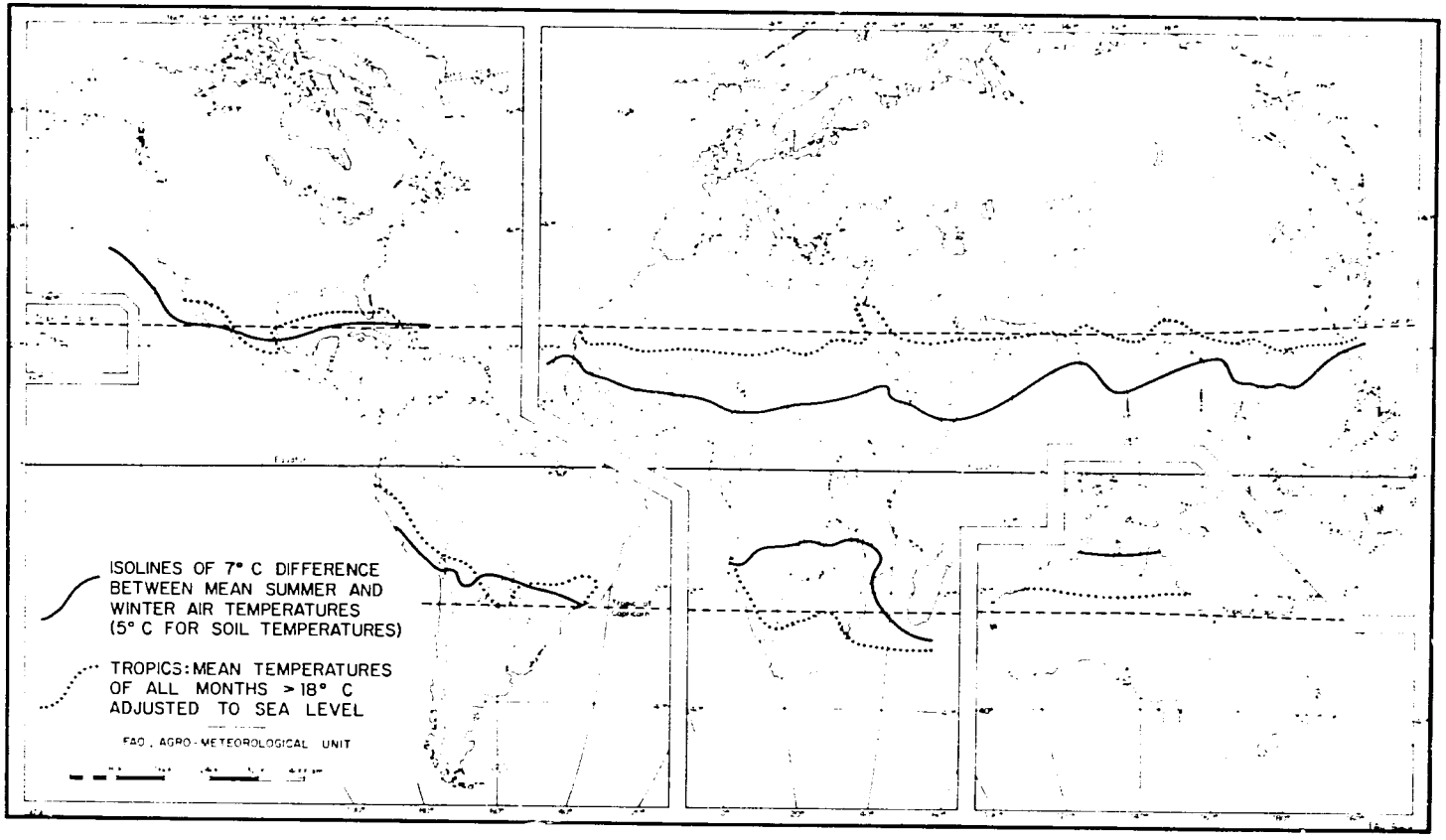
THE TROPICAL ENVIRONMENT

The most common definition of the tropics is the astronomical one, which refers to the region of the earth situated between 23.5° north and south of the equator. The area concerned is easy to delimit and quantify: 4.96 billion ha; 38% of the world's landmass spread over Africa (43%), South America (28%), Asia (20%), Australasia (5%), and Central and North America (4%).

Tropics can also be defined as areas having mean temperatures – adjusted to sea level – greater than 18°C in all months. Using these limits, the boundary between tropics and subtropics is shown in Figure 1 (FAO 1979).

Another definition is based on the concept of soil iso-temperature – meaning areas where the difference between winter and summer soil temperatures at 50 cm depth is less than 5°C (USDA 1975). Co-varying properties are the absence of seasonal soil freezing, the absence of concentrated seasonal leaf fall on moist soil, crop growth depending primarily on actual rainfall, and absence

Director, Land and Water Development Division, FAO, Rome.



1. Characterization of the tropical environment according to isotemperatures or mean monthly temperatures.

of growth restrictions due to periodically low temperatures. The isoline of 7°C difference between mean summer and winter air temperatures (Fig. 1), which is estimated to correspond to the 5°C soil iso-temperature boundary, considerably reduces the *tropical area.* The semiarid and arid areas of southern Bolivia, northern Chile, and northern Paraguay, the frost-prone areas of southern Brazil, the northern part of the Sahelian belt, northern and central India, southern China, and the arid and semiarid areas of Australia located between the Tropics of Cancer and Capricorn lie outside the iso-temperature zone.

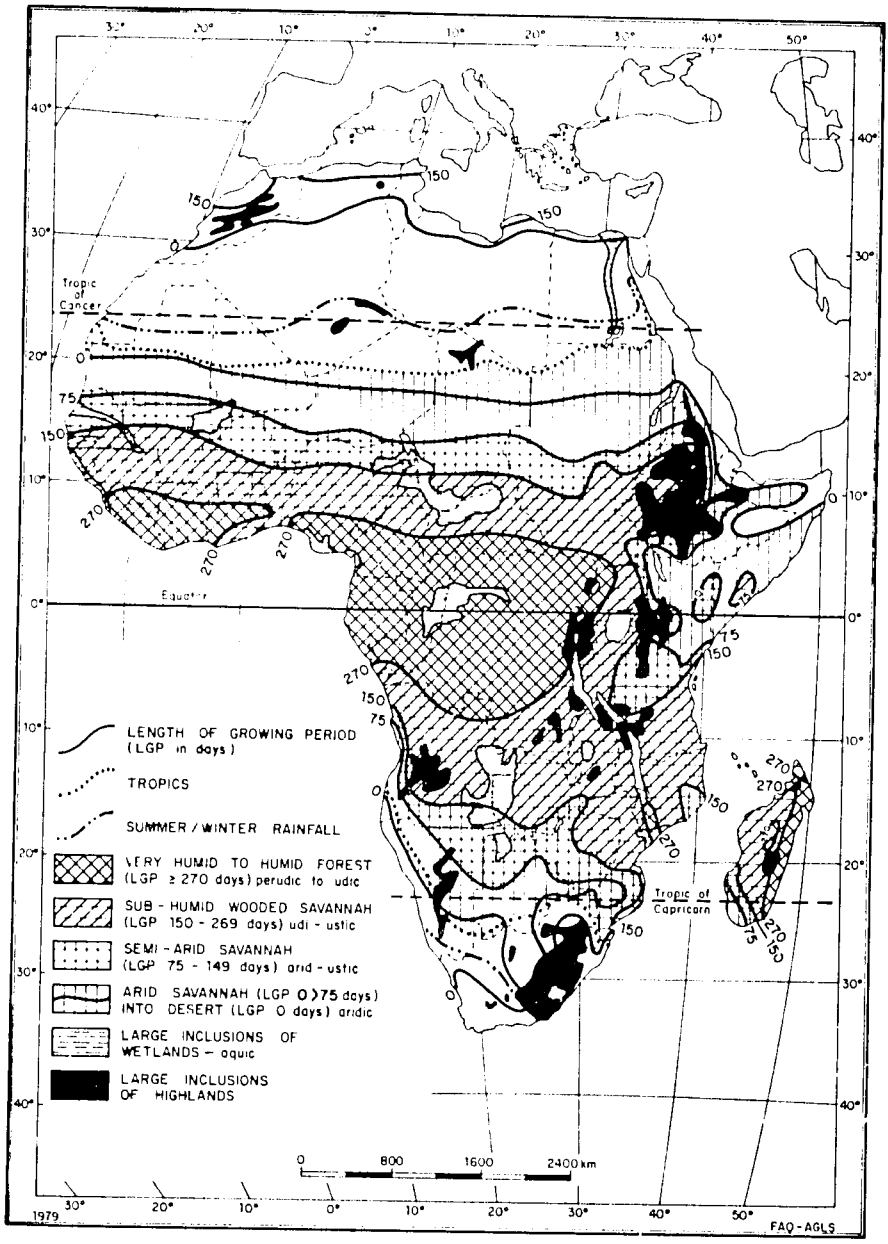
The question arises, however, whether air temperature does not have more interpretative value than soil temperature in the tropics. Soil temperature is not a limiting factor to crop growth while air temperature governs photosynthetic efficiency. In the tropics this efficiency is lower as a result of continuing plant respiration during warm nights. A boundary determined by an air iso-temperature may be more appropriate.

To separate areas of widely varying moisture conditions within the tropics, a subdivision is made according to different lengths of growing period. By growing period is meant the number of days during a year when precipitation exceeds half the potential evapotranspiration, plus the time required to evaporate an assumed 100 mm of soil moisture reserve. The calculation of the growing period is based on a simple water balance mode, comparing precipitation with potential evapotranspiration. Zones with similar lengths of growing period are delineated by constructing isolines at intervals of 30 days (e.g. 90–119 days, 120–149 days, 150–179 days, etc.). An additional isoline for a growing period of 75 days is included to cover possible interpretations for pearl millet in drier areas (FAO 1978b).

The projection of the growing periods on a soil resource base makes it possible to differentiate major agroecological zones that lend themselves to a comparative study of land use potentials. Five major zones have been separated: humid, sub-humid, semiarid, arid, and wetland (Fig. 2). This subdivision correlates broadly with different soil patterns and different types of natural vegetation, as shown in Table 1. These zones correspond with the bioclimatic regions recognized in Africa by Phillips (1959) and with the moisture regimes used in the USDA *Soil Taxonomy* (USDA 1975). A further subdivision of the ustic moisture regime was made into udi-ustic and arid-ustic, in line with current proposals in this respect (Tavernier and Van Wambeke 1978). Table 2 shows the extension of growing periods in Africa and South America. Although Africa covers over 40% of the tropical world, it is actually South America that has the largest extent of humid tropics.

SOILS OF THE TROPICS

Soil conditions listed in Table 1 reflect general trends only. The actual soils pattern is determined by differences in age, parent material, physiography, present and past climatic conditions, which even in the tropics show considerable variation (Van Wambeke and Dudal 1978).



2. Major agroecological zones in tropical Africa (Table 1).

Table 3 shows the distribution of major soils in the forest and the wooded savannah zones of Africa. The table lists soil associations named after the dominant soils. The extension of these soils obviously varies from the extent of the associations – which also include other soils – but Table 3 merely aims at

Table 1. Major agroecological zones in the tropics.

Zone (moisture regime)	Growing period (days)	Rainfall	Saturation deficit during dry season	Dominant soil conditions
Very humid to humid forest (perudic to udic)	≥270	High to excessive; reliable	Negligible to slight	Soils with oxic or deep argillic B horizon, low cation exchange capacity (CEC), low base saturation
Subhumid wooded savannah (udi-ustic)	150–269	Moderate to high; reliable to fairly reliable	Moderate to high	Soils with argillic or oxic B horizon, low CEC, medium to high base saturation; locally, soils with high CEC and expanding clays
Semiarid savannah (arid-ustic)	75–149	Slight to moderate; unreliable	High	Soils with argillic or cambic B horizon, high CEC, high base saturation; frequent occurrence of soils with expanding clays
Arid savannah into desert (aridic)	<75	Very slight to nil; very unreliable	Very high to excessive	Weakly differentiated soils, or with cambic or argillic B horizon; often saline, sodic, calcic, or gypsic properties
Wetlands (aquic)	occurring as inclusions in above zones			Soils with gleyic and histic horizons

Table 2. Major agroecological zones in tropical[a] Africa and South America.

Length of growing period (days)	Africa[b]		South America[c]	
	Area (million ha)	%	Area (million ha)	%
≥270	446	21.0	819	65.9
150–269	716	33.6	265	21.3
75–149	262	12.3	66	5.3
<75	705	33.1	93	7.5
Total	2129	100.0	1243	100.0

[a]The term tropical refers to areas with mean monthly temperature of more than 18°C – adjusted to sea level – in all months of the year. [b]Total area in Africa is 3,011 million ha; % tropical is 70.90. [c]Total area in South America is 1,766 million ha; % tropical is 70.38.

illustrating the soil distribution that is characteristic of these two major zones.

Ferralsols, Nitosols, and Acrisols, which are soils with low clay activity and low base saturation, occupy a large part of the humid tropical zone, but are by no means dominant throughout. Vast areas are occupied by weakly differentiated

Table 3. Estimated distribution of major soils in the humid forest and subhumid wooded savannah zones of Africa (FAO 1976).

Soil association dominated by[a]	Forest zone (growing period ≥270 days)		Wooded savannah zone (growing period 150–269 days)	
	Area (million ha)	%	Area (million ha)	%
Ferralsols	180	40.4	136	19.0
Nitosols	46	10.3	44	6.2
Acrisols	32	7.2	47	6.6
Luvisols	10	2.2	152	21.2
Vertisols	3	0.7	43	6.0
Planosols	–	–	2	0.3
Arenosols	53	11.9	59	8.2
Regosols	12	2.7	37	5.2
Cambisols	20	4.5	32	4.5
Andosols	1	0.2	1	0.1
Podzols	1	0.2	2	0.3
Fluvisols	9	2.0	28	3.9
Gleysols	55	12.3	48	6.7
Histosols	2	0.5	3	0.4
Solonchaks	–	–	1	0.1
Lithosols	13	2.9	71	9.9
Other soils	9	2.0	10	1.4
Total	446	100.0	716	100.0

[a]Terminology used in the Legend of the Soil Map of the World (FAO 1974). Correlation with the USDA *Soil Taxonomy* is given in the section "Soil-related constraints."

coarse-textured soils – Arenosols and Regosols; hydromorphic soils – Gleysols, Fluvisols and Histosols – are important elements of the landscape. Luvisols and Vertisols occur locally on basic parent materials. Podzols, which occur frequently as inclusions in Arenosol associations, extend beyond the few areas where they are mapped as dominant.

In the subhumid wooded savannah zone, Luvisols, mostly of low clay activity, are more extensive. Ferralsols – mainly orthic and rhodic groups – occupy 20% of the area, while acric and xanthic groups are more characteristic of the humid zone. Vertisols and Planosols are more extensive. Arenosols and Regosols occupy vast stretches.

In the semiarid savannah zone, Luvisols, with high clay activity, and Cambisols and Vertisols are prominent. Planosols become important. Saline and sodic soils are locally dominant. Arenosols and Regosols cover large areas and Xerosols appear.

The aridic savannah and desert areas are dominated by Xerosols, Yermosols, Solonchaks, Regosols, and Lithosols, but areas with an aridic moisture regime are very limited in the tropics.

The trend reflected by the soils pattern in tropical Africa is similar to that in the other continents, although the proportion between major groups may differ. Andosols are more prominent in Central America, South America, and Southeast

Asia. A recent review (Sombroek 1979) realized that Podzols are very extensive – as much as 20% of the landscape – in the northwestern part of the Amazon basin. In Southeast Asia Acrisols are more extensive than Ferralsols; Histosols and Fluvisols occupy vast stretches in the coastal plains (Dudal et al 1976). In the semiarid zone, Vertisols are particularly prominent in the Indian subcontinent, much more so than in northeastern Brazil. Hardened or concretionary ferruginous layers occur locally in the humid zone but they are more widespread in the subhumid wooded savannah associated with Luvisols, Nitosols, and Acrisols rather than with Ferralsols.

SOIL-RELATED CONSTRAINTS

Soil-related constraints have had a major influence on the economy and the distribution of population in the tropics. It is striking that all countries in the tropical belt belong to the developing world and have problems of food production and low incomes in the rural sector. In the humid tropics, populations are concentrated on river and coastal alluvial plains and in volcanic areas, even though vast stretches of land – acid or wet – are still available. In the subhumid wooded savannah zone, population per unit area is denser and more dispersed but concentrations are also on the more fertile soils.

Reports on *problem soils* in the tropics refer mostly to *infertile red soils* – Ferralsols and Acrisols – of medium to heavy texture. Though these soils are indeed prominent, especially in the humid tropics, a number of other soils are equally important features of the tropical environment. Constraints are, therefore, briefly enumerated, by major soil group, to make it possible to assess their importance and occurrence in terms of geographical distribution and area coverage. Constraints and management practices have recently been comprehensively reviewed in relation to the properties of soils in the tropics (Sanchez 1976).

Ferralsols (Oxisols)[1]

Constraints with Ferralsols result from a low level of plant nutrients, low cation exchange capacity and weak retention of bases applied as fertilizers or amendments, and strong fixation and deficiency of phosphates on fine-textured soils. Also included are sulfur deficiency; nitrogen losses through leaching in the high-rainfall areas unless a continuous plant cover ensures rapid recycling; acidity; exchangeable aluminum, which at high saturation becomes toxic to plants; and very low calcium content resulting in limited rooting volume and increased hazard of moisture stress. Trace element deficiencies are frequent. Microelement toxicities may occur, especially in soils formed from ultra-basic rocks.

The degree of the constraints varies considerably between the different kinds of Ferralsols. Acric Ferralsols show a higher aluminum toxicity than the orthic ones, which in turn have higher aluminum contents than the rhodic groups (Van

[1]Equivalents in USDA *Soil Taxonomy* are given in parentheses.

Wambeke 1974). Within the humid zone, Ferralsols under semideciduous forest have a considerably higher content of plant nutrients in the surface layer than those under evergreen forest (Sys 1976). Coarse-textured Ferralsols are less prone to phosphate fixation, but they are less resistant to erosion than the better structured clayey ones.

Acrisols (Ultisols, pp.)[2]
Acrisols have constraints of low nutrient levels, presence of exchangeable aluminum, nitrogen losses through leaching under high rainfall, and trace element deficiencies, e.g. boron and magnesium. Nutrient reserves are concentrated in the surface horizon and their maintenance depends on a continuous recycling through vegetation unless fertilizers are added. An additional constraint is sensitivity to erosion because of less favorable structure in the surface layers and the decrease of permeability in the argillic B horizon. Short-term surface waterlogging may occur during heavy rains. Acrisols are easily damaged by compaction and loss of surface soils when heavy equipment is used for deforestation or tillage operations. With adequate management, the presence of the argillic B horizon is an asset for moisture retention.

Nitosols (Paleudults, Paleustults, Paleudalfs, Paleustalfs, pp.)
Nitosols have a nutrient deficiency status similar to that of Ferralsols but less acute. A subdivision is made in dystric and eutric Nitosols, the latter having medium to high base saturation and hence no constraints of exchangeable aluminum. Moderate phosphate fixation occurs. Manganese toxicity may arise in the more acid Nitosols. The deeply stretched argillic B horizon and the progressive textural change favor moisture retention and reduce the hazard of erosion to which Acrisols are subjected.

Luvisols (Alfisols, pp.)
By definition Luvisols have a moderate to high base status and do not have major constraints related to acidity, calcium deficiency, or phosphate fixation. Luvisols straddle the subhumid and the semiarid zones. In the former, they often occur on strongly weathered parent materials, the clay fraction of which is of low activity (Moormann et al 1975). Hence the total amount of plant nutrients is still low and major elements are deficient. In the semiarid zone, Luvisols develop from a variety of parent materials – generally less strongly weathered – which determine their chemical composition. The saturation complex is dominated mostly by calcium, as a result of which microelement deficiencies – e.g. zinc – may occur. Moisture stress and sensitivity to erosion, particularly when there is inadequate crop cover, are major constraints (Krantz et al 1978). Low aggregate stability and surface sealing by rains, resulting in increased runoff and impeded plant germination, are common in Luvisols. In the subhumid wooded savannah,

[2]pp. = pro parte, i.e. the two terms correspond only in part.

subsurface layers of plinthite, ferruginous concretions, or hardpans are present over relatively large areas. Erosion is then particularly damaging, because layers unfit for production are surfacing irreversibly.

Vertisols (Vertisols)
Constraints with Vertisols are related to their physical properties and moisture regime. Their heavy texture and the presence of expanding-type clay minerals result in a very narrow range between moisture stress and water excess. Tillage is hampered by stickiness when wet and hardness when dry. Base saturation is high, with calcium and magnesium prevailing in the sorptive complex. Phosphorus availability is generally low. Erosion during fallow and seasonal waterlogging are serious hazards to crop production. They can be overcome through appropriate management practices (Krantz et al 1978).

Planosols (Albaquults, Albaqualfs)
The occurrence of Planosols in flat or depressed topography and the slow permeability of the subsurface horizons result in very slow external and internal drainage. Waterlogging in the wet season and acute water stress in the dry season are major constraints to crop production. Strong leaching and low cation exchange capacity in the surface horizons entail nutrient deficiencies. Aluminum toxicity may occur in strongly developed Planosols. When Planosols are used as rangeland copper and cobalt deficiencies often have to be remedied (Dudal 1973).

Arenosols (Psamments, pp.)
The low productivity status of the Arenosols is linked with a general paucity of nutrients in coarse-textured quartzy materials, low water retention, low cation exchange capacity, and a deficiency in minor elements normally bonded to the clay or organic matter (zinc, manganese, copper, iron). The efficiency of applied nutrients, especially nitrogen, is impeded by strong leaching. Sulfur and potassium deficiencies are common in the Arenosols. Weak structure leads to compaction and favors water and wind erosion. These characteristics equally apply to large areas of coarse-textured Regosols.

Andosols (Andepts)
The presence of amorphous hydrated oxides in Andosols induces a very high phosphate, borate, and molybdate fixing capacity. In basic volcanic ashes, nutrient imbalances may occur in the presence of a high proportion of ferromagnesium minerals, which by weathering provide a dominance of magnesium over calcium in the exchange complex. Aluminum toxicity is frequent in the more acid Andosols. Manganese deficiencies occur.

Podzols (Spodosols)
Nutrient deficiencies in Podzols are acute and related to coarse-textured quartzy materials, excessive leaching, and the formation of complex organic matter-

metallic compounds. There is a general lack of nitrogen and potash, and phosphate availability is reduced by the presence of exchangeable aluminum. Improvement of the Podzols is hampered by an extremely low retention capacity and rapid losses of applied nutrients. Copper and zinc deficiencies are common. Most of the Podzols in the tropics are of the groundwater type and have waterlogging during the wet season and water stress during drier weather. Shifting cultivation on these soils is hazardous because of very slow regeneration of the natural vegetation.

Cambisols (Tropepts)
Constraints on the various types of Cambisols (vertic, ferralic, calcic, dystric, gleyic) are similar, but normally less strongly pronounced than those of the more developed soils with which they are associated: Vertisols, Ferralsols, Luvisols, Acrisols, Gleysols.

Xerosols (Aridisols, pp.)
Moisture stress is the most serious limiting factor to plant growth on Xerosols. When water is available, fertility problems may result from high calcium carbonate content, reduced availability of phosphorus, salinity and alkalinity hazards, and deficiencies of iron and zinc. Xerosols with high gypsum contents may cause serious engineering problems for irrigation construction.

Yermosols (Aridisols, pp.)
Drought is a permanent feature with Yermosols. When irrigation is applied, fertility problems and salinization hazards are similar to those described for Xerosols.

Solonchaks (Salorthids and saline phases, pp.)
As a result of the high concentration of salt in the soil solution, moisture stress and hindrance to normal ion uptake by plants are major constraints in Solonchaks. Depending on the nature of the salt present, different elements may be in excess. The economic implications of reclaiming saline soils are a major constraint to increased production.

Fluvisols (Fluvents)
The great variability of the Fluvisols does not permit a characterization of the nutrient status for the group as a whole. The fertility of Fluvisols is directly related to the materials from which they are derived, which are not necessarily those adjacent to their location. Flood hazard is a common constraint on Fluvisols, especially in areas with seasonal rainfall patterns. Special mention should be made of thionic Fluvisols, which are widespread in the tropics. Waterlogging under natural conditions, and extreme acidity upon drainage leave a very narrow margin for the management of these soils. The very low pH is accompanied by toxicities of aluminum, manganese, and iron.

Gleysols (Aquepts, Aquents)
Water excess is a major feature of Gleysols. Their base status is usually related to the nutrient content of the surrounding upland soils. The effectiveness of nitrogen application is hampered by denitrification under wet conditions. Profile development varies considerably and determines the response to management techniques. In the humid and subhumid zones, Gleysols often show plinthite or concretionary layers in depth. Drainage designs should take account of these phenomena so as to avoid hardening or pan formation.

Histosols (Histosols)
Waterlogging, low bearing capacity, weak foothold for plants, subsidence upon drainage, frequent microelement deficiencies – e.g. copper – and irreversible shrinking of the organic material upon drying are major constraints to agricultural production on Histosols (Soepraptohardjo and Driessen 1976). Acid peats are very low in major nutrients. Soils that contain 60% or more organic matter on a dry weight basis show silica deficiency in plants that require this element for tissue strength. Poor accessibility and lack of infrastructure hinder reclamation of the Histosols.

It is obvious that the relationships that have been discussed are of a general nature and that constraints need to be specifically determined through a more precise characterization of soils, climates, and types of land use. Different crops, even their different varieties, may react very differently to certain soil properties. Tea is known to thrive in soils with relatively high exchangeable aluminum, but soybean yields decrease with increasing aluminum saturation. Cassava is more phosphate-efficient than maize. Waterlogging is damaging to yams but may not be a major constraint for rice. Furthermore, not all characteristics important to plant growth are reflected by taxonomic units. Stoniness, slope, texture of the surface layer, flood hazard, crusting or slaking, and erodibility are all properties that strongly influence crop growth. They may constitute constraints that are even more important than those related to the diagnostic criteria used in soil classification (Dudal 1978).

In general, most importance seems to be attached to nutrient deficiencies. But additional attention should be given to physical soil characteristics with special reference to erodibility, workability, and water storage capacity. Hazards of soil erosion, compaction, waterlogging, and moisture stress are often recognized only when the damage has been done.

OTHER OBSTACLES TO INCREASED PRODUCTION

The problems arising with the management of soils in the tropics can be serious obstacles to the intensification of agriculture and to ensuring sustained production from new lands in these regions. Since major constraints are known and the means to overcome them have been proposed, one would assume that the potential of soils of the tropics can now be fully developed. In reality, progress

has been slow and agricultural production is falling short of needs. The African situation is a case in point.

The total extent of African land variously suited to the production of one or more food crops is estimated at 625 million ha, which is about 20% of the continent's landmass. It is estimated that 196 million ha are presently cultivated, out of which – taking into account requirements for fallow – 108 million ha are harvested yearly. Average yields are between a third and a fourth of those that could be obtained with a high level of inputs.

The availability of land resources on the African continent stands out sharply against the current food situation in this region. During the period 1964–74 the food self-sufficiency of Africa declined from 98 to 90%. During the 1970s the per caput production of food crops declined by 1.4%/year. The average annual growth of population during the last 10 years has been 2.6%, greatly exceeding an average annual 1.3% increase of food production. The same contrast exists between the land resources available on a worldwide basis and the increase in the number of people who are undernourished.

An overall blueprint for restoring food self-sufficiency in Africa by 1990 was recently prepared (FAO 1978a). The Food Plan foresees how a production increase for the region as a whole could be derived – 53% from area expansion and 47% from yield increases. An additional 31 million ha would need to be taken into cultivation by 1990, of which 3 million ha would be irrigated (1.5 million ha south of the Sahara). The use of agricultural inputs would need to treble. Eradication of trypanosomiasis, undertaken progressively, would open up a potential of 700 million ha for cattle raising. It is estimated that US$ 27 billion (at 1975 prices) would be required to achieve this goal. An additional US$ 6.5 billion worth of inputs would be required annually by 1990.

Lands for the expansion of food crops are available and from an agroecological point of view the targets of the Food Plan can be attained. However, there are a number of prerequisites.

- Economic motivation of the small farmer is essential if he is to use agricultural inputs and implement technical recommendations for land improvement and soil conservation.
- Suitable areas are unevenly distributed, which means that inter-African trade will need to be intensified.
- In countries where foreign exchange is obtained from agricultural exports, competition for land between cash crops and food crops will need to be resolved.
- Expansion of arable land will require selective mechanization because tsetse fly infestation impedes a more extensive use of animal power.
- The small size of farmsteads may call for a community approach to land reclamation measures, such as irrigation, soil conservation, and salinity control.
- Full use will need to be made of results of research in order to make effective use of labor and financial resources.
- Additional research will need to be guided by constraints identified by the farmers themselves. Involvement of the farmer community in establishing priorities is urgently needed.

Although these constraints are not directly soil-related, it is important that they be fully recognized, so as to place soil research in a perspective of overall development.

A GLOBAL LAND EVALUATION

To meet food requirements for the populations of the future, it is estimated that agricultural production must increase by 60% by the year 2000. The greatest share of this increase is expected to come from intensification of agriculture, especially in developing countries, while the remaining part will need to be produced on new arable land – as much as 200 million ha, mainly in the tropics. How will these lands respond to intensification; which are the lands to be opened up for cultivation?

Being increasingly concerned with development, the evaluation of land needs to be dynamic and to reflect the response of the natural environment to changes in input and production objectives (Smyth 1979). Planning of improved and future land use requires an appraisal of available land resources based on the following principles (FAO 1977):

- Land suitability is only meaningful in relation to a specific use, e.g. land suited to the cultivation of cassava is not necessarily suited to the cultivation of pearl millet.
- The evaluation of production potential needs to be made in respect of specified input levels, e.g. whether fertilizers are being applied, if pest control is effected, if machinery or hand tools are being used.
- Suitability must refer to use on sustained basis; that is, the envisaged use of land must not result in its depletion, e.g. through erosion.
- Evaluation involves comparison of more than one alternative type of land use, e.g. suitability for millet or sorghum or corn, and not just for a single crop.
- Different kinds of land use are compared at least on a simple economic basis; that is, suitability for each use is assessed by comparing the value of the produce to the cost of production.
- A multidisciplinary approach is adopted with the evaluation based on inputs from crop ecologists, agronomists, climatologists, and economists, in addition to those from soil scientists.

At first sight, the principles proposed do not seem unprecedented, but in practice they call for a considerable change in traditional resource interpretation. First of all, the concept of land evaluation is wider than the appraisal of soil qualities or constraints, to which suitability classifications are sometimes limited. Land is defined geographically as a specific area, the attributes of which relate to soils, geology, hydrology, plant and animal population, climatic conditions, and the results of past and present human activities to the extent that these attributes exert a significant influence on present and future uses. The physical resource base needs to be matched with prevailing social, economic, and health conditions, which may considerably alter production perspectives. Fertile valleys in Africa remain unproductive as a result of river blindness. Expansion of agriculture is impeded by trypanosomiasis affecting draft animals. Weed infestation

is a major obstacle to the growth of food crops in the tropics. Radiation is 40% higher in the savannah zone than in the forest zone (Kassam and Kowal 1973). The fundamental concept is that land evaluation is wider than the appraisal of soil qualities or constraints and that it is meaningful only in relation to a clearly defined use under conditions prevailing at a specific date.

In this respect additional research is required to establish the relationship between soil and climatic parameters and the requirements of different crops. Furthermore, because soil, among environmental variables, is responsive to controlled change, the study of this capacity for change and for response may be no less important than the survey of permanent characteristics that are currently used as criteria in soil classification. An understanding of the changes that take place in the surface horizons, in which organic matter and plant nutrients are concentrated, seems crucial to the choice of inputs and to the design of management systems that will maintain or improve productivity in the tropics (Smyth 1979).

The focus in this paper on soil-related constraints should not detract from the considerable potential that the tropics offer for increased agricultural production. However, types of land use will need to be carefully selected and adapted to the physical resource base and to the socioeconomic conditions which prevail in the different countries of the tropical belt.

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Discussion summary

Session I.
J. F. Metz, Jr., chairman; G. Alcasid, Jr., reporter.

Toward an internationally coordinated program for research on soil factors constraining food production in the tropics, by L. D. Swindale

Comments and questions focused on problems of establishing a coordinating mechanism, the use of the soil benchmark concept versus other approaches, the need for developing strong national research programs, and the need for linking an international soils center or coordination program with crop research and socioeconomic studies.

The suitability of the benchmark soils concept as a basis for coordinating international soils research was questioned. Dr. Swindale responded that the benchmark approach provides the logical basis for coordination of research, not the institutional framework. Benchmark sites must be part of a logical taxonomic framework to be used for predictive purposes. Benchmark sites in different parts of the world will be on different soils.

A comment was that the benchmark soils network does not provide for geographical extrapolation of information. It was suggested that it be reinforced by a *land system* approach such as that developed at CIAT for describing agricultural land resources. This is basically compatible with the benchmark project philosophy and could enhance its effectiveness.

Some participants suggested use of benchmark farming systems, rather than a straight benchmark soils program, as a framework for research. Several cited the importance of climatic and socioeconomic factors in accounting for variability in production systems, and felt that those should be taken into account.

A comment was that soil mapping is as important as soil classification because it accounts for soil variability. Mapping should include other aspects of land, including climate, vegetation, hydrology, etc., and then be combined and translated into systematic land evaluation geared to different farming systems.

The group expressed concern about the effect of international research networks on resources for national programs. There is ample evidence of networks' positive effects on national programs, including greater focus on country problems, improved quality of research in the countries, more resources from national sources and outside donors, and improved training of national research staff.

Several participants noted the need for strengthening national research capability as a first step. There is a need for outside funds with which to construct and equip suitable laboratories to do soils research. Limited resources of developing countries and limited foreign exchange are constraints to getting the job done. It was asked whether the International Service for National Agricultural Research (ISNAR) could participate in strengthening national soil research centers. The response was that ISNAR could assist national governments in obtaining funds and strengthening soils research programs.

A question was raised about existing obstacles to the establishment of an international network or center, which was first proposed 8 years ago. Swindale and Brady commented that the gestation period for such an idea is long and it must be recognized that not all people share the view that such a coordinating effort is needed or desired.

In response to a question about possibilities for funding an international cooperative effort, Dr. Swindale replied that he questioned whether funds will be available for some time. However, an informal start could be made with the cooperation of scientists and especially among national and international research centers.

A comment was that any international soils center or coordinating body must have a strong link with crop research scientists and those involved with socioeconomic studies. There is some concern that donors would see a soils center as focusing on specialized narrow problems and lose sight of the role of soils research in increasing food production.

Soil-related constraints to agricultural development in the tropics, by R. Dudal

The statement that measurements of radiation could be as important as those of moisture and temperature in determining potential for food production in different parts of the tropics was followed by the comment that CIAT separates the major vegetation patterns in tropical South America on the basis of total wet-season evapotranspiration (TWPE) and temperature regimes. The TWPE concept will have practical application in the transfer of germplasm of perennial crops and annual crops.

High soil temperatures were mentioned as a limiting factor to crop production in many regions of the tropics. Early-season soil temperatures exceeding 40°C at 5-cm depth for a period of 4 to 6 hours a day are not uncommon in many upland soils. Crops such as maize and soybean may have 20–50% yield depressions solely due to high soil temperature. Improved research methodology for soil temperature in relation to crop growth is needed.

Soil depth was listed as a soil characteristic but not as a soil-related constraint to crop production. Experience shows it is one of the most important factors in agricultural productivity because it affects root penetration. The effect varies by crop and is more important for maize and cotton than for pigeonpea or millet. Soil depth should be considered as a major constraint.

Several questions were directed to Dr. Dudal. What would be the quantitative criterion for separation or subdivision of an ustic soil moisture regime? He said that the FAO agroecological zone study made a break at the 150-day growing period, distinguishing an udic-ustic regime (150–269 days) and the arid-ustic regime (75–149 days).

Another question concerned the influence of the top 10 cm of soil on the benchmark soil concept based on soil families. Dr. Dudal replied that the benchmark concept does not have to be limited to the soil family. It could be broadened to include data on the surface layers.

There was a clear call for more research and by the conference participants. Additional research should establish the relationships between edaphic and climatic parameters and the requirements of important food crops. It was also suggested that further research define agroecological zones. It should go beyond measuring the difference between rainfall and potential evapotranspiration, and should determine the start and cessation of rains and the possibility of drought during growth periods. Additional attention must be given to characteristics of soil surface layers, including the changes that take place after land development.

An international committee to study soil moisture and temperature regimes is being organized and is scheduled to meet next year.

In his paper Dr. Dudal called the attention of soil scientists to constraints to increased agricultural productivity that are not soil-related. He restated this after the presentation. Biological and physical scientists must be prepared to do interdisciplinary research – including research that considers the socioeconomic constraints – and to work with economists, sociologists, and anthropologists as members of the team. Special consideration should be given to the problems of the operators of small farms.

It was noted that Dr. Dudal's paper made no reference to soils of tropical highlands such as in East Africa and South America where most of the potentially productive soils are found. Dr. Dudal replied that there is a further division of soils into lowiands and highlands, but definitions of these divisions were not within the scope of his paper.

The suggestion was to refer to *Soil taxonomy* and the French classification system in addition to the FAO/UNESCO terminology. The author indicated that the final draft of his paper would include a correlation of *Soil map of the world* with *Soil taxonomy*.

Other issues were identified by the speaker: additional work is required to complete the survey of soils in the tropics because many areas are still not well known; there is great variability in soils of the tropics. therefore, constraints have to be quantified and expressed in terms of specific land utilization types.

OCCURRENCE OF MAJOR SOILS CONSTRAINTS

Soil-related constraints, soil properties, and soil taxonomy: a terminology for exchange of scientific information

W. M. JOHNSON

Soil taxonomy (USDA 1975) is a multicategoric system of soil classification based on concepts of real bodies of soils but influenced by modern theories of soil genesis. The diagnostic horizons and features used as differentiae are defined as quantitatively as present knowledge permits. The system is unique in employing soil temperature and soil moisture criteria at several levels. The nomenclature is uniform, systematic, and connotative. Thus, *Soil taxonomy* is particularly effective among soil classification schemes as a communications medium for scientific knowledge. It furnishes much of the soil information required to estimate potential production levels of specific crops on a given kind of soil. Special interpretive groupings of soils are helpful in conveying information on soil constraints and potentials to both scientists and laymen who are not familiar with details of *Soil taxonomy.*

Soil taxonomy (USDA 1975) is a multicategoric system of classification that attempts to include all known kinds of soils. It was designed to consider current theories of soil genesis, but the differentiating criteria are characteristics of the soils themselves, expressed as objectively and quantitatively as possible, so as to maximize uniformity in classification performed by scientists all over the world. The system was created to support soil surveys and the interpretations of soil surveys that are required by both developing agriculture and advanced farming methods. The system is flexible. It consists of classes that can be grouped or

Soil Conservation Service, U.S. Department of Agriculture, P.O. Box 2890, Washington, D.C. 20013.

subdivided and regrouped for the most effective kinds of interpretations of responses to soil treatments and management systems. The *taxonomy* is open-ended, permitting addition of new classes as they are identified and defined. Unlike many classification systems used in different times and places, *Soil taxonomy* is based on concepts of real bodies of soils, not on abstract theories of soil genesis or soil geography.

STRUCTURE OF SOIL TAXONOMY

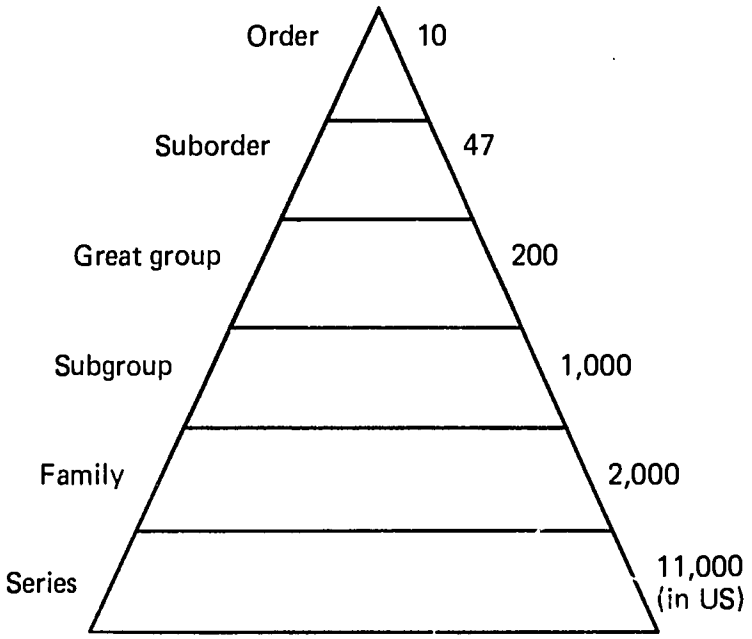
There are six categories in *Soil taxonomy*. In order of decreasing rank and increasing number of classes they are: order, suborder, great group, subgroup, family, and series. Figure 1 illustrates the hierarchical relationship and indicates the number of classes in each category. The number of soil series -- about 11,000 -- represents the present state of knowledge of the United States alone. Soil series are not recognized in many countries, and the total number theoretically occurring in the world can only be guessed at.

NOMENCLATURE

A new nomenclature was created along with *Soil taxonomy*. The importance and impact of soil names can scarcely be exaggerated. During the developmental years between 1951 and 1965, the various approximations to the final system employed decimal numbers rather than names, because disputes over the interpretation of soil names were seen to interfere with understanding and evaluation of the new principles being tested. The nomenclature was improvised from appropriate Greek and Latin roots to make the new class names as connotative as possible. The nomenclature was designed so that class names also are indicative of the category in the system. Because of the classical roots, the new terminology requires little translation in many languages. The name of each soil order, suborder, great group, subgroup, and family indicates the class in all categories of which it is a member. Soil series names are taken from local geographic features, and so indicate only the series -- they do not convey any information about the order, suborder, or other high category.

The names of all orders end in *sol*. Each order name contains a formative element that identifies that order in the names of suborders and lower categories. The formative element in the order Ultisol is *ult*. In the order Oxisol it is *ox*. The formative elements make the endings of names of suborders, great groups, and subgroups. Thus, all class names ending in *ult* are of soils in the order of Ultisols. Names ending in *ox* are names of taxa that belong to the order Oxisols.

Suborder names consist of exactly two syllables. The first indicates the diagnostic properties of the soils, the second is the formative element taken from the order name. The suborder of Ultisols that has an aquic moisture regime throughout is called Aquults (L. *aqua*, water, plus *ult* from Ultisol). Oxisols that have a torric moisture regime are in the suborder Torrox.



1. The categories of *Soil taxonomy* and approximate number of units in each category.

Great group names have three or four syllables. They include the name of the suborder and one or two additional formative elements that suggest important diagnostic properties. Aquults that have a fragipan are called Fragiaquults.

Names of subgroups are created by modifying the great group names with one or more adjectives. The adjective *typic* is applied to the subgroup thought to be typical of the great group. Intergrade subgroups are those that belong to a given group, but also have some property or properties of another order, suborder, or great group. For example, Humoxic Tropohumults are humus-rich Ultisols, usually dark-colored, with an isomesic or warmer iso-temperature regime, and their clay fraction has low activity. Extragrade subgroups belong to a given great group, but also have important characteristics that do not indicate a transition to any other known kind of soil. For example, Plinthic Fragiaquults have plinthite in the fragipan making up from 5 to 50% of the matrix.

Soil family names are polynomial. Adjectival modifiers of the subgroup name indicate particle-size class, mineralogy class, temperature regime, and in a few families, soil depth, consistence, moisture equivalent, and other properties. An example is coarse-loamy (particle-size), siliceous (mineralogy class), thermic (soil temperature) Typic Fragiaquults.

Examples of formative elements used in forming class names are in Tables 1 and 2. Formative elements in order names suggest the soil characteristics only in a very general sense, but many of the elements used in suborder and great group names have clear connotations and can be interpreted in terms of production constraints and management requirements. Prominent examples are *aqu* (L. *aqua*, water), connoting an aquic moisture regime; *xer* (Gr. *xeros*, dry), connoting a xeric moisture regime; *sal* (L. base of *sal*, salt), denoting the presence of a salic (highly saline) horizon; and *sulf* (L. *sulfur*, sulfur), denoting the presence of sulfides or their oxidation products.

Thus, from the class names alone it is possible to interpret many of the important characteristics of the soils. For example, one relatively extensive kind of soil in some tropical regions is a member of a clayey, oxidic, isohyperthermic family of Typic Acrorthox. This is believed to be the typical subgroup of Acrorthox. The Acrorthox is the most strongly weathered of the common Oxisols; the clay fraction consists of 20% or more extractable iron oxide plus gibbsite; cation exchange capacity and base saturation are very low; and phosphate-fixing power is great. The lower part of the oxic horizon has a net positive charge. Biologic activity is constrained by extremely low level of calcium below the upper few centimeters. Productivity is so low that these soils are little used for crops. The mean annual soil temperature is 22°C or higher, and the difference between mean summer and mean winter soil temperature is less than 5°C.

TEMPERATURE AND MOISTURE REGIMES

Soil taxonomy is the only major soil classification scheme that directly uses soil moisture and soil temperature values as differentiae among classes. The climatic criteria are not all used at one categorical level, but in various levels above the soil series. There were two important reasons for using climatic criteria; first, temperature and moisture of the soil significantly affect the direction and intensity of soil genesis, and, second, plant growth is strongly influenced by temperature and moisture.

Climatic criteria are used as differentiae at higher categories because of their importance to soil genesis, and at lower categories where they affect principally the growth of plants.

Climatic differentiae may be part of a categorical definition, as in Histosols (wet) and Aridisols (dry). In all orders except Aridisols and Histosols, moisture regime is used to define at least some of the suborders. Temperature regimes are used to differentiate only a few suborders: Tropepts, Borolls, and Boralfs. Temperature and moisture criteria are also used to differentiate some great groups and some subgroups. Finally, soil temperature regimes are prominent differentiae at the soil family level.

There are five classes of moisture regime, ranging from saturated (aquic) to dry (aridic or torric). These are all defined in terms of the proportion of time that the soil is moist during the growing season (USDA 1975).

Table 1. Formative elements in names of soil orders of *Soil taxonomy* (USDA 1975).

Name of order	Formative element in name	Derivation of formative element	Pronunciation of formative element
Alfisol	Alf	Meaningless syllable	Pedalfer
Aridisol	Id	L. *aridus*, dry	Arid
Entisol	Ent	Meaningless syllable	Recent
Histosol	Ist	Gr. *histos*, tissue	Histology
Inceptisol	Ept	L. *inceptum*, beginning	Inception
Mollisol	Oll	L. *mollis*, soft	Mollify
Oxisol	Ox	F. *oxide*, oxide	Oxide
Spodosol	Od	Gr. *spodos*, wood ash	Odd
Ultisol	Ult	L. *ultimus*, last	Ultimate
Vertisol	Ert	L. *verto*, turn	Invert

Table 2. Some formative elements in names of suborders and great groups of *Soil taxonomy* (USDA 1975).

Formative element	Derivation	Mnemonicon	Connotation
	Suborders		
Aqu	L. *aqua*, water	Aquarium	Aquic moisture regime
Bor	Gr. *boreas*, northern	Boreal	Cool
Ferr	L. *ferrum*, iron	Ferruginous	Presence of iron
Hum	L. *humus*, earth	Humus	Presence of organic matter
Psamm	Gr. *psammos*, sand	Psammite	Sand texture
Torr	L. *torridus*, hot and dry	Torrid	Torric moisture regime
Xer	Gr. *xeros*, dry	Xerophyte	Xeric moisture regime
	Great groups		
Alb	L. *albus*, white	Albino	An albic horizon
Calc	L. *calcis*, lime	Calcium	A calcic horizon
Dur	L. *durus*, hard	Durable	A duripan
Dystr, dys	Gr. *dys*, ill, infertile	Dystrophic	Low base saturation
Eutr, eu	Gr. *eu*, good, fertile	Eutrophic	High base saturation
Hal	Gr. *hals*, salt	Halophyte	Salty
Pale	Gr. *paleos*, old	Paleosol	Excessive development
Plac	Gr. *plax*, flat stone	–	Presence of a thin pan
Sider	Gr. *sideros*, iron	Siderite	Presence of free iron oxides
Trop	Gr. *tropikos*, of the solstice	Tropical	Humid and continually warm
Vitr	L. *vitrum*, glass	Vitreous	Presence of glass

Ten soil temperature regimes differentiate classes at various categoric levels in the system. They are:

Pergelic – Mean annual temperature lower than 0°C.

Cryic – Mean annual temperature between 0°C and 8°C.

Frigid – Mean annual soil temperature is lower than 8°C, but the soil in summer is warmer than one in the cryic regime; the difference between mean winter and mean summer soil temperature is more than 5°C.

Mesic – Mean annual soil temperature is between 8°C and 15°C, and the difference between mean summer and mean winter soil temperature is more than 5°C.

Thermic – Mean annual soil temperature is between 15°C and 22°C, and the difference between mean summer and mean winter temperature is more than 5°C.

Hyperthermic – The mean annual soil temperature is 22°C or higher, and the difference between mean summer and mean winter soil temperature is more than 5°C.

If the name of a soil temperature regime begins with *iso*, the difference between mean summer soil temperature and mean winter soil temperature is less than 5°C.

Isofrigid – Mean annual soil temperature is lower than 8°C.

Isomesic – Mean annual soil temperature is between 8°C and 15°C.

Isothermic – Mean annual soil temperature is between 15°C and 22°C.

Isohyperthermic – Mean annual soil temperature is 22°C or higher.

RELATION OF SOIL TAXONOMIC UNITS TO CLIMATIC REGIONS

As explained earlier, *Soil taxonomy* embodies a considerable degree of climatic influence. It must be remembered, however, that the moisture and temperature regimes used to differentiate among soils are classes of *soil temperature* and *soil moisture*. There is, nevertheless, a good deal of correspondence between broad climatic zones and broad soil areas. One does not look for Spodosols in the Sahel or the Kalahari Desert, nor does one expect to find Aridisols on Luzon. Unless they are relicts of earlier environmental conditions, Oxisols and Ultisols are expected in humid tropics and subtropics.

Members of some soil orders, such as Entisols and Inceptisols, are not sufficiently developed to reflect much of the regional climatic regime, so we may find them widely scattered over the globe and associated with a variety of more prominently developed soils – Alfisols, Mollisols, Ultisols, and Oxisols.

Of course, the moisture and temperature regimes used to differentiate among suborders, great groups, subgroups, and families are generally not refined enough to satisfy all the requirements of the agronomist who is seeking optimum growing conditions for specific crops, or who needs a precise estimate of the potential for production of certain food crops in a given locality. For such purposes more refined climatic data, relating both to atmospheric and pedologic conditions, are required.

RELATION OF SOIL TAXONOMIC UNITS TO LANDSCAPE FEATURES

Soil taxonomic units are intimately related to features of the natural landscape. Physiographic position, slope gradient, slope orientation, slope length, and eleva-

tion are reflected in soil temperature and moisture and erodibility and, therefore, in degree of weathering of minerals and strength of development of soil horizons and other diagnostic features. Landscape features also reflect previous geomorphic history, including the development of soils in previous environments, portions or all of which may be preserved at or near the present landscape surface. These, in turn, influence the genesis and characteristics of the contemporary soil mantle. It is difficult to generalize about these relationships across continents at categorical levels above the soil series. To be sure, some landscape relationships are clear and obvious: Entisols are to be found where soil parent materials are so youthful that little differentiation of horizons has occurred – on floodplains, in marshes and deltas, and on recent sandy and silty aeolian deposits; or where erosion is so vigorous that the parent material is worn away more rapidly than the process of soil genesis can cause differentiation of horizons, as in steeply sloping mountains, valley walls, and eroding coastlines. Aquents, the wet Entisols, are associated with tidal marshes, deltas, lake margins, and floodplains of streams. Cryaquents are characteristic of wet areas of high mountains or tundra. Orthents are Entisols of recent erosional surfaces. Several kinds of Orthents are recognized, depending on temperature and moisture regimes, but most occur on recently exposed regolith or on slightly consolidated rocks. Psamments are Entisols in well-sorted sands in sand dunes, cover sands, or other sandy parent materials.

Histosols, too, are generally associated with distinctive landscape features such as swamps, bogs, and marshes. Andepts occur mostly on volcanic slopes or nearby upland areas. Aquepts are in relatively recent deposits in depressions, very flat plains, or floodplains.

Other great groups and subgroups are not limited in occurrence to specific kinds of landscapes, but may be found on gentle to steep upland slopes, peneplains, plateaus, alluvial fans, or stream terraces. Most soil series, however, occupy rather specific positions in landscapes, and commonly such positions are important in identifying and mapping the soils. With a soil survey area of 200,000 to 300,000 ha, the soil surveyor carefully works out these soil-landscape relationships and uses them to accelerate mapping and improve quality control of the survey. The user of the soil survey will find that learning the soil-landscape associations helps in understanding the pattern of soil occurrence as well as the similarities and differences in response of the soils to management inputs.

RELATION OF DIAGNOSTIC HORIZONS AND FEATURES TO SOIL PROPERTIES

Chapters 3 and 4 of *Soil taxonomy* (USDA 1975) describe and define the horizons and other features that are diagnostic for the higher categories of mineral and organic soils. Space does not permit even a partial review of the properties in this paper. A few examples will perhaps illustrate the interpretive values of diagnostic horizons and properties.

The interpretations that can be made of many kinds of horizons are rather obvious and also rather general. An ochric epipedon suggests either youthfulness or environmental conditions that do not favor accumulation of organic matter. Depending on the other soil characteristics, it may mean low or moderate fertility, low infiltration rate, poor tilth, and erosiveness. A mollic epipedon, in contrast, reflects conditions that favor organic matter accumulation. High base saturation and granular structure favor growth of cereals and many legumes. The soils are resistant to erosion, have favorable infiltration rates, and usually have reasonable reserves of calcium, magnesium, and potassium.

The sulfuric horizon is characteristic of artificially drained and oxidized sulfide-rich mineral or organic materials. It has both a pH less than 3.5 and bright yellow jarosite (iron sulfate) mottles. Such a horizon is inhospitable to plants and even large applications of lime are usually ineffective in reclaiming the material for crop production.

"Amorphous material dominant in the exchange complex" is a property used in defining Andepts and Andaquepts. As used in *Soil taxonomy*, amorphous material is colloidal material that includes, but is not limited to, allophane and has all or most of the properties of allophane. Such material has a pronounced effect on the properties and qualities of the soil. Exchange capacity of the clay at pH 8.2 is more than 150 meq/100 g measured clay and commonly is more than 500 meq/100 g. It has enormous surface area and retains much water against 15-bar tension – as much as 100% or more. The material has high anion exchange capacity. It has the capacity to fix in essentially unavailable form large amounts of phosphate and to fix it very rapidly.

Clearly the practitioner who would use placement of soils in this classification scheme as a clue to production restraints must be thoroughly familiar with the diagnostic features and horizons and with their definitions in the text. Because many of the reasons for specific definitive criteria are not spelled out, and are not always self-evident, it is helpful to explore the implications of the various features with a skilled soil taxonomist. Published soil surveys identify and describe the crop production constraints and management requirements associated with the soils in the survey area, and they include tables of predicted crop yields under different levels of management, as well as tables of potentials for many nonfarm uses. These yield tables and potential tables, however, do not relate soil performance directly to diagnostic horizons and features, but rather to the whole interplay of soil characteristics.

PREDICTION OF SOIL CONSTRAINTS TO PRODUCTION

It is instructive to try to predict soil constraints to crop production simply by interpreting soil family names taken from *Soil taxonomy*. The examples that follow are of known kinds of soils. The predictions were verified by reference to published soil surveys. Note that Eswaran (1977) has tabulated the probable direct or inferred limitations derived from the names of classes in all categories

above the soil family in six orders: Oxisols, Ultisols, Vertisols, Alfisols, Inceptisols, and Entisols. By including the soil family designation the estimation of constraints to production can be considerably refined.

- The family of fine-loamy, mixed, isohyperthermic Fluventic Eutropepts is not extensive, but is important because of its high value for crop production. These are deep, well-drained, medium-acid, moderately permeable soils occurring in a warm, humid climate with slight variability in temperature from month to month. Base saturation is above 50%; the organic carbon content decreases irregularly with depth, as the modifier *Fluventic* suggests. Primary minerals are only slightly weathered or the soils receive bases from higher-lying soils or rocks. These soils, in fact, pose no important constraints to production of the climatically adapted crops, and are highly valued for sugarcane, subsistence crops, hay, and pasture.
- The family of clayey, oxidic, hyperthermic Typic Paleudults contrasts in many ways with the preceding example. The Paleudults are generally well-drained, humus-poor Ultisols in humid climates with well-distributed rainfall; they have developed on very old, stable land surfaces, generally on nearly level or gentle slopes. Weatherable minerals are sparse or absent and clay activity is low. They are strongly to extremely acid. They respond well to applications of lime and fertilizer. Most of them are erosive, so erosion-control management is required if row crops are grown.
- The family of clayey, oxidic, hyperthermic Fragic Paleudults has many of the qualities of the foregoing family of Typic Paleudults, but presents more problems in crop production. Because the fragipan restricts root penetration, the growing crops suffer difficulties in moisture supply and nutrition. The fragipan also restricts hydraulic conductivity, so water tends to pond above the pan during rain periods. Because of the difficulty of correcting the limitations, these soils are generally considered unsuitable for cultivated crops and are used for pasture, watershed, and wildlife.
- The family of fine, mixed, nonacid, isohyperthermic Tropic Fluvaquents consists of weakly developed wet soils formed in fine-textured sediments of mixed mineralogy in lowland areas of the tropics where there is an iso-temperature regime. The fine texture makes for tillage problems. The principal constraint to production, however, is the reducing conditions caused by excessive wetness and slow hydraulic conductivity. In the natural condition the soils may be used for pasture. If properly drained, they are productive for food crops, especially sugarcane.
- The family of fine, montmorillonitic, hyperthermic Typic Pelluderts comprises cracking clay soils of warm humid climates. They usually have gilgai microrelief and are dark gray or black. Tillage is difficult because of the vertic characteristics. Moisture-holding capacity is high, but the soils are subject to waterlogging. Hydraulic conductivity is slow. Under careful and skillful management the soils may be used for production of sugarcane and other crops, as well as for pasture.

• The family of mixed, isohyperthermic Typic Tropopsamments are weakly developed soils in well-sorted sands (commonly dunes) in warm, humid tropics. They have some weatherable minerals, are excessively drained and rapidly permeable, and are deep to water table. Constraints to crop production are dryness, low available water-holding capacity, and low fertility. They are little used for crop production.

The foregoing few examples illustrate the interpretations that can be made by one who either knows *Soil taxonomy* well, including the background of many of the differentiating criteria, or takes time to study the text and data fully. It is apparent that a great deal of the information needed for agricultural development can be gained from the soil classification at the family level. More of the critical information can be derived from classification at the series level, if that is available. But at the series level, not all needed knowledge can be derived from the classification. Local climatic conditions, slope gradients, soil depth, and previous use and management of cultivated fields cause significant variations in productive potential and must, therefore, be accounted for in soil phase classification and by appropriate additional investigation. The additional investigation may include laboratory analysis to guide fertilizer application and liming.

SPECIAL-PURPOSE SOIL GROUPINGS

Many planners and investigators find the nomenclature and technical details of *Soil taxonomy* burdensome to manipulate and remember. Many lay people seek simple groupings of soils that reflect suitability for specific crops or specific nonfarm uses, or that indicate the limitations of soils, and management requirements, for specific uses. Modern published soil surveys always include some of these special-purpose groupings.

One of the most widely used special groupings is called the Capability Classification (USDA 1961). It is a general way of showing suitability of soils for the major adapted crops and the intensity of conservation management required to maintain soil quality and productivity. The Roman numerals I through VIII indicate progressively greater limitations and narrower choices for practical use. Capability subclasses indicate the kind of major constraint or limitation: *e* for erodibility, *s* for soil limitation, *c* for climatic limitation, and *w* for wetness. The Capability Classification was developed for United States conditions but has been adapted for use in other countries. It is not quantitative or precise enough for evaluating production potentials over broad areas, but it is a useful device for communicating with planners and cultivators about soil management requirements.

Woodland suitability groupings, range site classification, wildlife suitability groupings, windbreak site classification, and pasture groupings are examples of other general-purpose classification commonly found in United States soil surveys. Many are *ad hoc* classifications designed to be helpful in the particular county or soil survey area.

Soil management groupings of soils for specific crops are sometimes created to simplify the transfer of information to cultivators. Examples are the Sugarcane Grouping and the Pineapple Grouping found in published soil surveys of Hawaii (Foote et al 1972, Sato et al 1973). Dent (1978) reviewed several earlier attempts to synthesize a suitability classification for wetland rice. He suggested that a rice yield prediction equation might be formulated by multiple regression analysis and that this, linked with soil classification at the family level, offers potential for a useful rice suitability classification.

Buol et al (1975) proposed a technical soil classification system "for grouping soils with similar fertility limitations." The system's differentiae include three mineral surface soil textural groups and an organic class; the substrata textures are grouped into three classes also, plus a rock class. Condition modifiers for the plowed layer emphasize moisture conditions, cation exchange capacity, exchangeable aluminum, free iron oxides, amorphous materials, salinity and alkalinity, free sulfides, potassium deficiency, free calcium carbonate, and vertic soil properties. Trial groupings of soils in a worldwide sampling indicate that about 127 fertility capability units might suffice to account for the variability in response, which is obviously a considerable reduction from the total number of kinds of soils studied. A system like this does not replace *Soil taxonomy* and soil surveys, but it can be tremendously useful in practical agricultural development initiatives.

More complex schemes for soil and land evaluation have been devised in a number of other countries in an attempt to comprehend all of the physical, economic, and sociopolitical resources that influence significantly the opportunities for new or more intensive land development. The Food and Agriculture Organization of the United Nations (FAO) has had a large leadership role in attempting to systematize land evaluation worldwide. Like North Carolina's Soil Fertility Capability Classification, the FAO proposal does not take the place of soil classification and soil survey, but builds on them. It involves the execution and interpretation of basic surveys of climate, soils, vegetation and other aspects of land in terms of the requirements of alternative forms of land use (FAO 1976). Using an incremental procedure that starts with basic surveys and goes on through physical land classification and economic and social analyses, a quantitative land classification suitable for guiding planning decisions is reached. The procedure is completely flexible, and permits the development of such detailed groupings as criteria and ratings for moisture availability for oil palm in Surinam, or degrees of limitation for mechanization in Brazil. The methodology is highly analytical and will require the use of computers for effective application to extensive areas. It is indicative of the direction of contemporary thinking in respect to information requirements for development planning, especially in developing countries where research and experience with modern agricultural technology are limited.

Finally, FAO has proposed a methodology of agroecological inventory as a means of approximating the production potential of the world's land resources (FAO 1978). The procedure begins with a soil-climate inventory for the physical

basis of the assessment. Climatic and soil requirements of selected individual crops are compared with the soil and climatic conditions of the agroecological zones delineated as the final step in the soil-climate inventory. This comparison, or matching procedure, provides anticipated, restraint-free crop yields by main climatic divisions. The restraints are evaluated next (moisture stress, excess moisture, diseases, endemic pests, weeds, etc.) and yield reductions due to the various constraints are estimated to get agroclimatically attainable yields. The final land suitability assessment gives areas of lands that are very suitable, suitable, marginally suitable, and not suitable for production of each crop at each of two levels of inputs. Colored maps in the published reports give a graphic display of land suitability by crops.

Special interpretive groupings of soils, like the soil fertility capability classification and the sugarcane and pineapple groupings are effective in communicating a lot of detailed soil management information to cultivators in condensed form. Such groupings do not require the user to be knowledgeable about the nomenclature and definitions of *Soil taxonomy*, nor even about the local soil series. Complex land classification (land suitability) schemes based in part on soil classification may enlarge the evaluation of resource potentials and they, too, obviate the need to be familiar in detail with soil taxonomic criteria. They may require of the user an equally strenuous effort to become familiar with complicated interrelationships among other sorts of differentiating criteria.

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Major production systems related to soil properties in humid tropical Africa

F. R. MOORMANN AND D. J. GREENLAND

Tropical humid Africa is defined as the part of Africa with a crop growing period in excess of 210 days and with an isothermic or warmer iso (soil) temperature regime. Rainfed traditional and transitional food crop systems are dominant in Africa. They range from extensive to intensive natural fallow rotation systems (shifting cultivation) and, locally, to continuous or semipermanent cultivation. The semipermanent systems are related both to demographic pressure and to the quality of the land for supporting such systems.

Most traditional systems are closely related to the environment, and maintain productivity at a low level without serious soil deterioration. Major constraints to increased production are low nutrient levels, and rapid erosion and increased acidity, if cultivation is prolonged. Land resources are degraded when pressure on the land becomes too high or when unsuitable land and crop management practices are introduced. Substantial improvement of crop production within the context of the existing traditional and transitional systems is possible, and preferable to attempts to introduce land management systems developed for other regions, which give insufficient attention to locale-specific land qualities and soil properties, as well as climate characteristics.

Large-scale capital-intensive arable food crop farming based on systems developed on temperate regions has not been successful in the lowland humid tropical regions of Africa and has led to considerable land deterioration. Tree crop production, both in plantations and by smallholders, has generally succeeded because such land use is ecologically adapted to the region and causes little or no damage to soil resources.

University of Utrecht, P.O. Box 80. 003, 3508 TA, Utrecht; IRRI, P.O. Box 933, Manila, Philippines.

Zero-tillage cultivation systems in which crop and weed residues are used as a mulch, fertilizers are used, a soil cover is maintained, and full advantage is taken of water and radiation by intercropping are an adaptation of traditional practice, which can allow more intensive crop production without soil deterioration. Association of the system with recycling of basic cations by deep-rooted tree or other species may assist in controlling increase of soil acidity.

The development of rice-based cropping systems is increasing productivity in the restricted areas of hydromorphic lands. Considerable potential in this respect exists in Africa.

THE DESCRIPTION and analysis of major production systems and their relation to qualities of the environment, with emphasis on soils, must be a tentative endeavor if done on a continental scale. Although agricultural production systems in Africa are the subject of many studies, they are extremely varied and are not well known in geographic detail. Since 1945 there have been many studies and surveys of African soils, but detailed knowledge of their geographical distribution is, as yet, lacking. With the completion of the *FAO/Unesco soil map of the world* (FAO 1973), the distribution of the major taxa of the African continent was established. Variability as well as microvariability of soils in the humid and subhumid tropics is now known to be greater than in arid and cooler zones (van Wambeke and Dudal 1978, Moormann and Kang 1978). But, the diversity of agro-environmental conditions, as related to the taxonomic characteristics of the soils, is not well known. No concerted effort has been made to relate the multitude of African farming systems, their viability, and their economic relevance to soil-related land qualities. At best, very locale-specific studies have been made, and a few taxonomic soil properties have been given tentative interpretations to link the growth and productivity of agriculturally important crops (and, hence agricultural production systems) with those properties.

This paper should, therefore, be seen in the light of our incomplete knowledge. We highlight the necessity of more, and more detailed, pedological-edaphological studies.

CLIMATIC CHARACTERISTICS OF HUMID TROPICAL AFRICA

Humid tropical Africa falls, roughly, in the tropical wet and tropical wet-and-dry climate types (Finch et al 1957, Trewartha 1966). The tropical humid climate defined by those authors has a relatively abundant rainfall (rarely less than 750 mm), and uniform temperature.

In terms of *Soil taxonomy* (USDA 1975), humid tropical Africa can be defined on the basis of the soil temperature and soil moisture regimes, the latter

being covered by udic and the moister portions of the ustic regimes. Comparing the areas with an isotemperature regime according to Euverte (1967, van Wambeke and Dudal 1978) with the areas covered by tropical humid climates (Trewartha 1966) the latter almost completely have iso soil temperature regimes -- mostly isohyperthermic and isothermic, but, at the higher altitudes, also isomesic and cooler. We exclude the highest altitudes, where conditions for crop production are atypical for tropical Africa.

An agroecological approach for assessing the potential agricultural use of the world's land resources was initiated by FAO in 1976, and the first report from the project (FAO 1978) gives results for Africa. The methodology developed by FAO allows one to relate the agroclimatic requirements of individual crops to environmental characteristics, and hence provides a tentative indication of the suitability of the land for farming systems involving a range of those crops.

For purposes of this paper, we define humid tropical Africa as that region with a crop growing period in excess of 210 days/year and in the zone with a warm isotemperature regime. Its extent is shown in Figure 1 (FAO 1978).

TRADITIONAL AND TRANSITIONAL FARMING SYSTEMS IN HUMID TROPICAL AFRICA

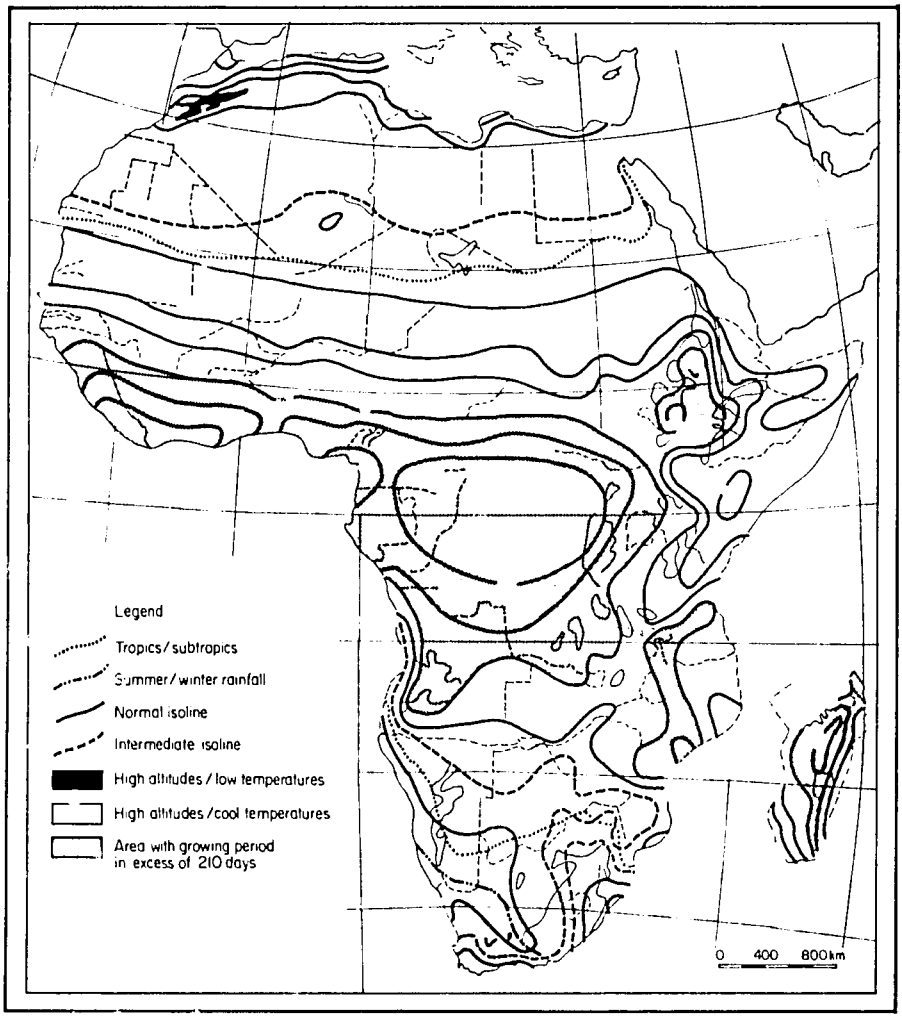
Farming systems in Africa are diverse (Allan 1965, Jurion and Henry 1969, Ruthenberg 1971, Okigbo 1979). A classification by Okigbo (1979) is shown in Table 1. For humid tropical Africa, certain systems are not important in terms of total agricultural area or value of production. Nomadic herding is not, or is only very locally, practiced; terraced farming and floodland agriculture, which are important for Asia, are rare in Africa. Terraced farming of rainfed crops other than rice is found in areas of steep land and high population density, e.g. in Ruanda and Burundi, and in various small pockets such as the Lama Kara region of Togo. Terraced farming of wetland rice is even more scarce, except in Madagascar, where Asian types of rice-based cropping systems are prevalent. A modest start of the construction of terraced wetland rice fields is observable in Sierra Leone, Liberia, and Guinea.

Mixed farming and livestock ranching are not found to any extent in humid tropical Africa. Cattle raising in that part of the world is seriously hampered by trypanosomiasis, spread by tsetse flies (*Glossina* sp.). Although land as pastures for cattle offers possibility, given the present state of our knowledge and level of development, it will be some years before it becomes an important system.

Intensive small livestock production, although as yet not important, is expanding, especially in areas serving large urban communities.

Food crop production by large farms in irrigation projects is rare; some such farms are found in lowlands on the boundary between the subhumid and semi-arid zones, but they are mainly in the drier agroclimatic zones.

Specialized horticulture similar to the modern intensive livestock production farming system is increasing in areas close to urban centers.



1. Length of growing period for crop production in Africa (FAO 1978).

Traditional and transitional systems

Most food crops in humid tropical Africa are still produced in natural fallow rotation (shifting cultivation) systems. Okigbo (1979) indicates that, in the course of development of African agriculture, slash-and-burn shifting cultivation (Phase I shifting cultivation of Table 2) has gradually given way to more sedentary natural fallow rotation or bush fallow systems. The intensity of land use under these systems depends on many factors. Most shifting cultivation systems in Africa belong to Phases II, III or IV of Table 2, with a marked tendency, since about the turn of this century, to the more intensive phases (van der Walle 1972). Traditional farming systems in Africa are changing in response to the

Table 1. A classification of farming systems in humid tropical Africa.[a]

Traditional and transitional systems[b]	Frequency	Modern farming systems and their local adaptations	Frequency
1 a. Nomadic herding	Rare	1 Mixed farming	Rare
b. Shifting cultivation (phase I) with L>10[c]	Rare	2 Livestock ranching	Rare
2 Bush fallowing or land rotation (shifting cultivation, phase II) with L = 50–10	Common	3 Intensive livestock production (Poultry, pigs, dairying)	Rare
3 Rudimentary sedentary agriculture (shifting cultivation, phase III) L = 2–4	Common	4 Large-scale farms and plantations	
		a. Large-scale food and arable crop farms based on natural rainfall	Rare
4 Compound farming and intensive subsistence agriculture (shifting cultivation, phase IV) L<2	Less common	b. Irrigation projects involving crop production	Rare
		c. Large-scale tree crop plantations	Uncommon
5 Terrace farming and floodland agriculture	Rare	5 Specialized horticulture	
		a. Market gardening	Uncommon
		b. Truck gardening and fruit plantations	Rare
		c. Commercial fruit and vegetable production for processing	Rare

[a]Adapted from Okigbo 1979. [b]Many traditional and transitional systems involve the farming of land according to two or more of the systems mentioned here; but usually a major part of the landholding will be farmed according to one of the systems indicated. [c]$L = \frac{C+F}{C}$ where C = cropping period, F = fallow, and L = land use factor (see Table 2).

general increase in population density (Cleave 1974). Thus, in most regions African food crop farming is essentially transitional agriculture, with low or negligible purchased inputs, and high labor input.

Okigbo (1979) distinguishes two major groups of traditional farming systems. One is a *vegecultural complex*, based primarily on root crops, characteristic of forest regions and hence of the moister climatic zones with mainly udic soil moisture regimes, but also covering parts of areas with ustic soil moisture regimes, transitional to udic. The other group is a *seed agricultural complex*, characteristically developed in savannah zones with modal ustic to dry ustic moisture regimes, and based principally on grain crops such as millet, sorghum, and, in the moister areas, corn. Both are found in humid tropical Africa.

Table 2. Phases of shifting cultivation (Greenland 1974) and tentative relationships with land categories (Allan 1965) and soil orders.

	Phase I	Phase II	Phase III		Phase IV
Land cultivation	Simple shifting cultivation	Recurrent cultivation	Recurrent cultivation with continuously cultivated plots		Continuous cultivation
	Dwellings and cultivated area shift together	May be complex, with several field types	Always complex, with several field types		May involve alternate husbandry with planted and cultivated pastures or fallow crops
Land categories	Shifting cultivation land L>10[a]	Recurrent cultivation land			Permanent (L<2) and semi-permanent land, L<2–3
		Long-term recurrent cultivation L = 7–10	Medium-term recurrent cultivation L = 5–7	Short-term recurrent cultivation L = 3–5	
Principal soil order with which associated (very tentative)	Any	Alfisols Ultisols Oxisols	Alfisols Deeper Ultisols[b]	Alfisols Deeper Ultisols[b] Andepts	Tropohumults Rhodustalfs Andepts

[a] L = land use factor, defined as $L = \frac{C+F}{C}$ where C = length of cropping period in years, F = length of fallow period in years (Allan 1965). [b] No discontinuities to a depth of more than 180 cm.

Within these more or less clearly distinguishable complexes, many forms exist, varying in virtually all aspects of agricultural endeavor. Not only do we find a rich mosaic of crops and crop combinations, as in multiple and mixed cropping (Okigbo and Greenland 1976); various intensities or phases of shifting cultivation also exist side by side. An example is the mixed oil palm-root crop farming in eastern Nigeria (Lagemann 1977), where the basic agricultural production is in compound farms (Phase IV of Table 2) and the land is in permanent use, and where the soils have been chemically enriched by household refuse. Away from the compound farm, the land use is less intensive with fallow rotation, corresponding to Phase III shifting cultivation in most cases, but to Phase II in the areas with more sandy soils and inherent poorer fertility (e.g. coarse loamy, siliceous, Typic Paleudults dominated by low activity clays).

A combination of traditional systems, without purchased inputs, with more advanced systems that produce cash crops is common in Africa. The purchased inputs are mainly fertilizers and insecticides. Production of cotton in the savannah zone, and of tree crops such as cocoa, coffee, oil palm, and rubber is frequently combined with natural fallow systems of food crop production. Although tree crops are commonly produced in monoculture by smallholders, they are frequently interplanted with annuals, especially in the younger stages of the tree crops. In southeastern Nigeria most food production occurs under widely spaced oil palms.

Some common characteristics of the systems currently used in humid tropical Africa are listed:

- cultivated area per household is usually small, rarely exceeding 2 ha;
- crops are normally grown in mixture;
- farming systems usually involve, besides a wide range of crops, a varying number of small animals;
- virtually all farm work is done with human labor and simple tools;
- permanent cultivation occurs mainly on compound farms and homestead gardens, where the largest number and kinds of crops are found;
- in the traditional systems in the forest zone, the soil is rarely exposed directly to sun and rain, but is protected by crops and redeveloping fallow vegetation;
- soil fertility maintenance relies heavily on natural or planted fallow and, as regards compound and garden plots, on household, kitchen, and animal refuse; and
- the cultivation period is short, rarely exceeding 3 years, before the land reverts to natural fallow (Table 2).

Relationship of traditional and transitional systems to the environment

Soil physical properties. Where traditional agriculture is practiced, soil erosion is mostly slight; accelerated erosion may occur if demographic pressure on the land increases. Multiple and mixed cropping systems keep the soil partly or totally covered during the early rainy season, when the danger of erosion is

strongest. Soils remain uncovered for short periods only during the beginning of the rains in areas with seasonal rainfall, but in udic and perudic soil moisture regimes, virtually no bare soil can be found at any time. These factors, combined with the lower erodibility of the Ultisols and Oxisols, which are dominant in those humid areas, result in little erosion being found. Land management and preparation of the seedbed by simple hand tools also limit erosion. Burning of the fallow vegetation is seldom complete; and tree crops and shrubs or their stumps are rarely completely removed. A sort of mulch, comprising half-burned branches and leaves plus remnants of ground vegetation remains on the seedbed.

After planting, the soil between the young plants is often purposely covered with leafy branches or crop residues from harvested components of the several crops planted. Weeds are not removed, but are slashed or hoed, and remain on the surface. Two indications of the lack of surface erosion in these areas dominated by traditional farming systems under udic and perudic moisture regimes should be mentioned.

Firstly, creeks and rivers are virtually devoid of a silt-charge throughout the year. In parts of eastern Nigeria, where population pressure reaches 500 persons/km^2 (Lagemann et al 1976), the water in creeks and rivers is limpid, with a bluish-black tinge in some seasons, because of dissolved organic matter.

Secondly, no signs of excessive stripping of the A_1 horizon can be found. This is seen in many West African soil areas on basement complex rocks where the Alfisols and Ultisols possess gravelly subsurface horizons, covered with a gravel-free biogenetic horizon, formed mainly by the soil fauna (Nye 1954, Smyth and Montgomery 1962). This gravel-free horizon of a remarkably constant thickness (15–25 cm) is maintained in areas that have long been used for Phase II or Phase III (Table 2) shifting cultivation. Where mechanized arable cultivation has been introduced, the gravel is frequently exposed.

In traditional agriculture, planting on heaps of soil is common. Although heaping may in part be purely traditional (Lal and Hahn 1973), it frequently serves a specific purpose, as in the construction of high heaps on hydromorphic soils, or in the cultivation of yam (*Dioscorea* sp.) on soils with gravel layers at shallow depth. There are also indications that in the traditional systems the construction and maintenance of clean weeded heaps protect the crop at early growth stage against the influence of weeds, which compete for nutrients, water, and light (Moody 1975). Observations on eastern Nigeria indicate that, whatever the reason for heaping, little erosion results from this practice in traditional systems. Surface erosion, if it takes place, transports soil from the top to the bottom of individual heaps but runoff and erosion are effectively stopped because of the mulch cover normally present in the hollows between the heaps. This is so, even though in clean weeded lands, heaps have been shown to accelerate erosion in the exposed and connected hollows. The key factor is the application of various mulches on the parts of the land exposed to rains. The mulches prevent direct impact of raindrops on the soil, eliminate particle detachment, and thus reduce erosion to acceptably low levels (Lal 1976a).

Soil fertility. A recent review of soil fertility in shifting cultivation is given by Sanchez (1976), who discusses much West African work. The soil fertility aspects of traditional farming systems are site dependent, varying with the original soil type, the climate, the system itself, including the type of crop mixtures, the frequency of cultivation, and the nature of the fallow vegetation. Nevertheless, some generalizations regarding soil fertility relationships are possible.

The central concept of traditional systems is the dependence on forest or savannah fallow periods for restoring soil fertility, which diminishes during the cropping cycle. When land use is not intensive, and fallow periods are 6–15 years, depending on the nature of the soil, a nearly closed nutrient cycle exists, and production of food crops can be maintained at an acceptable, although low, level (Nye and Greenland 1960, Allan 1965). Increased intensity of land use for cropping leads almost inevitably to lower yields and overall loss of fertility, but considerable differences exist according to the nature of soils.

In the few areas with upland soils of high base status and with a clay mineralogy not dominated by low activity clays (mainly Andepts and Rhodustalfs), rainfed agriculture can be permanent or semipermanent even without the use of fertilizers (Allan 1965). But often, fertility declines because of intensified cropping. The decline may be less for Alfisols, which are dominant in the savannah areas and at the forest-savannah boundary (Nye and Greenland 1960, FAO 1973, Jones and Wild 1975), than for Ultisols and Oxisols, which dominate in the udic and perudic parts of Africa. As population density increases a breakdown of the traditional system, due to progressive soil fertility depletion under intensified land use, becomes more common in the extensive areas of Ultisols and Oxisols. The higher levels of adsorbed Al^{3+} in the root zone of these soils, together with other factors, lead to poorer growth of most crops.

Besides decline of nutrient status, other factors contribute to diminished returns from intensified traditional farming. Weed infestations may be as important as nutrient depletion.

Much information on nutrient and yield decline with continued cropping exists (Nye and Greenland 1960, Sanchez 1976). It has been well established that appropriate fertilizer use can not only arrest the decline but also maintain yields at high levels (Kang et al 1977, Sanchez 1979). Economic restrictions may occur, however, particularly in the more acid soil areas where lime is often not readily available.

Relationship of rainfed agriculture to land types and land qualities

Low-intensity shifting cultivation systems (Phase I of Table 2) show little relationship to kind of soils. However, these systems do not commonly use very shallow and very steep phases or very wet soils. Within the confines of the agroclimatic zones, there is no evidence that production under low-intensity shifting cultivation varies according to kind of soil and related land qualities. Of more importance for the level of production in such systems are rainfall pattern and

crop management, especially as regards weeding.

Increased intensity of land use under shifting cultivation in Phase II or Phase III is, on the contrary, dependent on land types and their qualities. As Allan (1965) further indicates, the great variability of land-use systems in African agriculture is related to soil properties. At increasing population pressures, the intensity or *category* of land use is directly related to soil properties. Physical soil properties determine whether intensified land use under traditional and transitional systems can be stable. Deep soils, with medium to fine textural profiles (fine loamy and clayey families) and without interfering gravelly layers or horizons, are the ones most frequently used for these intensified systems. In view of the importance of root crops in the areas, the volume of soil available for free root development is important. Examples of intensive and even permanent agricultural use can be found on clayey, kaolinitic families of Palehumults and Paleudults developed from basic parent materials, such as basalts.

Land use in such soil areas in Ruanda and Burundi (van der Walle 1972) and in the western part of the Cameroons has been intensive. Very intensive land use is also found in West Africa where Paleustalfs and Paleudults have developed on deep sediments in slightly undulating terrains. Here too, the determining factor appears to be soil depth and the absence of root-impeding factors in the profile (Babelola and Lal 1977).

Only rarely are intensive (Phase IV) traditional and transitional systems found in areas dominated by soils with less favorable physical characteristics, e.g. most soils in acid and intermediate crystalline basement complex areas. Even in those areas, local patches or pockets of deeper soils, including examples where the soils belong to sandy or coarse loamy families, are preferred for intensified agriculture.

Certain chemical soil properties may interfere in the intensification of land use on physically favorable soils. Land use remains extensive in deep, clayey Aerorthox areas of Zaire (personal communication with C. Sys, University of Ghent), because of extreme nutrient deficiency, and in spite of their favorable physical characteristics. In the various families of Paleudults, where base saturation is very low – practically from the surface – and where high Al^{3+} saturation is found at shallow depth, intensified land use is rare. The restricted root development due to Al^{3+} means that plants often suffer from drought during their early development, and this appears to be an additional limiting factor for intensified cultivation of such soils.

Thus intensified systems of traditional and transitional agriculture in Africa are related to soil properties and specific land qualities, with permanent or semi-permanent land use being found exclusively where conditions are favorable. Not all favorable soils are intensively cultivated, however. Demographic pressure is partly an independent variable (see section on demographic aspects).

Use of wetlands in traditional agriculture

In humid tropical Africa, land that receives water additional to rainfall (groundwater, surface water) is underutilized compared with similar land that forms the

backbone of food crop production in South and Southeast Asia (Moormann and van Breemen 1978). Geographers give many reasons for the underutilization, the main ones being the prevalence of schistosomiasis and other water-borne diseases, and the late introduction of rice *Oryza sativa*.

The use of wetlands is indeed limited in all areas where rice is not a major or even a minor food crop. Nevertheless, use of hydromorphic valley lands for crops other than rice is common, and most indigenous cultivation systems involved recognition of the need for each farm to include land of this type.

Agricultural use of wetlands is less in the forest than in the savannah zone. In the areas of highest rainfall, traditionally little use is made of the wetlands, except for the gathering of forest products (e.g. bamboo) and the production of palm wine. In the drier zones, transitional to the udic and perudic regions, two specific land use systems occur. Firstly, marginal wetlands that only become water saturated well into the rainy season are frequently used for yearly cropping of early corn and, to some extent, for yam (*Dioscorea* sp.), plantain (*Musa* sp.), and cocoyam (*Xanthosoma* sp. and *Colocasia* sp.). Secondly, giant heaps, sometimes as high as 150 cm with an estimated base surface of up to 30 m^2, are constructed in wetlands. Each individual heap is a *microcosmos*, with a whole range of crops planted according to their relative susceptibility to high groundwater. Yams are usually planted on or near the top; cassava, corn, grain legumes, and melons lower on the heap; and rice between the heaps (Okigbo and Greenland 1976). The system is an effective, although labor-consuming, means of artificial soil drainage. It is well developed in parts of eastern Nigeria (e.g. in the Abakaliki area), where hydromorphic soil conditions abound (Ruthenberg 1971). It is also used in other West African valleys and small plains, which are not subject to deep flooding.

Rice cultivation is increasing rapidly in Africa (Buddenhagen and Persley 1978). Although most rice is still produced as a dryland crop (upland or pluvial rice), a change toward wetland rice cultivation is taking place. An example is again the Abakaliki area in eastern Nigeria, where rice was not introduced until the mid-1940s (von Blanckenburg 1962). Here, rice has become the main crop on the hydromorphic lands. Originally grown in combination with the mixed crops on high heaps, it is now grown more and more in monoculture.

Although total rice production in West Africa is only of the order of 2 million t/year, and the annual rate of increase in production over the past 2 decades was only 2.7%, this rate is greater than that for any other crop in West Africa (Winch and Kirunja 1978).

Rice cultivation in Africa is in the process of becoming an integral part of traditional and transitional farming systems. Because rice is a cash crop, for most small farmers the use of purchased inputs, particularly fertilizers, is slowly increasing. Rice cultivation in Africa is still far from reaching the position it has in South and Southeast Asia. The relative surface of suitable wetlands in humid tropical Africa is much less than that in Asia, and water control by leveling, bunding, and irrigation still has to be developed. The introduction of this type of water control is essential to successful development of rice cultivation in

Africa (Moormann and Veldkamp 1978).

Demographic aspects of traditional and transitional agricultural systems

Few data on population density relevant to soils and land as a natural resource are available for tropical humid Africa. Total population data show that Africa is relatively empty; however, crude national and subnational statistics of population density are not very useful (Hance 1972). High population densities and concomitant pressure on land are already critical in Africa in scattered rural pockets (Prothero 1972), even though overall population pressure may not be severe.

Boserup (1965) suggests that increasing density of population will normally bring about successful intensification of land use, irrespective of where it occurs. Enough examples support this theory, but at the same time, there is often a correlation between such increased intensity of cultivation and the overall quality of the land (Allan 1965).

It is doubtful, however, if a valid generalization regarding the relationship between land resources and demographic pressure can be derived. Firstly, relative overpopulation occurs in many areas in Africa where production potential is low because of soil and soil-related constraints. Such soil areas may be overused, even if they are only extensively used for Phase I or Phase II shifting cultivation. Secondly, not all areas suitable for intensified shifting cultivation are so used. For example, in an IITA (International Institute of Tropical Agriculture at Ibadan, Nigeria) study of a climosequence of loamy to clayey siliceous or kaolinitic, isohyperthermic Paleustalfs and Paleudults on coastal sediments in Togo, Benin, and Nigeria, which had consistently favorable physical properties throughout the sequence, population density and intensity of land use behaved as independent variables (Forbes 1975). Low-intensity land use predominates in the portion of the sequence situated in Bendel State, Nigeria, where socioeconomics and land use policy appear to determine the density of land use. Other limiting factors, such as the lack of potable water in parts of the middle belt of Nigeria, which have deep to very deep soils on (probably) old terrace formations, may also interfere with intensification of land use.

Given the present rapid changes in communications, water availability, and other factors, it is difficult to make a general statement regarding the relationships between future population density and intensity of land use in humid tropical Africa, and qualities of the land. Certain discernible trends point to increasing overpopulation in many localities, but it is impossible to generalize from the data obtained. Historical and other factors too frequently intervene (Prothero 1972).

IMPROVED CROP PRODUCTION FROM TRADITIONAL AND TRANSITIONAL FARMING SYSTEMS

The natural fallow rotation systems of the lowland humid tropics of Africa differ substantially from crude slash-and-burn practices in which land is cultivated

damagingly for a brief period and becomes unsuited to further cultivation, even after lengthy periods in natural fallow. The destructive slash-and-burn common in many steeply mountainous areas of South America, where it is practiced mainly by new settlers (Watters 1971), is rare in Africa (Nye and Greenland 1960, Allan 1965). The African natural fallow rotation system has evolved through centuries of man's adaptation to his environment. Except for wetland paddy rice and permanent tree crop production, it is the only demonstrably stable farming system developed for the Alfisols, Ultisols, and Oxisols of the humid tropics. However, it is primarily suited to the maintenance of a subsistence economy where ample land is available; it still is not known whether, on a wide range of soils, it can be intensified to provide the higher returns required to establish a better standard of living, or to support much higher population densities.

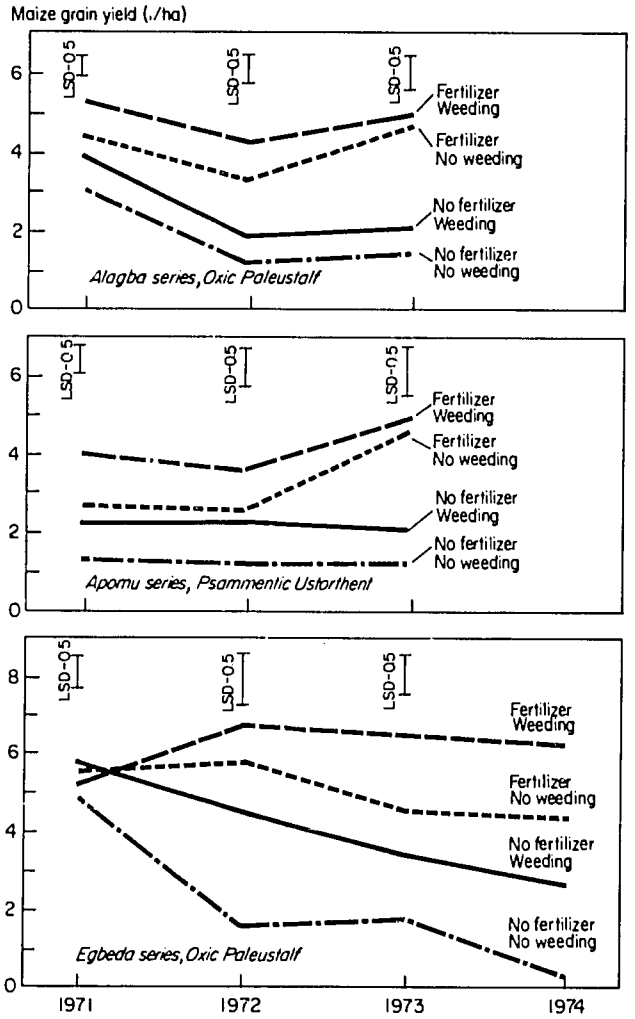
The reasons for the success of the traditional system are its close adaptation to soil properties and land qualities. Fallow periods are determined according to the ecological succession, which reflects the restoration of nutrients and the suppression of weed species. Different soil and land types are recognized in relation to their suitability for different crops, and are planted accordingly. Plantain and cassava, which occupy the soil for more than a year, are often planted together with mixtures of shorter duration crops, and ensure the maintenance of soil cover to protect the soil against erosion. If the system is to be intensified it is essential that the changes made preserve its main virtues, which overcome the environmental constraints of the region (Greenland 1975).

The *corridor system* developed in Zaire (Jurion and Henry 1969) attempted to rationalize shifting cultivation by arranging the areas of cultivated and fallow land in straight lines in the landscape. Such arrangement obviated the system's adaptation to soil variation and destroyed its ecological sensitivity, and offered little by way of compensation.

The *taungya* system (planted forest and crop rotation) is extensively used in the forest areas of Nigeria and other parts of Africa (King 1968). It allows the land to be used productively throughout the "rotation" and preserves the advantages of the natural fallow rotation system. The relative advantages of land use for timber or for more frequent food crops depend on economic factors.

Introduction of improved varieties and fertilizer into the natural fallow system is possible. The usual response to increased population pressure and consequent lower availability of land is reduction of the length of the fallow period. This can mean reduced restoration of nutrients, inadequate improvements in soil physical conditions, and incomplete suppression of weeds. Although fertilizers and improved crop varieties may more than sustain the ability of the soil to produce crops, the soil's physical condition can still impose a serious constraint. The results of Kang et al (1977; IITA 1974, 1975) show that on 2 Alfisols and 1 Entisol, high yields could be maintained for periods of at least 5 years (Fig. 2). The results are for small plot trials where erosion was not important.

Although fertilizers have produced positive yield responses in the humid



2. Effect of cultural factors on maize yield on three soils in southern Nigeria (from IITA 1974, 1975; Kang et al 1977).

tropical regions of Africa, their use has tended to develop only where cash crops are produced. Their use on food crops has been limited by the relatively low prices for food crops and inadequately developed marketing facilities.

The many research results available clearly disprove the idea that in the African humid tropical regions high phosphate fixation limits responses to fertilizers. With suitable varieties and nonlimiting soil physical conditions, excellent phosphorus responses are obtained and high yields can be maintained. Severe phosphate fixation may be a problem in the extremely acid Oxisols and in some Ultisols with high active aluminum present. Le Mare (1979) has shown that in many Ultisols and Alfisols in West Africa most added phosphate remains in

equilibrium with the soil solution for several months after addition, and is available to crops. Pichot and Roche (1972) and Kang and Fox (1979) have reported substantial residual responses to phosphate on Alfisols and Ultisols in West Africa.

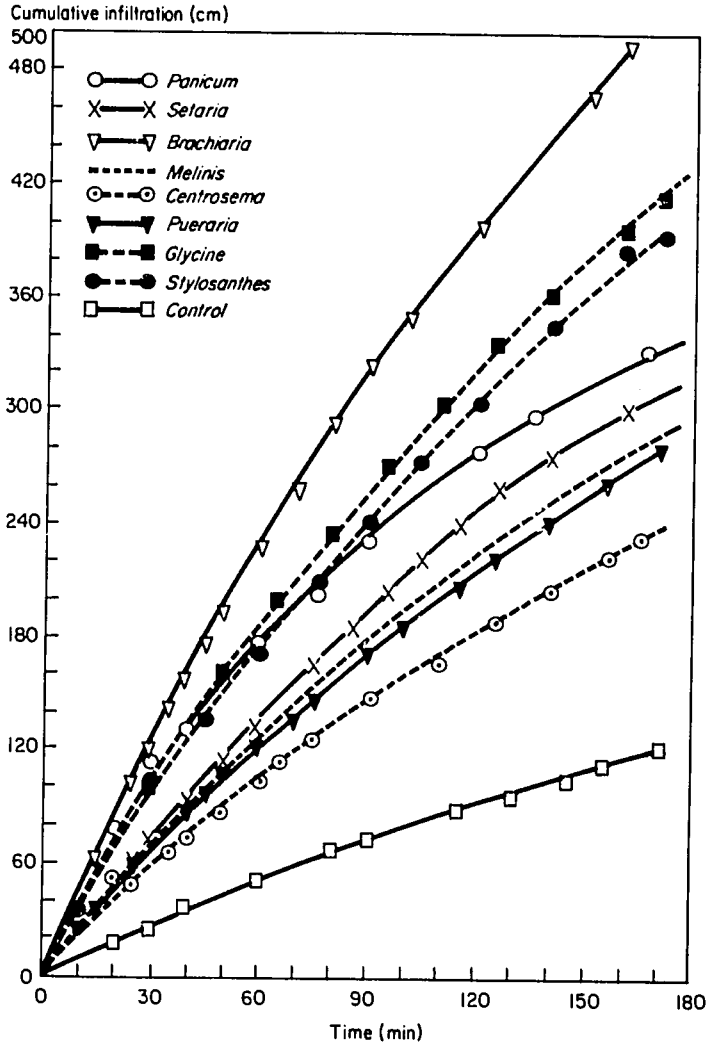
When fertilizers are used during a cropping period of a few years before fallow regrowth, increased acidity does not become a problem, and the cations depleted by leaching and crop removal and nitrification of added nitrogen fertilizers should be restored by recycling of basic cations through the fallow vegetation. If the cropping period is prolonged, however, depletion of basic cations and acidity development can become serious (Greenland 1974). This is a greater problem in the wetter areas on Ultisols and Oxisols. Low rates of lime (<1 t/ha) have given substantial responses in eastern Nigeria (Juo and Uzu 1977). But because lime is scarce and expensive in the area, the responses are not necessarily economical. Alternative liming materials must be sought. If trees are not grown in succession to food crops, they could be grown elsewhere, ashed, and the ash used as a soil amendment (Greenland 1974).

Zinc and copper are present in very low amounts in the Alfisols and Ultisols developed from basement complex rocks and sediments in West Africa (Cottenie et al 1979); deficiencies of those elements must be anticipated with continued cropping, or with injudicious use of liming materials. Early liming experiments using high rates failed, probably because of induced micronutrient deficiencies (Juo and Uzu 1977).

The major problem associated with extended cultivation periods is maintaining the physical condition of the soil and avoiding erosion. The *red earths* of the tropics have, or had, the reputation of possessing excellent physical conditions. In fact, the Alfisols and Ultisols of West Africa have relatively weak aggregation. Their available water retention is often less than 10 g/100 g (Lal 1978) and on a volumetric basis is reduced further by the common presence of substantial quantities of gravel. They are easily erodible (Lal 1976b) and crops grown on them frequently suffer from drought despite high, if sometimes intermittent, rainfall.

Many long-term experiments on the Alfisols and Ultisols of the humid areas of West Africa have tested different planted fallows for their ability to restore soil physical conditions. Although many planted fallows are effective (Fig. 3), none are significantly superior to natural fallow, and are more demanding in terms of establishment. Animal disease problems limit the use of the fallows for animal production.

On an Oxic Paleustalf at IITA a zero-tillage system, with crop and weed residues used as a mulch, was highly successful in maintaining physical conditions and preventing erosion (Lal 1979a). The system needs testing in a wider range of environments, but appears suitable for continuous production on most uplands with an undulating to gently rolling topography in the humid tropics. The zero tillage is not the essential component; the use of residues as mulch is the all-important factor.



3. Effect of planted fallows on infiltration into an Alfisol in southern Nigeria (Lal 1979b). Infiltration under adjacent secondary forest is close to the highest rate found in this experiment.

MODERN FARMING SYSTEMS

For humid tropical Africa, two subsystems in Okigbo's classification (Table 1) are important: large-scale food and arable crop farms using natural rainfall, and tree crop plantations.

Large-scale food and arable crop farms

The subsystem of large-scale food and arable crop farms includes all farming operations with high purchased capital and recurrent inputs. A common charac-

teristic is the high degree of mechanization of all or important portions of the farm operation, starting with initial clearing.

Large-scale farms of this type, using standard Western technology, have generally been unsuccessful in Africa. The well-publicized failure of the groundnut scheme in Tanzania, and of the less well-known, but equally disastrous large agricultural scheme at Sefa in southern Senegal, are only two examples of a mismatch of this type of imported technology with the qualities and constraints of the environment. Both schemes fall somewhat outside of the humid tropics as defined here, but the causes of failure are also found in the regions under discussion here.

In the Tanzanian scheme, recurrent low rainfall paired with the low available water-holding capacity of the soils was the main environmental constraint. In the Sefa scheme, unanticipated high rates of surface soil erosion after large-scale mechanical clearing rapidly led to crop loss and failure (Charreau and Fauck 1970).

The two failures are not exceptional. Throughout humid and subhumid Africa, scores of large to medium-large farming schemes have been abandoned. Although the basic reason for failure is lack of understanding of the environmental constraints, unfavorable socioeconomic conditions and management problems have often accelerated the process of abandonment of such schemes. Of the many failures, the Ejura farms in Ghana should be mentioned. The project, organized by U.S. private enterprise and the Ghana government, is in the transition zone between forest and savannah on loamy and clayey families of Oxic Paleustults, with inclusion of arenic subgroups and of Plinthustults. Maize was the main crop, grown under high levels of *Western* management: complete mechanization of operations, improved varieties, fertilizers, control of pests and diseases, and postharvest storage to allow sale of the produce at the time of lowest (national) supply and highest market prices. The scheme failed because of an unplanned low benefit-cost ratio, which did not allow for amortization of the costly capital inputs for mechanization. Yields remained well below expectations, and costs were higher than planned, because of a number of land-related factors. The most important of those were:

- Soil degradation, including erosion, induced by the mechanized system adapted, which required clearing and regular exposure of large areas of soil. Despite bunding, the erosivity due to climate was greater than that for which the system was designed.
- The difficulty of getting a crop started at the beginning of the rainy season, when soils were depleted of available water and rains were irregular.
- The effect of the dry spells during the growing season on soils with low available water-holding capacity. The effect was clearly aggravated after a few years of cultivation because of diminished organic matter in the surface soil.
- The formation of plow pans upon mechanical cultivation. The pans were so dense that they hampered root development, and made the water less available to the crops.
- The high incidence of weeds competing for water and nutrients. On the

Ejura farms, *Rottboelia* sp. was the most harmful; *Imperata cylindrica,* which is common in areas of humid West Africa where large-scale farms operate, also occurred.

The constraints observed in Ejura are found in most large-scale schemes in humid tropical West Africa, on Alfisols and Ultisols. Most of the constraints can be managed, as indicated by work on experimental farms and stations. The price for such management is, however, too high under prevailing socioeconomic conditions. Alternate land management systems are needed if large-scale arable farming on these soils is to be successful. Minimum tillage techniques that minimize or even avoid loss of structure (tilth), loss of organic matter, and the collateral increase of erodibility offer one such system (Lal 1979a). Although highly adapted to the Alfisol zone of West Africa, the system has not been tested in other environments, notably on the Ultisols of the wetter regions. Thorough land evaluation and testing of such systems in pilot schemes are necessary.

Tree crop plantations

A review of plantation crops in Africa by Grigg (1974) indicates that most tree crops in humid tropical Africa are grown by smallholders in conjunction with traditional subsistence farming of food crops. This is true, for instance, of coffee and cocoa in West Africa. Rubber and oil palm are main large-scale plantation crops, but are also grown in smallholdings. As regards soil properties, the two systems of tree crop plantations are substantially comparable and will be treated together.

Ecologically, tree crop plantations are much more related to the original and secondary forest vegetation than are systems of food crop farming. Thus the constraints imposed by soil physical conditions are diminished, especially as regards the maintenance of favorable physical conditions and the avoidance of erosion. Surface runoff and superficial erosion are rare in plantations. The only erosion occurs as gullies and is simply controlled. The gullies often form along access roads and plantation tracks.

Maintenance of soil fertility with tree crops is much less of a problem than with cultivated food crops. The export of plant nutrients in the tree produce is small relative to total biomass production, with concurrent more efficient use of nutrients from the deeper soil horizons. Less nutrients are lost by leaching and by erosion than in tilled crop land, and plantations with low inputs of fertilizers can succeed where low-input annual cropping systems fail.

Weeds are a problem only in the early stages of the tree crop plantation. Once a relatively closed canopy has formed, weeds are easily controlled during normal operation and maintenance activities.

Economic returns from the produce of most tree crops are in the first place determined by world market prices. Fluctuations in those prices influence this type of land use. Falling rubber prices, for instance, were instrumental in the abandonment by many smallholders of rubber gardens in the humid part of Nigeria.

Level of management is the second important factor in the degree of success of tree crop plantations. In smallholders' plantations, management level is relatively low and yields are consequently low. With an unfavorable price structure on the international market, therefore, the low management levels tend to go lower. In addition to and in conjunction with these economic parameters, land qualities play an important role. For a given commodity price and a given intensity of management, the returns are better on soil that has properties most suited to the particular tree crop.

Some ecological requirements of the various important tree crops are known, usually in a pragmatic way, because of the failure of plantations under specific circumstances. An example is the commercial production of oil palm. One of the most important production-determining factors is the distribution of rainfall. A long dry season causes the preferential development of male flowers and a high degree of abortion of fruits. Although oil palm shows good vegetative growth in zones with a moderately long dry season or even in much drier zones on hydromorphic soils, its productivity is much less than in water areas. Oil palm fruit is harvested from trees that form part of the secondary bush regrowth in drier areas, but productivity per tree is too low for plantation levels. Hence, the limit of useful climates for oil palm as a plantation crop is set by a growing period isoline (Fig. 1) of roughly 300 days with an isothermic or warmer iso (soil) temperature regime.

Much data on land qualities that favor diverse plantation crops are available from the literature, but because of the commercial character of many of the plantations, many relevant data have never been published. Most plantation crops in humid tropical Africa are grown on suitable land, and a large reserve of soil for similar crops is still available.

CONCLUSIONS

There is no consistent relationship between the intensity of land use in humid tropical Africa and either soil and climate characteristics or population density. Rapidly increasing population density in several areas is accentuating the need to develop more productive and stable agricultural production systems for those areas. The principal soil constraints to the development of more productive farming systems on the Alfisols, Ultisols, and Oxisols, which dominate the landscapes of the region, are summarized as follows:

- Alfisols
  - susceptibility to erosion;
  - low retention of available water;
  - low reserves of nitrogen, phosphorus, zinc, sulfur, and copper; and
  - development of acidity with continued cultivation.
- Ultisols and Oxisols
  - low nutrient retention;
  - low reserves of nitrogen, phosphorus, potassium, calcium, magnesium, zinc, and possibly copper; and

– problems associated with soil acidity.

The major constraint on hydromorphic soils relates to water control.

Research priority must be given to the development and wide testing of farming systems that alleviate these constraints within the socioeconomic parameters that exist in the region.

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Major production systems and soil-related constraints in Southeast Asia

F. J. DENT

A direct result of the fast expanding population of Southeast Asia is that more people are forced to eke out a living from the land, which is already a scarce factor of production under traditional agricultural systems.

Despite the technological breakthrough in cereal crop production the region has an overall calorie deficit. Consequently an increase in production is essential if the food and population problem is to be solved.

To obtain a clearer picture of potentials for increased production, eight major production systems combined in three main groups are described and their broad crop requirements are reviewed.

Eight soil-related constraints are identified. Their severity for each production systems group on each major soil and the level of inputs required for alleviating them are indicated.

Future short- and long-term potentials for production are reviewed, putting soil-related constraints in the political, social, and economic context of the region. Finally, research pathways to the technological support necessary to realize full production potential are indicated.

ASIA ACCOUNTS for over 25% of the total world population. The present growth rate of 2.3%/year is expected to continue for some time, although a reduction of fertility is considered likely within this century (Narain et al 1973). There is a downward trend in the ratio of agricultural population to total population, but the rate of decline is not sharp enough to arrest the increasing trend in absolute numbers dependent on agriculture (Table 1). The result is that more people are forced to eke out a living from the land, which has already become a scarce factor of production. Although the introduction of improved technology

FAO Project Manager, Land Resources Evaluation with Emphasis on Outer Islands Project, Soil Research Institute, Jalan Ir.H. Juanda 98, Bogor, Indonesia.

Table 1. Estimates of total and agricultural population and population economically active in agriculture for East and Southeast Asia.[a]

Category	Estimates (million)			
	1950	1960	1970	1980
Total population	189.6	240.6	313.3	413.4
Agricultural population	142.0	171.7	208.0	246.0
Population economically active in agriculture	60.8	70.7	80.1	90.6

[a]Based on FAO country classification for statistical purposes.
Source: Narain et al 1973.

has contributed to increased agricultural output, the great mass of the rural population has received little share in the benefits, and average dietary energy intake per caput remains below minimum requirements.

POPULATION AND FOOD SUPPLY

In the 1950s food production in humid tropical Asia increased faster than population growth, but more than half the increase in the production of cereals came from expansion of the cropped area.

In the 1960s food production struggled to keep pace with population growth, and imports of food grains rose steeply in the mid-1960s. The slower rate of production growth – partly due to bad weather – was indicative of the increasing scarcity of new tillable land. Since the late 1960s food production has steadily increased, largely because of the increasing adoption of modern varieties (MV) and associated new technology, and good weather.

The technological breakthrough in cereal crop production changed the agricultural situation in humid tropical Asia and made possible higher yields per unit area. The greatest impact has been on rice, the basic staple in the diet. Relatively little advance in technology has been achieved for most of the other food and nonfood crops, and the region has an overall deficit in calories that the rapid population growth threatens to aggravate.

Comparison of future projected rates of increase of food production and population growth shows that the increase in cereal requirements is, in absolute terms, overwhelmingly larger than increases in all other items (Table 2). An additional 16 million t would be required for East and Southeast Asia[1] alone within this decade. Although of the same order of magnitude, increases in other

[1]Definitions of the geographical coverage of humid tropical Asia vary. *East and Southeast Asia* refers to a subregion of the FAO country classification for statistical purposes and includes the territories of Brunei, Burma, Hong Kong, Indonesia, Kampuchea, Republic of Korea, Laos, Macau, Malaysia, Philippines, Ryukyu Islands, Singapore, Taiwan, Thailand, and Vietnam. Data quoted for *Southeast Asia* from the *FAO/Unesco soil map of the world* relate to the territories of Vietnam, Kampuchea, Laos, Thailand, Malaysia, Singapore, Indonesia, and the Philippines.

Table 2. Total demand for food in East and Southeast Asia.[a]

Year[b]	Demand (million t) for food											Annual rate of growth (%)
	Cereals	Starchy roots	Sugar	Pulses and nuts	Fruits and vegetables	Meat	Eggs	Fish	Milk	Fats and oils	Total economic grain equivalent	
1970	46.81	21.08	4.26	4.67	22.37	3.23	0.60	5.70	2.69	1.16	91.97	–
1980 N	63.34	28.53	5.77	6.32	30.27	4.37	0.80	7.72	3.65	1.57	127.86	3.4
1980 T	61.14	27.28	6.74	6.45	32.45	5.29	0.99	8.60	4.55	1.74	130.30	3.6
1980 H	61.39	27.24	7.36	6.61	33.94	5.83	1.12	9.14	5.04	1.90	135.62	4.0

[a]Based on FAO country classification for statistical purposes. Source: Narain et al 1973. [b]1980 N represents quantities needed to meet per caput requirements of calories; 1980 T represents quantities needed to meet *Trend*, which assumes income growth will follow past trends as interpreted by FAO; 1980 H represents quantities needed to meet *High* assumptions based on targets for economic growth established by the United Nations and its regional commissions for the Second Development Decade.

foodstuffs are not big in absolute terms; but the lack of tillable or grazing land limits increase, particularly of livestock products.

To avert the threat of aggravated calorie deficiency, food production must at least keep pace with population growth through either expansion of land under permanent cultivation or higher yields per unit area, or both.

PRODUCTION SYSTEMS

In 1970 estimates of land use in East and Southeast Asia (Table 3) indicated that arable land accounted for about 16% of the total area, with rice as the dominant crop. Estimates of the proportion of rice areas in five major production categories (Table 4) indicate that rainfed rice occupies the major portion of the total rice area, with one rice crop being grown in most years. With the exception of West Malaysia, only a small proportion of the areas under irrigation receives year-round water for continuous rice cultivation. Such wetland rice-based production systems support dense populations who have attained a highly structured and efficient society founded largely on many small, partly to semicommercialized (Ruthenberg 1971) permanent farms with established field rotations.

Other production systems of the region occur in dryland rainfed areas. The most widespread system is shifting cultivation, defined as an agricultural system in which temporary clearings are cropped for fewer years than they are allowed to remain in fallow (Buol and Sanchez 1978). Shifting cultivation is subsistence farming at best, the sole input being labor. While it attains near-stability of land (Chorley and Kennedy 1971) in areas of low population density, it cannot keep pace with an increase in population.

Permanent cultivation of dryland short- and long-term annual crops is carried out where relatively fertile soils and incentives of transportation and market infrastructure exist. Such areas are generally densely populated and have a highly structured and efficient society based on small, partly to highly commercialized farms with established field rotations. Although largely rainfed, they receive supplemental irrigation when feasible and necessary.

Dryland perennial crop production systems are largely a result of past European intervention and are highly commercialized, whether based on planta-

Table 3. Land use in East and Southeast Asia in 1970.[a]

Category	Land use	
	Total (million ha)	Per caput (ha)
Arable land	71.0	0.2
Permanent meadows and pastures	17.2	0.1
Forested land	278.1	0.9
Other land	79.3	0.2
Land area	445.6	1.4

[a]Based on FAO country classification for statistical purposes.
Source: Narain et al 1973.

Table 4. Estimates of the proportion of rice area in 5 major categories in selected countries in humid tropical Asia, 1975.

Country	Total rice area[a] (thousand ha)	Proportion (%) in major categories				
		Irrigated	Rainfed	Upland	Deep-water	Second-crop
Indonesia	8482	47	31	17	5	19
Malaysia, West	771	77	20	3	0	50
Philippines	3488	41	48	11	0	14
Thailand	7037	11	80	2	7	2
Vietnam	2713	15	60	5	20	5

[a]1970–74 av (FAO data).
Source: Barker et al.

tions or on small holdings. In terms of area under permanent production, commercial perennial crops are second only to rice, the main crops being rubber, coconut, and oil palm.

Permanent meadows and pastures account for a very small proportion of the total area of the region – most small holdings of livestock are raised on rough pasture or grass pasture between crops during fallow periods of an established field rotation, or in combination with perennial crops, especially coconut.

A production system based on the temporary cultivation of dryland annual crops and the planting of commercial timber species covers a limited area along the edges of primary forest. The system is not widespread and is largely an alternative to shifting cultivation. A more common development is a *mixed garden* type of land use, which is semipermanent and consists of tree, bush, and field crops each occupying their share of soil and space. This basically traditional production system is an alternative to reforestation or to intermittent or shifting cultivation.

Production systems that have developed spontaneously within humid tropical Asia or are the result of outside intervention and local adaptation to the prevailing physical, economic, and social context are summarized:

1. Wetland production systems
   a. *irrigated rice* – permanent farming with an established field rotation, semicommercialized to highly commercialized with more than 25% of the gross product sold.
   b. *rainfed rice* – permanent farming with an established field rotation, semicommercialized to partly commercialized with 25–75% of the gross product sold.
   c. *deepwater rice* – permanent to semipermanent farming, generally with an established field rotation, partly commercialized with 25–50% of the gross product sold.
2. Dryland production systems
   a. *rainfed shifting cultivation* – cropped less than 30 years/100 years, long-term wild vegetation fallow, subsistence farming with less than 25% of the product sold.

b. *rainfed short- and long-term annual crops* – permanent farming with an established field rotation, partly to highly commercialized with more than 25% of the gross product sold.
c. *rainfed perennial crops* – permanent farming, highly commercialized with more than 75% of the product sold.
d. *rainfed crop-pasture* – permanent or stationary cultivation with fallow, grass pasture between crops, partly to semicommercialized with 25–75% of the product sold.
e. *rainfed crop-timber* – semipermanent cultivation, partly commercialized, 25–50% of the product sold.

SOIL-RELATED CONSTRAINTS TO INCREASED PRODUCTION

On a global basis, the main soil-related constraints to the use of the world's soil resources are drought, mineral stress, shallow depth, water excess, and permafrost (Table 5). Estimates for Southeast Asia indicate that only 14% of the total soil resources have no serious limitations for agriculture, while 59% suffer from mineral stress, 19% from excess water, 6% from shallow depth, and 2% from drought.

To obtain a clearer picture of problems and potentials for increased production, the eight production systems identified were combined in three groups based on similarities in broad requirements. Shifting cultivation is excluded as it is unsuitable for increasing production. The groups are:

1. wetland rice production systems incorporating irrigated, rainfed, and deepwater rice cultivation;
2. dryland rainfed short- and long-term annual crop production systems incorporating grass pasture between crops; and

Table 5. World soil resources and their major limitations for agriculture.[a]

Region	Percent of total land area					
	With limitation					No serious limitation
	Drought	Mineral stress[b]	Shallow depth	Water excess	Permafrost	
North America	20	22	10	10	16	22
Central America	32	16	17	10	–	25
South America	17	47	11	10	–	15
Europe	8	33	12	8	3	36
Africa	44	18	13	9	–	16
South Asia	43	5	23	11	–	18
North and Central Asia	17	9	38	13	13	10
Southeast Asia	2	59	6	19	–	14
Australia	55	6	8	16	–	15
World	28	23	22	10	6	11

[a]Data compiled from *FAO/Unesco soil map of the world.* [b]Nutritional deficiencies or toxicities related to chemical composition or mode of origin.

3. dryland rainfed perennial crop production systems incorporating grass pasture between crops and annual crop-timber associations.

Basic crop requirements for each group are presented in Table 6, while Tables 7, 8, and 9 identify main soil-related constraints for each group by major soils of Southeast Asia (FAO, in press). Eight constraints are identified.

Water deficit – Water (precipitation and surface water) may be insufficient to meet growing season requirements because of rainfall distribution, poor water-holding capacity, high permeability and rapid runoff, or any combination of these.

Water excess – Waterlogging and deep and prolonged flooding may be considered constraints depending on crop tolerance.

Texture – Coarse textures, surface stoniness and rockiness, or poor workability may mechanically impede land preparation and seeding.

Shallow depth – Shallow soil layers mechanically impede root distribution.

Fertility – Soil fertility relates to availability of nitrogen, potassium, and phosphorus; biological nitrogen fixation; sulfur deficiency; and micronutrients.

Soil reaction – The constraints result from acidity in dryland and wetland soils.

Soil salinity – The constraint is mainly evident in coastal soils.

Soil erodibility – The constraint is due to a combination of factors including high rainfall, the slope of the land, vegetation cover, nature of the soils, and cultivation practices.

Table 6. Basic requirements of production system groups of Southeast Asia.

Basic crop requirement	Requirements of production system groups		
	Wetland rice production	Dryland rainfed short- and long-term annual crop production	Dryland rainfed perennial crop production
Soil			
Texture	Loams to clays, coarse textures only suited when flooded	Sandy loam to clay, loams optimal, surface stoniness rockiness limit tillage	Sandy loam to clay, loam to clay loam optimal
Depth	Shallow rooting but depth >40 cm optimal	Moderate and shallow rooting depth >50 cm optimal	Moderate and deep rooting depth >50 cm optimal
Permeability	Moderate to slow, permeable soils require high water table or puddling	Moderate	Moderate

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Table 6 continued

Basic crop requirement	Requirements of production system groups		
	Wetland rice production	Dryland rainfed short- and long-term annual crop production	Dryland rainfed perennial crop production
Drainage	Well to very poorly drained, short periods of deep flooding tolerated	Somewhat poorly to well-drained, short periods of water-logging tolerated	Moderately well to well, short periods of waterlogging tolerated
Fertility	Low to high, excessive salinity and toxicity limiting	Low to high, medium to high optimal, excessive salinity and toxicity limiting	Low to high, medium to high optimal, excessive salinity and toxicity limiting
Soil reaction	Range pH 4.0–7.0, optimum 5.0–6.0, >8.0 and <4.0 limiting	Range pH 4.0–7.0, optimum 5.0–6.0, >8.0 and <4.0 limiting	Range pH 4.0–7.0, optimum 5.0–6.0, >8.0 and <4.0 limiting
Climate			
Temperature range during growing period	Range 15–40°C, optimum 20–30°C	Range 15–40°C, optimum 15–35°C	Range 14–40°C, optimum 24–30°C (optimum 16°C for China tea)
Water	>250 mm/mo or equivalent during growing period, only short dry period (topsoil) tolerated	100–250 mm/mo will tolerate short dry periods (up to 3 wk) which are beneficial before harvest	140–300 mm/mo will tolerate dry periods of 1 to 2 mo duration
Humidity	Moderate to very high	Moderate to high	Moderate to high
Topography	Flat relief, sloping or irregular land must be leveled or terraced	Nearly level to moderately steep, erosion control needed on steeper areas	Nearly level to moderately steep, but can be grown on steeper areas
Elevation	0 to 2000 m	Less than 2000 m, some crops less than 1000 m	Variable – arabica coffee 1000 to 1700 m, other crops less than 1000 m
Growing period	120 to 180 days inclusive of nursery stage and dependent on variety and altitude	Variable, 90 to 180 days short term, 6–18 mo long term, depending on crop, variety, and altitude	Continuous cropping after reaching maturity – 8 mo banana, 2 to 5 years other crops

Table 7. Soil-related constraints to wetland rice production systems in the major soils of Southeast Asia.

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Acrisols	Ultisols								
Ferric	Udults/Ustults (oxic)	EC							
Gleyic	Aquults	Ni-Hi	Ni	Ni	Ni	Mi	Li	Ni-Mi	Ni-Mi
Humic	Humults	EC							
Orthic	Udults/Ustults	EC							
Plinthic	Udults/Ustults (plinthic)	EC							
Cambisols	Tropepts								
Dystric	Dystropepts	Hi	Ni	Ni	Ni	Mi	Li	Ni	Mi-Hi
Eutric	Eutropepts	Hi	Ni	Ni	Ni	Li	Ni	Ni	Mi-Hi
Ferralic	Oxic Tropepts	EC							
Gleyic	Aquic Tropepts	Ni-Mi	Li	Ni	Ni	Li	Ni	Ni	Li
Humic	Humitropepts	EC							
Vertic	Vertic Tropepts	Mi	Ni	Li	Ni	Li	Ni	Ni	Li
Rendzinas	Rendolls	EC							
Ferralsols	Oxisols								
Acric	Acrox	EC							
Humic	Humox	EC							
Orthic	Orthox/Ustox	EC							
Rhodic	Orthox/Ustox	EC							
Xanthic	Orthox	EC							
Gleysols									
Dystric	Aquents/Aquepts	Ni-Mi	Li	Ni	Ni	Mi	Li	Ni-Mi	Ni

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Table 7 continued

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Eutric	Aquents/Aquepts	Ni-Mi	Li	Ni	Ni	Li	Ni	Ni-Hi	Ni
Humic	Histic Aquepts	Ni-Mi	Li	Ni	Ni	Mi	Mi	Ni	Ni
Lithosols	Lithic subgroups	EC							
Fluvisols									
Dystric	Fluvents	Ni-Mi	Li	Ni	Ni	Mi	Ni	Ni	Ni
Eutric	Fluvents	Ni-Mi	Li	Ni	Ni	Li	Ni	Ni-Hi	Ni
Thionic	Sulfaquents/Sulfaquepts						EC		
Luvisols	Alfisols								
Chromic	Udalfs/Ustalfs (rhodic)	Hi	Ni	Ni-Mi	Ni-Mi	Li	Ni	Ni	Hi
Ferric	Udalfs/Ustalfs (oxic)	EC							
Gleyic	Aqualfs	Ni-Hi	Ni	Ni	Ni	Li	Ni	Ni	Ni-Mi
Calcic	Haplustalfs	EC							
Orthic	Tropudalfs	Hi	Ni	Ni	Ni	Li	Ni	Ni	Hi
Vertic	Udalfs/Ustalfs (vertic)	Hi	Ni	Li	Ni	Li	Ni	Ni	Hi
Nitosols	Ultisols								
Dystric	Udults/Ustults	Hi	Ni	Ni	Ni	Mi	Li	Ni	Hi
Eutric	Udults/Ustults	Hi	Ni	Ni	Ni	Li	Ni	Ni	Hi
Humic	Humults	Hi	Ni	Ni	Ni	Mi	Li	Ni	Hi
Histosols	Histosols								
Dystric	Hemists					EC			
Eutric	Fibrists/Saprists					EC			
Podzols	Spodosols								

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Table 7 continued

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Gleyic	Aquods								
Humic	Humods	EC				EC			
Orthic	Orthods	EC							
Arenosols	Psamments								
Albic	Psamments	EC							
Cambic	Psamments	EC							
Ferralic	Psamments	EC							
Regosols									
Calcaric	Psamments	EC							
Dystric	Psamments	EC							
Eutric	Psamments/Orthents	EC							
Andosols	Andepts								
Humic	Dystrandepts	EC							
Mollic	Eutrandepts	Hi	Ni	Ni	Ni	Li	Ni	Ni	Hi
Ochric	Dystrandepts	Hi	Ni	Ni	Ni	Mi	Li	Ni	Hi
Vitric	Vitrandepts	EC							
Vertisols	Vertisols								
Chromic	Uderts/Usterts (chromic)	Mi-Hi	Ni	Mi	Ni	Li	Ni	Ni	Li
Pellic	Uderts/Usterts (pellic)	Mi-Hi	Ni	Mi	Ni	Li	Ni	Ni	Li

[a] *FAO-Unesco soil map of the world. Vol. 9, Southeast Asia.* [b] EC = excluding condition, i.e., cannot be corrected at currently acceptable cost; Ni = no input, i.e., no constraint; Hi = high input; Mi = moderate input; Li = low input.

Table 5. Soil-related constraints to dryland rainfed short- and long-term annual crop production systems in the major soils of Southeast Asia.

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Acrisols	Ultisols								
Ferric	Udults/Ustults (oxic)				EC				
Gleyic	Aquults		EC						
Humic	Humults	Ni	Ni	Ni	Ni-Hi	Mi	Mi	Ni	Hi
Orthic	Udults/Ustults	Li	Ni	Ni	Ni-Hi	Mi	Mi	Ni	Li-Mi
Plinthic	Udults/Ustults (plinthic)				EC				
Cambisols	Tropepts								
Dystric	Dystropepts	Ni	Ni	Ni	Ni	Mi	Li	Ni	Li-Hi
Eutric	Eutropepts	Ni	Ni	Ni	Ni	Li	Ni	Ni	Mi-Hi
Ferralic	Oxic Tropepts	Ni	Ni	Ni	Ni	Mi	Li	Ni	Mi-Hi
Gleyic	Aquic Tropepts	Ni	Mi	Ni	Ni	Li	Ni	Ni	Li
Humic	Humitropepts	Ni	Ni	Ni	Ni	Mi	Li	Ni	Hi
Vertic	Vertic Tropepts	Mi	Ni	Li	Ni	Li	Ni	Ni	Li
Rendzinas	Rendolls	Mi	Ni	Ni	Mi-Hi	Li	Ni	Ni	Li-Hi
Ferralsols	Oxisols								
Acric	Acrox	Mi	Ni	Ni	Ni	Mi	Li	Ni	Li-Mi
Humic	Humox				EC				
Orthic	Orthox/Ustox	Li	Ni	Li	Ni	Mi	Li	Ni	Li-Mi
Rhodic	Orthox/Ustox	Ni	Ni	Ni	Ni-Mi	Mi	Li	Ni	Li-Hi
Xanthic	Orthox				EC				
Gleysols									
Dystric	Aquents/Aquepts		EC						
Eutric	Aquents/Aquepts		EC						
Humic	Histic Aquepts		EC						

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Table 8 continued

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Lithosols	Lithic subgroups				EC				
Fluvisols									
Dystric	Fluvents		EC						
Eutric	Fluvents		EC						
Thionic	Sulfaquents/Sulfaquepts		EC						
Luvisols	Alfisols								
Chromic	Udalfs/Ustalfs (rhodic)	Li-Mi	Ni	Ni	Ni	Li	Ni	Ni	Mi-Hi
Ferric	Udalfs/Ustalfs (oxic)				EC				
Gleyic	Aqualfs	Li	Li	Ni	Ni	Li	Ni	Ni	Li-Mi
Calcic	Haplustalfs	Li	Ni	Ni	Li	Li	Ni	Ni	Li
Orthic	Tropudalfs	Li-Mi	Ni	Ni	Ni	Li	Ni	Ni	Mi-Hi
Vertic	Udalfs/Ustalfs (vertic)	Li-Mi	Ni	Li	Ni	Li	Ni	Ni	Mi-Hi
Nitosols	Ultisols								
Dystric	Udults/Ustults	Ni	Ni	Ni	Ni	Mi	Li	Ni	Li-Hi
Eutric	Udults/Ustults	Ni	Ni	Ni	Ni	Li	Ni	Ni	Mi-Hi
Humic	Humults	Ni	Ni	Ni	Ni	Mi	Li	Ni	Li-Mi
Histosols	Histosols								
Dystric	Hemists		EC						
Eutric	Fibrists/Saprists		EC						
Podzols	Spodosols								
Gleyic	Aquods		EC						

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Table 8 continued

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Humic	Humods	EC							
Orthic	Orthods	EC							
Arenosols	Psamments								
Albic	Psamments	EC							
Cambic	Psamments	EC							
Ferralic	Psamments	EC							
Regosols									
Calcaric	Psamments	Hi	Ni	Hi	Ni	Li	Ni	Ni	Li
Dystric	Psamments	EC							
Eutric	Psamments/Orthents	Ni-Hi	Ni	Ni-Hi	Ni	Mi	Ni	Ni	Ni-Hi
Andosols	Andepts								
Humic	Dystrandepts	Ni	Ni	Ni	Ni	Mi	Li	Ni	Mi-Hi
Mollic	Eutrandepts	Li	Ni	Ni	Ni	Li	Ni	Ni	Li-Hi
Ochric	Dystrandepts	Ni	Ni	Ni	Ni	Mi	Li	Ni	Li-Hi
Vitric	Vitrandepts			EC					
Vertisols	Vertisols								
Chromic	Uderts/Usterts (chromic)	Mi	Ni	Mi	Ni	Li	Ni	Ni	Li
Pellic	Uderts/Usterts (pellic)	Mi	Ni	Mi	Ni	Li	Ni	Ni	Li

[a] *FAO-Unesco soil map of the world. Vol. 9, Southeast Asia.* [b] EC = excluding condition, i.e., cannot be corrected at currently acceptable cost; Ni = no input, i.e., no constraint; Hi = high input; Mi = moderate input; Li = low input.

Table 9. Soil-related constraints to dryland rainfed perennial crop production system in the major soils in Southeast Asia.

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Acrisols	Ultisols								
Ferric	Udults/Ustults (oxic)	Ni	Ni	Ni	Li-Mi	Mi	Li	Ni	Li-Mi
Gleyic	Aquults		EC						
Humic	Humults	Ni	Ni	Ni	Ni-Hi	Mi	Li	Ni	Mi-Hi
Orthic	Udults/Ustults	Ni	Ni	Ni	Ni-Hi	Mi	Li	Ni	Li
Plinthic	Udults/Ustults (plinthic)				EC				
Cambisols	Tropepts								
Dystric	Dystropepts	Ni	Ni	Ni	Ni	Mi	Ni	Ni	Li-Mi
Eutric	Eutropepts	Ni	Ni	Ni	Ni	Li	Ni	Ni	Mi
Ferralic	Oxic Tropepts	Ni	Ni	Ni	Ni	Mi	Ni	Ni	Mi
Gleyic	Aquic Tropepts		EC						
Humic	Humitropepts	Ni	Ni	Ni	Ni	Mi	Ni	Ni	Mi-Hi
Vertic	Vertic Tropepts	Mi	Ni	Li	Ni	Li	Ni	Ni	Li
Rendzinas	Rendolls	Li	Ni	Ni	Mi-Hi	Li	Ni	Ni	Li-Mi
Ferralsols	Oxisols								
Acric	Acrox	Li	Ni	Ni	Ni	Mi	Li	Ni	Li
Humic	Humox				EC				
Orthic	Orthox/Ustox	Li	Ni	Ni	Ni	Mi	Ni	Ni	Li
Rhodic	Orthox/Ustox	Ni	Ni	Ni	Ni-Mi	Mi	Ni	Ni	Mi
Xanthic	Orthox				EC				
Gleysols									
Dystric	Aquents/Aquepts		EC						
Eutric	Aquents/Aquepts		EC						

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Table 9 continued

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Humic	Histic/Aquepts		EC						
Lithosols	Lithic subgroups				EC				
Fluvisols									
Dystric	Fluvents		EC						
Eutric	Fluvents		EC						
Thionic	Sulfaquents/Sulfaquepts		EC						
Luvisols	Alfisols								
Chromic	Udalfs/Ustalfs (rhodic)	Li-Mi	Ni	Ni	Ni	Li	Ni	Ni	Mi-Hi
Ferric	Udalfs/Ustalfs (oxic)				EC				
Gleyic	Aqualfs		EC						
Calcic	Haplustalfs	Ni	Ni	Ni	Li	Li	Ni	Ni	Li
Orthic	Tropudalfs	Li-Mi	Ni	Ni	Ni	Li	Ni	Ni	Mi
Vertic	Udalfs/Ustalfs (vertic)	Li-Mi	Ni	Ni	Ni	Li	Ni	Ni	Mi
Nitosols	Ultisols								
Dystric	Udults/Ustults	Ni	Ni	Ni	Ni	Mi	Ni	Ni	Li-Mi
Eutric	Udults/Ustults	Ni	Ni	Ni	Ni	Li	Ni	Ni	Li-Hi
Humic	Humults	Ni	Ni	Ni	Ni	Li	Ni	Ni	Li
Histosols	Histosols								
Dystric	Hemists		EC						
Eutric	Fibrists/Saprists	Ni	Hi	Mi	Ni	Mi	Ni	Ni-Hi	Li
Podzols	Spodosols								

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Table 9 continued

Soil units[a]	USDA *Soil taxonomy* equivalent	Requirements[b] for alleviating the constraint							
		Water deficit	Water excess	Texture	Shallow depth	Fertility	Soil reaction	Soil salinity	Soil erodibility
Gleyic	Aquods		EC						
Humic	Humods	Mi	Ni	Mi	Ni	Mi-Li	Li	Ni	Li
Orthic	Orthods	Mi	Ni	Mi	Ni	Mi-Hi	Li	Ni	Li
Arenosols	Psamments								
Albic	Psamments	Li-Mi	Ni	Ni-Li	Ni	Mi	Li	Ni	Li
Cambic	Psamments	Li-Mi	Ni	Li	Ni	Mi	Li	Ni	Li-Mi
Ferralic	Psamments	Li-Mi	Ni	Li	Ni	Mi	Li	Ni	Mi
Regosols									
Calcaric	Psamments	Ni-Li	Ni	Mi	Ni	Li	Ni	Ni	Li
Dystric	Psamments	Ni-Li	Ni	Mi	Ni	Mi	Li	Ni	Li
Eutric	Psamments/Orthents	Ni-Li	Ni	Ni-Mi	Ni	Mi	Ni	Ni	Ni-Hi
Andosols	Andepts								
Humic	Dystrandepts	Ni	Ni	Ni	Ni	Mi	Li	Ni	Li-Hi
Mollic	Eutrandepts	Ni	Ni	Ni	Ni	Li	Ni	Ni	Li-Hi
Ochric	Dystrandepts	Ni	Ni	Ni	Ni	Mi	Li	Ni	Li-Hi
Vitric	Vitrandepts	Li	Ni	Mi-Hi	Ni	Mi	Ni	Ni	Hi
Vertisols	Vertisols								
Chromic	Uderts/Usterts (chromic)	Li	Mi	Li	Ni	Li	Ni	Ni	Li
Pellic	Uderts/Usterts (pellic)	Li	Li	Li	Ni	Li	Ni	Ni	Li

[a]*FAO-Unesco soil map of the world. Vol. 9, Southeast Asia.* [b]EC = excluding condition, i.e., cannot be corrected at currently acceptable cost; Ni = no input, i.e., no constraint; Hi = high input; Mi = moderate input; Li = low input.

Depending on severity, one or more constraints may limit the number of possible crops or increase the inputs required, or do both. Where the constraint cannot be corrected because technology is inadequate or the cost of correction is not economically justified, it is considered an *excluding condition*, which precludes the production system in question.

In Tables 7 to 9 connotative symbols indicate development costs required to alleviate the constraint. Where there is an *excluding condition*, no assessment is made for secondary constraints.

Ni = no input, no constraint;

Li = low input; the constraint is slight, development costs can generally be borne by the farmer;

Mi = moderate input; moderate constraint, development costs can be borne by the farmer with credit facilities or subsidies;

Hi = high input; severe constraint, development costs involve substantial government funding or long-term credit;

EC = excluding condition; the constraint is severe and either permanently precludes any possibility of sustained production, or cannot be corrected with existing knowledge at currently acceptable cost.

Acrisols

Acrisols cover some 51% of Southeast Asia; Orthic Acrisols alone account for about 35%. Most steeply sloping, lithic, stony, and petric Acrisols offer severe physical constraints to permanent cultivation.

Combined with the Acrisols' low inherent fertility, the constraints result in low to very low agricultural potential. In the rooting depth deep, gently sloping Acrisols without physical limitations have low inherent fertility and are subject to erosion on exposed slopes. Their use for permanent agriculture is entirely dependent on the feasible level of management.

Because it is difficult or impossible to impound water on Acrisols water deficit generally precludes any expansion of wetland rice on most of them. Only low-lying and level Gleyic Acrisols (northeast Thailand, Kampuchea, and Laos) show any potential for wetland rice production; however, crop failures may occur in years of low or poorly distributed rainfall. Sustained cultivation requires heavy fertilizer inputs to counter low inherent fertility and acidity. In addition, salt-affected spots may occur in years of low rainfall.

A combination of constraints including low inherent soil fertility, acidity, erodibility, shallow depth, and poor water economy generally precludes the use of Gleyic Acrisols, Plinthic Acrisols, and shallow, steeply dissected and mountainous Ferric, Orthic, and Humic Acrisols for dryland production systems.

Possibilities for the expansion of annual crop production are restricted to deep, level to undulating Humic and Orthic Acrisols. Perennial crop production is feasible on deep to moderately deep, undulating and rolling Ferric, Humic, and Orthic Acrisols, which are easy to manage and maintain under commercial tree crops such as rubber and oil palm.

Expansion of permanent agriculture on Acrisols is practical only under good management. Without essential management inputs, a high risk element may lead to serious and widespread physical and chemical soil degradation.

Cambisols

Cambisols cover about 5% of Southeast Asia. These soils have moderate to high agricultural potential, except those with steeply dissected slopes or adverse physical properties.

Gleyic Cambisols of the Philippines and Java have good chemical and physical properties and are highly favorable for irrigated rice. The main constraint is occasional flooding. Deep, gently sloping Dystric, Eutric, and Vertic Cambisols of Indonesia support terraced, spring-irrigated rice. Dystric Cambisols have low inherent fertility, but respond well to fertilizer application; the physical properties of Vertic Cambisols are less favorable for tillage. Water deficit in Ferralic and Humic Cambisols precludes their use for wetland rice.

The permanent production of annual crops can be maintained on deep, level to undulating Cambisols. Eutric Cambisols have favorable physical and chemical properties. Ferralic, Humic, and Dystric Cambisols have low inherent fertility. Water control is essential to the successful utilization of Gleyic Cambisols, and unfavorable physical properties and susceptibility to water deficit limit Vertic Cambisols.

Deep to moderately deep, undulating to rolling Dystric, Eutric, Ferralic, Humic, and Vertic Cambisols offer good possibilities for perennial-crop production under good management with emphasis on erosion protection. However, excess water is generally an excluding condition for Gleyic Cambisols.

Rendzinas

Rendzinas cover only 1% of Southeast Asia, mainly in parts of Indonesia. Water deficit generally precludes their use for wetland rice, and only limited possibilities exist for dryland production systems. Although Rendzinas are chemically rich, their productive capacity is determined by their water-holding capacity, which varies widely depending on depth, organic matter content, and the hardness or brittleness of the underlying limestone. Rendzinas on exposed slopes are highly susceptible to erosion.

Ferralsols

About 4% of Southeast Asia is covered by Ferralsols. Water deficit usually precludes their use for wetland rice. Petric and petroferric phases of Humic, Xanthic, Orthic, and Rhodic Ferralsols severely limit plant growth in the rooting zone. Such limitations, combined with the soils' low inherent fertility, usually preclude the permanent production of dryland crops.

However, deep, gently sloping Acric, Orthic, and Rhodic Ferralsols of continental Southeast Asia have moderate potential for dryland crop production. Their good physical properties offset, to some extent, their low inherent fertility.

The main constraints on Acric and Orthic Ferralsols are low fertility, acidity, and low available water-holding capacity. Orthic Ferralsols also suffer from poor workability and are susceptible to erosion on unprotected slopes. Low inherent fertility is the principal constraint on Rhodic Ferralsols.

Gleysols

Gleysols cover about 5% of Southeast Asia. They are important rice-growing soils, but water excess generally precludes their use for dryland production systems.

With irrigation, continuous rice production is feasible in most years on Dystric Gleysols of Thailand, Malaysia, Laos, and Indonesia. The main constraint is low inherent fertility; in northeast Thailand potential or actual salinity is a constraint in dry years. Aluminum toxicity in strongly acid soils also depresses yields and flash flooding endangers crop growth.

With the exception of a saline phase on coastal flats of Thailand, West Malaysia, and Vietnam, Eutric Gleysols are fairly fertile and continuous rice cropping under a combination of irrigation and drainage is successful.

The Humic Gleysols of Indonesia have a high organic matter content due to the presence of dystric histic material in surface layers. The constraints are acidity, low inherent fertility, and flash flooding. Consequently water control, fertilizer application, and liming are essential to sustained wetland rice cultivation.

Lithosols

Lithosols occur in all countries of Southeast Asia and cover about 3% of the total land area. Their shallowness and the presence of stones and rock outcrops generally preclude any form of permanent cultivation.

Fluvisols

Fluvisols cover about 8% of Southeast Asia and are important wetland rice-growing soils. Water excess usually precludes their utilization for extensive dryland production, although levee soils are traditionally used for settlement sites with home gardens, orchards, and banana plantations.

The Dystric Fluvisols of Indonesia have a low inherent fertility and variable organic matter content and soil reaction. They respond well to moderate applications of nitrogen and phosphate fertilizers. Water control is the main constraint, but the combination of irrigation and drainage makes intensive cultivation possible.

The combined area of Eutric Fluvisols is less than that of Dystric Fluvisols, and a saline phase on coastal flats is unsuitable for wetland rice production. Most Eutric Fluvisols have moderate to high inherent fertility, but their potential for intensive rice cultivation is again dependent on water control.

Thionic Fluvisols are more extensive in the Chao Phraya and Mekong deltas. Smaller areas in Malaysia and Indonesia include a saline phase. The main diag-

nostic character of these soils is a sulfuric horizon or sulfidic materials within the 125-cm depth. At present it is not possible to suggest generally applicable techniques for improved agriculture on Thionic Fluvisols, but water control, leaching, and liming are possibilities. In general their agricultural potential is low.

Luvisols

Luvisols cover about 5% of Southeast Asia. They have moderate to high agricultural potential, except for soils with steeply dissected slopes or adverse physical properties. They have moderate to high inherent fertility, but are highly susceptible to erosion. In drier areas their intensive use is dependent on irrigation water availability.

Wetland rice production is limited to Gleyic Luvisols of Laos, Thailand, and Kampuchea. To a lesser extent, it occurs on deep gently sloping Chromic, Orthic, and Vertic Luvisols of Indonesia and the Philippines where terraced irrigation systems are feasible. Water deficit in Ferric and Calcic Luvisols precludes their use for wetland rice.

Water excess precludes the use of Gleyic Luvisols for perennial crops and is the main constraint to their use for annual dryland crops. Water deficit during the dry season and susceptibility to erosion of Chromic, Calcic, Orthic, and Vertic Luvisols are the main constraints to their use for dryland production systems. Shallow depth and poor workability are additional constraints on Calcic and Vertic Luvisols. Very low inherent fertility and shallow depth of Ferric Luvisols generally preclude their use for permanent cultivation.

Nitosols

Nitosols cover about 5% of Southeast Asia. They occur in parts of Laos, Kampuchea, Thailand, Malaysia, and Indonesia, but are most extensive in the Philippines.

Main constraints to agricultural production on Nitosols are erodibility and low to moderate inherent fertility. In Java these soils are terraced for spring-irrigated rice cultivation. In general, however, they are better suited to dryland production systems.

Dystric and Humic Nitosols are slightly to strongly acid and have low to moderate inherent fertility. They respond well to combined dressings of phosphate and nitrogen, but occasionally require trace elements. Eutric Nitosols have a higher level of inherent fertility and a high agricultural potential.

Nitosols in general have good physical properties for tillage and are resistant to erosion, provided adequate conservation measures are applied.

Histosols

Histosols cover about 6% of Southeast Asia and are extensive in low coastal areas of Sumatra, Borneo, and Irian. Their environmental properties appear to favor wetland rice cultivation, but to date, attempts to grow rice on them have failed. Reclamation for dryland cultivation introduces a number of physical limitations

and gives a low potential.

Dystric Histosols are chemically poor, oligotrophic peats with low ash contents. Physical properties are marginal, even after reclamation. Rice failure is thought due to ertain organic compounds that directly or indirectly hinder (through copper ion) one or more essential enzyme-catalyzed carbohydrate formations (Drie- a and Suhardjo 1976).

The inherent fertility of Eutric Histosols is greater than that of Dystric Histosols, if soil salinity level does not interfere with crop growth. With cautious drainage to minimize subsidence and specialized cultural practices, nonsaline Eutric Histosols have potential for perennial crop production.

Podzols

The Podzols cover about 2% of Southeast Asia, occurring mainly in Indonesia. Their coarse texture and poor water and nutrient retention capacities generally preclude their use for permanent cultivation.

Water excess in Gleyic Podzols precludes their use for dryland crops, while low inherent fertility and acidity generally preclude their use for wetland rice.

Water deficit in Humic and Orthic Podzols, coarse texture, very low inherent fertility, and acidity generally preclude their use for dryland annual crops. Limited possibilities exist for the production of perennial crops and commercial timber.

Arenosols

Arenosols, which cover about 2% of Southeast Asia, occur mainly in Indonesia, Sarawak, and the Philippines.

Water deficit combined with coarse soil texture, low inherent fertility, acidity, and erodibility generally preclude their use for wetland rice and dryland annual crop production. Limited possibilities exist for dryland perennial crops, and the high management inputs required to counteract the constraints may not be economically justified.

Regosols

Regosols occur over less than 1% of Southeast Asia. Water deficit precludes their use for wetland rice.

Calcaric Regosols are chemically rich, but have a low moisture retention capacity and show water deficit during dry spells. Their potential for dryland annual crop production is dependent on the availability of supplemental irrigation water. Calciophile perennial crops are successful where the water table is not too deep.

Dystric Regosols exhibit water deficit, coarse texture, low inherent fertility, and acidity. In combination these constraints usually preclude the soils' use for annual crops. Limited possibilities exist for perennial crops and commercial timber.

Sandy Eutric Regosols and Calcaric Regosols have similar constraints and potential. A steeply dissected, stony phase of Eutric Regosols occurs on volcanic

slopes in Indonesia. Main constraints are stoniness, shallow depth, water deficit, and soil erodibility. Deeper, less stony soils can support terraced, spring-irrigated rice or annual and perennial crops.

Andosols

Andosols cover about 2% of Southeast Asia and occur mainly in Indonesia and the Philippines.

Water deficit generally precludes the use of Humic and Vitric Andosols for wetland rice. Terraced, spring-irrigated rice is feasible on some lower slopes of Mollic and Ochric Andosols.

Humic and Ochric Andosols have good physical and chemical properties and moderate potential for dryland crop production where slope and elevation are not constraints. Their natural productivity depends on acidity, levels of exchangeable aluminum, texture, organic matter content, and mineral reserves.

Mollic Andosols have good physical and chemical properties and a high potential for dryland crop production where water deficit, slope, and elevation are not severe constraints.

The main constraints on Vitric Andosols are water deficit, coarse texture, and erodibility. The soils are chemically rich, but lack sufficient capacity to retain cations. Very limited possibilities exist for perennial crops where texture and stone and boulder content permit their cultivation.

Vertisols

Vertisols cover about 1% of Southeast Asia. They are chemically rich, but are difficult to work and have water deficit to a greater or lesser extent during the dry season.

The Chromic Vertisols of Java and Luzon have adverse physical properties and poor workability. Their use for wetland rice production is largely dependent on the availability of sufficient irrigation water. Dryland crop production is successful in areas with a short dry season if the soils are not waterlogged in the rainy season. In drier areas, however, the overall productivity is low and dry-season use is limited to low-intensity grazing.

Pellic Vertisols occur in Indonesia, the Philippines, Laos, Vietnam, Kampuchea, and Thailand where a pronounced monsoon climate prevails. Their physical conditions are often more favorable than those of Chromic Vertisols. Pellic Vertisols are susceptible to water erosion if no protective measures are taken. Water deficit is the main constraint, but with favorable climatic conditions or with sufficient irrigation water, the soils are well suited to wetland rice and dryland production systems.

FUTURE PRODUCTION POTENTIALS

Few of the soils of humid tropical Asia are without constraints in some degree, and their potential for development largely depends on the level of management

practiced by the farmer and, hence, his ability to understand the technology required to alleviate the constraints, and his access to the required inputs.

Increased production required to keep pace with a fast expanding population cannot be achieved by traditional farming systems. Increased output means increased input and hence increased farmer investment. Traditional farming systems involve minimal investment and minimal risk. Increased inputs involve higher investment risks, and a farmer needs sufficient incentives to change from subsistence or partially commercialized traditional systems to the semicommercialized or highly commercialized systems required for increased production.

The threat of a fast expanding population outpacing growth in agricultural production is incentive enough for national planners to recognize the need for change; but in practice rural development programs have often failed because they could not achieve two essential objectives:

1. to increase the productivity of the rural poor, particularly the small and marginal farmers; and
2. to ensure their full participation in planning and executing the program.

The small farmers in Southeast Asia are poor because of the smallness of their holdings and as they control few resources, their incomes are low. They are thus generally handicapped by the limited availability of irrigation, credit, chemicals, and other inputs for increased production and suffer from unfavorable market conditions and prices.

If farmers are to actively participate in rural development, the reasons for increased production and hence change in farming methods must be expressed in such a way that the farmer perceives the benefits for himself. Incentives for change must include improved farmer access to basic resources and better relationship with transportation and market infrastructures. Technologies for increasing production must exist and either the farmer must be capable of applying them, or extension services must exist to teach the use of new inputs.

Where sociological inertia is great, new technologies are slow to take root without adequate farmer education to bridge the communications gap between farmers and academics. It is unrealistic to expect a sudden surge in production through widespread application of instant technology. Short-term production potential (the present decade) will focus on areas that are already benefiting from new technology, i.e. wetland rice production systems.

The principal rice-growing soils in Southeast Asia are Gleysols and Fluvisols. With the exception of the saline phases and Thionic Fluvisols, the two soils are highly productive under irrigation. Gleyic Cambisols, Luvisols, and, to a lesser extent, Acrisols are utilized mainly for rainfed rice, but where potential for irrigation exists greater production can be expected. Vertisols and Vertic Cambisols are utilized for rainfed rice, and the potential from irrigation depends on local availability of year-round water supplies. Dystric and Eutric Cambisols; Chromic, Orthic, and Vertic Luvisols; Nitosols; and Mollic and Ochric Andosols support terraced, spring-irrigated rice; but a rainy season rice crop followed by short-term dryland annuals uses water more efficiently.

In the final analysis wetland rice production depends on the availability of sufficient water to satisfy the high water requirements of the crop. This automatically restricts the areal extent of wetland rice production systems in the region, and there is little scope for expanding the area under production. Production potential is dependent on higher yields per unit of area made possible by the technological breakthrough of MV and associated technology.

Acceptance of MV technology has resulted in a fairly steady increase in MV in proportion to total rice; however, the rate of adoption among countries and within countries of the region varies (Table 10). This variation is apparently related to physical conditions rather than to institutional factors.

If the full potential of present generation MV is to be realized, assured and controlled water supplies, fertilizers, crop protectants, and new implements and sources of power for carrying out field and postharvest operations are required. Although fertilizers have contributed significantly to the growth of rice production, the combined effect of area and yield increase due to expanded irrigation facilities exceeds the contribution of fertilizers.

MV adoption appears slow because traditional varieties perform as well as or better than MV in non-irrigated areas. Another limit to a more rapid expansion of the current generation of MV is that most of the land presently under irrigation has already been planted to some form of MV. Recent changes in irrigated area and in the proportion of net cropped area under irrigation vary considerably (Table 11), and not all irrigated areas have produced net gains.

The potential exists for expansion of area under irrigation, especially under small-scale irrigation schemes, and for the continued spread of MV. The potential for a steady rise in rice production through increased yields per unit area therefore exists and although the efforts and resources required will be very large indeed, the increase is essential if calorie requirements of the region are to be met.

Long-term production potential (year 2000) is focused on the expansion of the area under permanent dryland crop cultivation. At present permanent cropping is restricted to highly commercialized tree crop production of rubber and oil palm; and semicommercialized to highly commercialized annual crop produc-

Table 10. Area planted to modern rice varieties (MV) in selected countries in humid tropical Asia, 1970–71 and 1974–75.

Country	Area planted to MV (thousand ha)		Annual rate of growth (%)	Proportion (%) of rice areas under MV	
	1970–71	1974–75		1970–71	1974–75
Indonesia	903	3440	40	11.1	40.3
Malaysia, West	165	217[a]	10	31.4	37.5
Philippines	1565	2175	9	50.3	61.5
Thailand	30	450	95	0.4	6.1
Vietnam	502	900	16	20.0	17.6

[a]1973–74. Source: Dalrymple 1976.

tion in areas where relatively fertile soils and transportation and market infrastructure incentives exist. While possibilities exist for increasing production per unit area on Cambisols, Luvisols, Nitosols, Andosols, and Vertisols where adverse properties, steeply dissected slopes, and prolonged waterlogging are not excluding conditions, their relatively limited extent in the region restricts the areal expansion of permanent cultivation.

In terms of area, Acrisols and, to a lesser extent, Ferralsols have the greatest potential. But, the constraints on them are severe. With the exception of deep, level to rolling Orthic, Humic, and Ferric Acrisols; and Acric, Orthic, and Rhodic Ferralsols, their combined constraints are usually excluding conditions for permanent production.

Few farmers in this area have the necessary skills or resources for implementing the technology required for permanent production on these soils. To a certain extent, the technology itself is also lacking. Relatively little advance in technology has been achieved for most nonfood crops and food crops other than rice.

There have been striking improvements in yields of rubber (7.5%) and oil palm (2.9%), but yields of cop and tea have remained low in recent years. Most dryland soils are easy to manage and maintain under commercial tree crops, but although considerable potential for the expansion of the area under permanent tree and perennial crop production exists, production potential itself is controlled by fluctuating foreign and local demand for agricultural commodities. Actual potential, therefore, is limited except in Malaysia where development plans emphasize industrialization.

The expansion of permanent dryland annual crop production on Acrisols and Ferralsols without excluding conditions involves high risk – their combined constraints require considerable investment in erosion protection, lime, fertilizers, crop protectants, transportation and farmer education for projected long-term returns. Any attempt to introduce permanent dryland cropping systems on these soils without provision of essential management inputs may well result in crop failures and serious and widespread physical and chemical soil degradation.

RESEARCH ORIENTATION

Wetland rice production systems

To realize the full potential for increased production in wetland production systems, research should be directed toward:

- the extension of irrigation facilities to provide water control essential to the adoption of the present generation of MV, with emphasis on small-scale irrigation and utilization of mechanical power for pumping (to alleviate water deficit or excess, acidity, and salinity constraints to higher yields per unit area);
- increased crossing of MV with local varieties to establish strains resistant to pests and diseases, periodic drought, deep flooding and soil acidity with equal emphasis on increasing yield potential of rainfed varieties (to alleviate water

Table 11. Irrigated area and proportion of net cropped area irrigated in selected countries in humid tropical Asia, 1970–75.[a]

Country	Irrigated area (thousand ha)		Annual rate of growth (%)	Proportion (%) of net cropped irrigated area		Annual rate of growth (%)
	1970	1975		1970	1975	
Indonesia	4280	4380	0.5	32.9	32.8	–0.1
Malaysia, West	231	300	5.4	37.9	48.0	4.8
Philippines	1150	1391	3.9	24.8	27.1	1.8
Thailand	1960	3149	9.9	15.9	21.3	6.0

[a]Source: FAO 1978.

deficit or excess, and acidity constraints to increasing land under permanent cultivation and higher yields per unit area); and

- in-depth fertilizer research on *benchmark* sites, with emphasis on micronutrient studies to establish transferable fertilizer packages at acceptable cost to alleviate fertility constraints to increased production.

Dryland production systems

Research on means to alleviate soil constraints to expanding production of permanent annual and perennial crops should be directed toward:

- alternatives to mechanized land clearing to minimize topsoil destruction, soil compaction, and susceptibility to erosion;
- erosion protection after land clearing, incorporating continuous vegetation cover and conservation work commensurate with slope and the labor and capital resources available to the farmer;
- fertilizer research, including liming and micronutrient studies on *benchmark* sites, to establish transferable fertilizer packages for maintaining fertility levels and meeting crop requirements at acceptable cost;
- varietal research to establish strains tolerant of soil acidity stresses; and
- crop protection research covering resistant varieties, disease and pest protectants, cropping sequences, and intercropping systems.

The practical application of new technology is always dependent on incentives for change and the farmer's understanding of the technology required. The importance of farmer education cannot be overemphasized, for a permanent solution to the food and population problem can only be attained when a smaller-family norm has taken root in the social organization of the people of the region. More of the available resources can then be utilized in raising the standard of living rather than sustaining a fast expanding population.

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Soil constraints in relation to major farming systems of tropical America

P. A. SANCHEZ AND T. T. COCHRANE

Farming systems in tropical America are extremely diverse, but can be grouped into two major regions of occurrence: Region A, covering 27%, with mostly high base status soils and dense populations with generally intensive land use; and Region B, covering 70%, with mostly acid soils in the savanna and selva.

Soils in Region A are mostly Alfisols, Inceptisols, Mollisols, Vertisols, and Entisols. The most extensive soil constraints affecting 10 major farming systems are drought stress, erosion, and nitrogen and phosphorus deficiencies. Because of topography and soil physical properties, erosion is the most critical constraint in areas with a severe dry season.

Five major farming systems are described for Region B, which consists mainly of Oxisols, Ultisols, acid Inceptisols, and Entisols. Soil constraints are mostly chemical; the most extensive ones are aluminum toxicity; phosphorus deficiency and fixation; nitrogen, potassium, calcium, magnesium, sulfur, and zinc deficiencies; and low cation exchange capacity. Low water-holding capacity is important in Oxisols and Psamments; soil compaction and erosion are important in sandy-textured Ultisols on steep slopes. Soil management technology for high input agriculture is generally available but can be transferred only to areas close to markets or well served by access routes. Low-cost soil management technology is urgently needed to efficiently utilize these vast areas. Key technology components must include 1) identifying soils suitable for cropping, pastures, tree crops, and those that should remain untouched, 2) selecting cultivars tolerant of acid soil infertility and drought, 3) developing low-cost fertiliza-

Centro Internacional de Agricultura Tropical (CIAT) Apartado Aéreo 67-13 Cali, Colombia; and Soil Science Department, North Carolina State University, Raleigh, N.C., 27650, USA.

tion practices, and 4) developing annual crop-pasture-tree crop sequential or simultaneous systems.

Agronomic, economic, and ecologically sound technology for managing the Oxisol-Ultisol region could have a major and lasting impact on increasing world food production. It can also be a viable alternative for alleviating the erosion problems on the high base status soils.

TROPICAL AMERICA, which encompasses the land area between the tropics of Cancer and Capricorn in the western hemisphere, has extremely variable soil properties and farming systems. There are no dominant systems equivalent to the systems of rice cultivation in tropical Asia, shifting cultivation in tropical Africa, or extensive cattle grazing in tropical Australia.

To our knowledge the tropical American farming systems have not been systematically described. The data base on soils and soil-related constraints is, however, somewhat more developed. Because farming systems and soil constraints are site-specific we present broad generalizations, which may have limited site-specific validity, in an attempt to provide an overview of the soil factors limiting food production in tropical America.

The methodology for our overview comprised making estimates of the areal distribution of the main soils, defining the soil constraints, estimating the extent of each constraint, describing the main farming systems and the relationships between them and the constraints, and finally determining the soil management priorities designed to alleviate the main constraints. We relied largely on our experience and observations and not on an exhaustive literature review.

We calculated the areal distribution of soil orders in relation to soil moisture and temperature regimes from tabular data in the FAO-Unesco soil maps of the world (FAO 1971, 1975) at the scale of 1:5 million and from an ongoing study of the Oxisol-Ultisol regions by Cochrane (1979a) at the scale of 1:1 million. The FAO-Unesco maps use the temperature regimes of Papadakis (1975); the FAO-Unesco mapping legends were converted to USDA soil taxonomy equivalents (USDA 1975). We defined physical and chemical soil constraints according to the soil fertility capability classification system of Buol et al (1975), and developed additional criteria as a first approximation.

Fifteen major farming systems were selected to represent the existing continuum. Farming systems were defined in terms of commodity combinations, temperature and moisture regimes, farm size, and the degree of purchased and labor inputs. The term multiple cropping is used as defined by Andrews and Kassam (1976) – growing two or more crops, either intercropped, or in sequence, on the same field in a year. The relationships between major farming systems and soil constraints are based largely on properties of the main soils used for each farming system, plus additional constraints such as distance to markets, infrastructure, and others.

THE TWO REGIONS

Tropical America can, in terms of farming systems and soil constraints, be divided into two major regions. Region A comprises mainly high base status soils classified as Alfisols, Inceptisols, Mollisols, Entisols, and Vertisols that cover about 405 million ha or 27% of the area. Region B with 1,043 million ha, or 70% of the total area, consists mainly of acid, infertile soils classified as Oxisols, Ultisols, and dystric groups of Inceptisols and Entisols. The remaining 3% consists of tropical deserts. Except for their irrigated areas, which are included in Region A, deserts are excluded from this discussion. The high base status soil regions can be defined as those where the dominant soils have more than 50% base saturation within the top 50 cm and have high activity clays (more than 16 meq/100 g clay). The acid infertile soil regions do not meet the above criteria. Inclusions of high base status soils into Region B and acid infertile ones in Region A are of great local importance. However, these cannot be considered at the level of generalization of this paper.

As a result, two main strategies for increasing food production exist in tropical America:

1) increase yields in existing farming systems on high base status soils, and

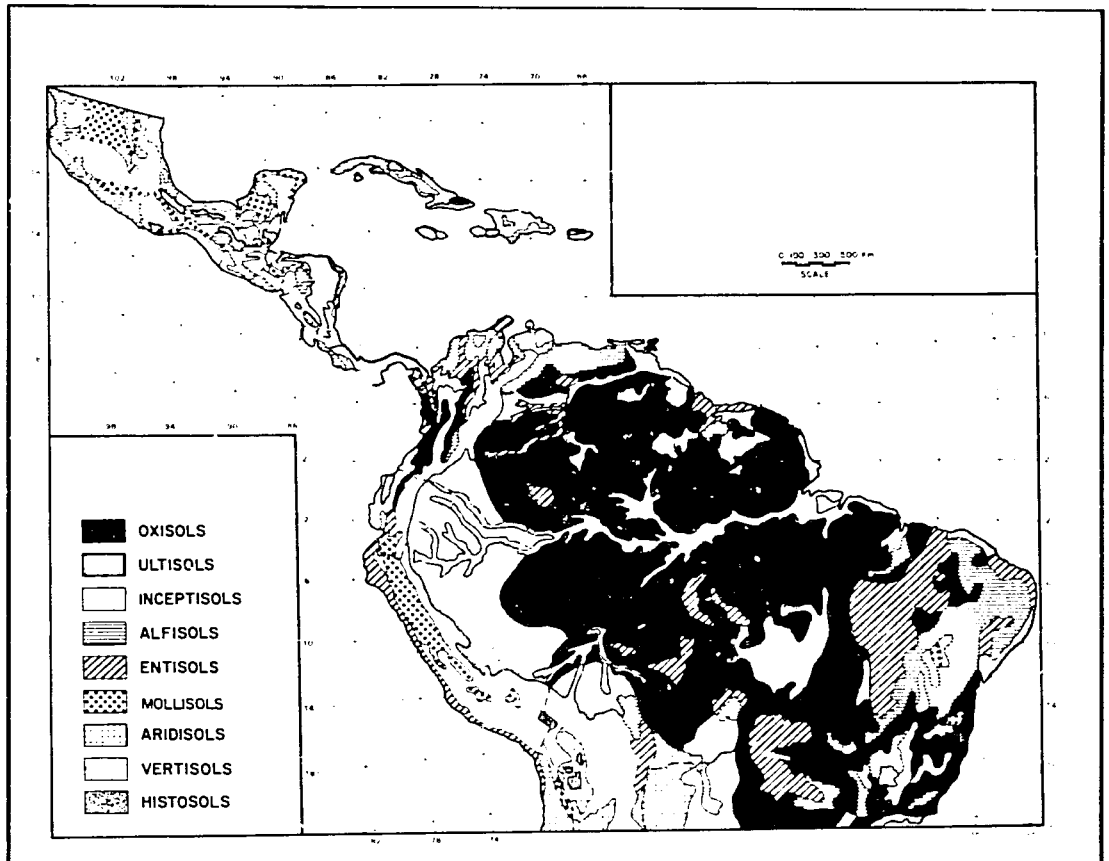
2) expand the agricultural frontier in the vast areas of acid infertile soils which are mostly under savanna or forest vegetation.

These two strategies are complementary rather than competitive, and the interaction between them already plays a major role in the overall development strategy of many countries.

SOIL GEOGRAPHY

A preliminary soil order map of tropical America, modified from that developed by Sánchez and Isbell (1979), is shown in Figure 1. Oxisols comprise the most extensive soil order, covering 34% of tropical America. Ultisols cover 22%, Inceptisols 16%, Alfisols 12%, and Entisols 8%. Mollisols, Aridisols, Vertisols, and Histosols are in small areas. Spodosols also occur but their areal extent is too small to be detected at the scale used. Table 1 shows the soil order distribution by altitudinal belts (and approximate soil temperature regimes).

Much of tropical America (86%) is lowlands with isohyperthermic soil temperature regimes. A significant amount of land (9%) is at intermediate elevations with isothermic temperature regimes. That this altitudinal belt supports several of the most productive farming systems of the continent emphasizes the underutilization of tropical America's lowlands. Highland isomesic regions in the Andes at elevations of 1,800 to 3,000 m are important sources of such temperate region crops as wheat, barley, and potato. Although this altitudinal belt covers only 4% of tropical America, it supports dense populations along the inter-Andean valleys. Finally, 1% of tropical America is close to or above the limits for crop growth, with isofrigid soil temperature regimes typical of the Andean Páramos and Altiplanos.



1. Tentative soil order map of tropical America. Second approximation. Adapted from Sanchez and Isbell (1979).

Table 1. Approximate distribution of soil orders by altitudinal belts (and approximate soil temperature regimes) in tropical America.[a]

Soil order	Distribution (million ha) of soil orders					Percent
	Lowland 0–900 m (isohyperthermic)	Intermediate 900–1800 m (isothermic)	Montane (Sierra) 1800–3000 m (isomesic)	Alpine (Altiplano) 3000–5000 m (isofrigid)	Tropical America	
Oxisols	484	28	0	0	512	34
Ultisols	310	10	0	0	320	22
Inceptisols	134	56	41	4	235	16
Alfisols	151	24	8	0	183	12
Entisols	108	15	0	1	124	8
Mollisols	55	3	7	0	65	4
Aridisols	23	0	0	7	30	2
Vertisols	20	0	0	0	20	1
Histosols	4	0	0	0	4	–
Total belt	1289	136	56	12	1493	–
% of tropical America	86	9	4	1	100	–
Total high base status soils	268	74	50	12	405	
% high base status soils	21	55	90	100	30	

[a]Figures are rough estimates subject to change as more information is obtained.

Table 1 also shows the distribution of high base status soils – Alfisols, Vertisols, Mollisols, and Aridisols. Subdivisions were needed to differentiate between high base status and acid infertile Inceptisols and Entisols. We arbitrarily included Andepts, even though some are acid, because they seldom have toxic levels of aluminum, are relatively well supplied with bases, and have high activity clays. Dystric groups of Inceptisols and Entisols were excluded. No further refinements were possible because of the limited data base. All Oxisols and Ultisols were included in the low base status, or acid infertile category although areas of high base Oxisols (Eutrorthox) occur.

Table 1 shows that the percentage of high base status soils increases with elevation. The term *high base status soils* is not, however, synonymous with very productive soils because factors such as drought, steep topography, and low temperature may limit their productivity potential. The terms *high base status soils* and *acid infertile soils* are essentially identical to the term *soils with high or low activity clays* used in other chapters of this book.

The relationships between the two broad soil regions and soil moisture regimes are shown in Table 2. About 47% of tropical America's soils have a udic soil moisture regime, which means drought stress for 3 months or less. Forty percent have an ustic soil moisture regime, with a dry season of 3 to 9 months. The 12% with an aquic soil moisture regime include large areas of seasonally flooded plains such as the Casanare-Apure Llanos of Colombia and Venezuela, the Pampas de Moxos of Bolivia, and the Pantanal of Brazil. The remaining 3% consist of true tropical deserts. Table 2 also shows that most soils with udic soil moisture regimes are acid infertile ones, that there is an equal proportion of high base status and acid infertile soils in ustic areas, and that most poorly drained soils are also acid. Table 3 shows a more detailed breakdown of soil orders by moisture regime for the major zones.

Compared with other tropical continental regions, tropical America is probably the best supplied with moisture, and has the largest proportion of acid infertile soils. It also has large areas of high base status soils with good moisture supply along the Andean chain, coastal and riverine regions, and in much of Central America and the Caribbean.

Table 2. Approximate areal distribution of high base status, acid infertile, and tropical desert soil regions by soil moisture regimes in tropical America.[a]

Region	Main property	Area (million ha) of given soil moisture regime					Area (%)
		Udic	Ustic	Aquic	Aridic	Total	
A	High base status soils	46	299	60	0	405	27
B	Acid, infertile soils	620	299	124	0	1043	70
C	Tropical desert soils	0	0	0	45	45	3
	Total	666	598	184	45	1493	
	%	47	40	12	3	100	

[a]Calculated from FAO-Unesco soil maps (FAO 1971, 1975) and authors' observations. Rough information subject to change as more data become available.

Table 3. Broad geographical distribution of soil orders and soil moisture regimes in tropical America by main region.[a]

Soil order	Area (million ha)									Overall area	
	Region A: High base status soils				Region B: Low base status soils				Region C Aridic	Million ha	%
	Udic	Ustic	Aquic	Total	Udic	Ustic	Aquic	Total			
Oxisols	0	0	0	0	342	170	0	512	0	512	34
Ultisols	0	0	0	0	213	35	72	320	0	320	22
Inceptisols	5	82	8	95	56	15	48	119	21	235	16
Alfisols	18	127	38	183	0	0	0	0	0	183	12
Entisols	22	14	0	36	9	79	0	88	0	124	8
Mollisols	0	57	8	65	0	0	0	0	0	65	4
Aridisols	0	0	6	6	0	0	0	0	24	30	2
Vertisols	1	19	0	20	0	0	0	0	0	20	1
Histosols	0	0	0	0	0	0	4	4	0	4	–
Total	46	299	60	405	620	299	124	1043	45	1493	–

[a]Figures are rough estimates subject to change as more data become available.

SOIL CONSTRAINTS

The definitions of soil-related constraints used in this paper are shown in Table 4. Many of them are modifiers in the Soil Fertility Capability Classification system (Buol et al 1975), including depth, drought or waterlogging stress, vertic properties, low cation exchange capacity, aluminum toxicity, salinity, alkalinity, phosphorus fixation, and acid sulfate soils. Additional constraints are included to identify the low water-holding capacity of many soils, erosion, compaction and laterite hazards, and low but constant soil temperatures in the isomesic and isofrigid areas, which severely limit the use of crops or animal species.

Additional constraints are included to characterize the widespread deficiency of essential nutrients, but the degree of quantification is limited to "soil test values below the critical level." This lack of specificity is in itself an important constraint in our knowledge of soil fertility management.

High base status soils (Region A)

The extent and importance of the different soil constraints are estimated in Table 5 for the high base status soils region of tropical America.

Nitrogen deficiency is almost universal. But it is not 100% because the humic groups of Alfisols, Inceptisols (except Andepts), and all Mollisols are expected to provide a reasonably high organic matter mineralization rate for several years. Nitrogen deficiency per se is not a major constraint in terms of economic importance as most cropping systems already involve the use of nitrogen fertilizers (Sánchez 1973). Furthermore, widespread kikuyo (*Pennisetum clandestinum*)-white clover (*Trifolium repens*) pastures throughout the isothermic and isomesic belts provide excellent symbiotic nitrogen fixation for livestock production.

Drought is probably a much more important constraint than nitrogen deficiency. Drought occurs in the lowlands in the Sertão of Northeast Brazil, which has no major limitations of soil, topography, or infrastructure. Severe protracted drought is also typical of many lowland areas of Colombia, Venezuela, Central America, and the Caribbean. Where water resources are available and topography is favorable, irrigation has been an effective solution. Most of Latin America's lowland rice is produced under such circumstances. The total irrigated area for all crops in tropical America is estimated from FAO (1976) data to be 5 million ha; most is in high base status soils regions.

Drought stress is particularly important in Andean regions with isothermic and isomesic temperature regimes. There is sharp contrast between the productive, intensive multiple cropping systems of the Pasto region of southern Colombia and the adjacent northern provinces of Ecuador. The Pasto region has a udic soil moisture regime; much of the northern Ecuadorian sierra has a strong ustic regime.

In our opinion, the most important soil constraint in the high base status soil region is the danger of severe soil erosion in about 53% of the area. In densely populated regions of the Andes, and in countries such as El Salvador and Haiti,

Table 4. Definition of soil-related constraints used in this paper.

Constraint	Definition	Source[a]
Physical		
Shallow depth	Rock or other hard, root-restricting layer within the first 50 cm. Includes Lithosols and lithic groups.	1
Water stress for 3 months or more	Ustic or aridic soil moisture regime, control section of the subsoil dry for more than 90 consecutive days/year.	1
Waterlogging for 3 months or more	Aquic soil moisture regime. Evidence of gley or mottled colors. Gleysols in FAO legend.	1
Low soil water-holding capacity	Less than 10% available soil moisture (0.1–15 bars) by wt in top 50 cm.	2
Vertic properties	Sticky, plastic clays subject to cracking, shrinking and swelling, causing difficult physical soil management. Vertisols or vertic groups.	1
Severe erosion hazard	Erosion susceptibility due to slope, abrupt textural changes, poor structure, or both.	2
Severe compaction hazard	Presence of compacted horizons, or susceptibility to compaction due to texture and structure.	2
Laterite or plinthite	Presence of soft or hardened plinthite within 125 cm.	2
Mechanization difficulties	Slopes >30%, or other topographic irregularities seriously limiting large-scale mechanization.	2
Low soil temperature	Mean annual air temperatures 15°C or lower. Isomesic and isofrigid soil temperature regimes.	2
Chemical		
Low CEC	<4 meq/100 g of effective cation exchange capacity in top 50 cm. Denotes high leaching potential.	1
Aluminum toxicity	>60% Al saturation in top 50 cm or pH <5.0.	1
Manganese toxicity	>100 ppm dilute double acid extractable Mn in top 50 cm.	2
Salinity	Electrical conductivity >4 mmho/cm in top 50 cm.	1

continued on next page

Table 4 continued

Constraint	Definition	Source[a]
Alkalinity	>15% Na saturation in top 50 cm.	1
N deficiency	Widespread agronomic evidence of nitrogen deficiency in principal crops. No quantitative soil definition.	2
K deficiency	<0.2 meq K/100 g soil in top 50 cm.	1
P fixation	Topsoil clay fraction dominated by X-ray amorphous minerals or >20% of clay fraction as Fe and Al oxides and >30% topsoil clay content.	1
P deficiency	Widespread occurrence of available soil test values below critical levels for main crops.	2
Ca deficiency	As above.	2
Mg deficiency	As above.	2
S deficiency	As above.	2
Fe deficiency	As above.	2
Zn deficiency	As above.	2
B deficiency	As above.	2
Cu deficiency	As above.	2
Mo deficiency	As above.	2
Acid sulfate soils	pH <3.5 after drying or Sulfaquept or sulfic great group classification.	1

[a]1 = Fertility Capability Soil Classification System (Buol et al 1975) with slight modifications. 2 = proposed definitions.

entire watersheds with Alfisols, Inceptisols, Mollisols, and Entisols are severely eroded because of attempts to increase cropping intensity beyond the limits of the land, often combined with overgrazing. Erosion is most critical in ustic and aridic soil moisture regimes. In udic regimes there is more plant cover throughout the year to protect the soil.

Phosphorus deficiency is another widespread constraint, but its solution is straightforward except in the 26% of the area with clayey Andepts and oxic Alfisols with high phosphorus fixation capacity. Sulfur deficiency is extensive only in Andepts, and deficiencies of iron and zinc are increasingly being detected in calcareous soils. Salinity is important in many irrigated areas because of poor water management, particularly poor drainage.

Table 5. Approximate areal extent of soil-related constraints in the high base status soils region of tropical America.[a]

Constraint	Extent (million ha) of constraint							Percent of total
	Alfisols (183)	Inceptisols (116)	Mollisols (65)	Entisols (36)	Vertisols (24)	Aridisols (30)	Total area (450)	
Physical								
Drought stress >3 months	114	101	57	14	19	30	335	74
Erosion hazard	113	45	14	23	24	20	239	53
Shallow depth	5	56	14	5	1	1	82	18
Low temperatures	8	45	7	1	0	7	68	15
Waterlogging	38	8	8	0	0	6	60	13
Low water-holding capacity	0	21	0	22	0	0	43	10
Vertic properties	1	2	0	0	20	0	23	5
Laterite	7	0	0	0	0	0	7	2
Chemical								
N deficiency	177	98	0	34	24	30	363	81
P deficiency	107	52	14	22	20	0	215	48
P fixation	85	31	0	0	0	0	116	26
Fe deficiency	30	15	25	2	3	21	96	21
Zn deficiency	30	15	25	2	3	21	96	21
S deficiency	0	52	0	0	0	0	52	11
Low cation exchange capacity	0	21	0	22	0	0	43	10
Salinity	0	0	1	0	0	9	10	2
Alkalinity	1	0	1	0	0	7	9	2
Al toxicity	0	0	0	0	0	0	0	0
Mn toxicity	0	0	0	0	0	0	0	0
K deficiency	0	0	0	0	0	0	0	0
Ca deficiency	0	0	0	0	0	0	0	0
Mg deficiency	0	0	?	0	0	0	0	0
Acid sulfate soils	0	0	0	0	0	0	0	0
B deficiency	?	?	?	?	?	?	?	?
Cu deficiency	?	?	?	?	?	?	?	?
Mo deficiency	?	?	?	?	?	?	?	?

[a]The total extent of each order is in parentheses. For definitions, see Table 4. Question marks indicate insufficient information. Figures are rough estimates subject to change as more information becomes available.

The absence of aluminum toxicity and calcium and magnesium deficiencies in this region is noteworthy. Shallow soils, waterlogging, vertic properties, low temperatures, low cation exchange capacity, and other properties such as stoniness, are only of local importance.

Acid infertile soils (Region B)

Soil constraints in Region B, which encompasses 70% of tropical America, are mostly chemical. Table 6 shows that more than 50% of the area are affected by phosphorus, potassium, calcium, magnesium, and sulfur deficiencies, aluminum toxicity, phosphorus fixation, nitrogen deficiency, zinc deficiency, and low water-holding capacity. The region also has vast areas of poorly drained and seasonally flooded soils. Unlike in the high base status soil region, drought and erosion are significantly less important, with some exceptions. Although the tropical rain forest portions of this region are fragile ecosystems, it appears to us that the densely populated areas with high base status soils in ustic regimes have more fragile ecosystems.

Laterite or plinthite formation is limited to only 11% of the region and occurs in two forms: as petric phases of Oxisols, with already hardened or concretionary laterite at the edges of scarps, and as soft plinthite in subsoils of flat Plinthaquults where the danger of exposure by erosion and subsequent hardening is minimal. The petric Oxisols are usually assets, because they provide excellent construction and road building material. However, many areas mapped as petric phases of Oxisols are actually exposures of parent rock other than laterite.

Estimating the extent of soil chemical constraints was difficult because of lack of data. It was arbitrarily assumed that 80% of the Oxisol and Ultisol areas have aluminum saturation levels above 60%, based on soil pH values of 5.0 or below. Low cation exchange capacity was considered to exist in all Oxisols except the humic groups, and in all deep sands classified as Oxic Quartzipsamments. To estimate phosphorus fixation it was assumed that 50% of the Ultisols would have clayey topsoil textures and thus would be high phosphorus fixers.

Estimates of potassium, calcium, magnesium, sulfur, and micronutrient deficiencies also are subjective because of lack of data. The book of Malavolta et al (1974) and the survey of the fertility status of Cerrado soils by Lopes and Cox (1977a, b) are useful guides. However, no areal estimates were possible for manganese toxicity, and iron, boron, and molybdenum deficiencies. The 2 million ha of acid sulfate soils are concentrated in the Orinoco delta and coastal areas of the Guyanas. A significant area of acid sulfate soils in Guyana has been reclaimed for sugarcane production by leaching with seawater (Evans and Cate 1962). Histosols are also found in these areas, and along the Atlantic coast of Central America.

Despite the limited data base, it is clear that the well-drained soils in the region are acid and low in native soil fertility. In addition, most Oxisols and Entisols have low water-holding capacities and the sandy Ultisols are susceptible to compaction and often to erosion. These physical limitations, although important, are not as serious as those reported for the high base status region.

Table 6. Approximate areal extent of soil-related constraints in the acid infertile soils region of tropical America.[a]

Constraints	Extent (million ha) of constraint						Percent of total
	Oxisols (512)	Ultisols (320)	Inceptisols (119)	Entisols (88)	Histosols (4)	Total area (1043)	
Physical							
Low water-holding capacity	504	0	0	79	0	583	56
Water stress >3 months	170	35	15	79	0	299	29
Erosion hazard	17	160	47	80	0	304	29
Compaction	0	160	0	9	0	169	16
Waterlogging	0	72	47	0	4	123	12
Laterite	48	71	0	6	0	119	11
Shallow depth	17	11	47	6	0	81	8
Vertic properties	0	0	0	0	0	0	0
Low temperatures	0	0	0	0	0	0	0
Chemical							
P deficiency	512	320	83	83	4	1002	96
N deficiency	504	306	71	88	0	969	93
K deficiency	512	160	0	40	4	799	77
Al toxicity	409	256	18	73	0	756	72
S deficiency	512	160	0	73	0	745	71
Mg deficiency	496	224	0	7	4	731	70
Ca deficiency	504	224	0	0	4	732	70
P fixation	512	160	0	0	0	672	64
Zn deficiency	468	100	0	77	0	645	62
Low CEC	504	0	0	73	0	577	55
Cu deficiency	256	50	0	?	4	310	30
Salinity	0	0	0	0	0	0	0
Alkalinity	0	0	0	0	0	0	0
Fe deficiency	0	0	0	0	0	0	0
Acid sulfate soil	0	0	2	0	0	2	—
Mn toxicity	?	?	?	0	0	?	?
B deficiency	?	?	?	?	?	?	?
Mo deficiency	?	?	?	?	?	?	?

[a]Total extent of each order is in parentheses. For definitions, see Table 4. Question marks indicate insufficient information. Figures are rough estimates subject to change as more information becomes available.

MAJOR FARMING SYSTEMS AND SOIL CONSTRAINTS

Land use

Table 7 shows land use of tropical America and the changes since 1966. Tropical America has a lower proportion of cropland (6%) than tropical Africa (8%) or tropical Asia (27%), according to calculations by Sánchez (1976). The region also has a lower proportion of permanent pastures (22%) than tropical Africa (30%), but far greater than tropical Asia (2%).

The changes in land use in tropical America since 1966 indicate a rather rapid rate of forest clearing for crop or pasture use. Much of the shift seems to be in the acid infertile soil regions. According to McKenzie (1974), 85% of the projected increases in cropland or pastures in Brazil, Colombia, Peru, Ecuador, and Venezuela for 1982–85 will take place in the Amazon, with 35 million ha added.

Lowland farming systems in high base status soils regions

A description of the major farming systems in tropical America is in Table 8. Their tentative geographical distribution appears in Figure 2.

1. *The lowland, semiarid, multiple cropping system* is the most important farming system in the largest rural poverty area in tropical America: the semiarid Sertão of northeastern Brazil where the per-capita income of more than 11 million people is less than US$ 200/year (Sanders 1979).

The area has an extremely erratic rainfall – 500-800 mm – during a 3- to 4-month season. Drought is the major crop production constraint. Alfisols and sandy Entisols are the main soils. The main farming system is intercropped cotton, corn, and cowpea on farms of less than 10 ha. Large farms devoted to extensive bush-grazing of cattle are interspersed among the small farms.

Some chemical soil constraints exist, but no fertilizers are used because of high risk due to rainfall irregularities. Water resources are limited to small areas where other food crops are grown; the possibilities of large scale-irrigation are limited.

Agronomic and economic analyses summarized by Sanders (1979) show that the probabilities of significantly improving this system are low, and that the best

Table 7. Land use in tropical America 1966–75 (including temperate Mexico and Brazil).[a]

Land use	1975		Change 1966–75 (million ha)
	Million ha	%	
Arable crops	82	5	+11
Permanent crops	16	1	+ 1
Permanent pastures	358	22	+26
Forest and woodlands	947	57	–24
Others	255	15	–22
Total	1659	100	–

[a]Calculated from FAO 1976.

Table 8. Generalized description of major agricultural production systems in tropical America.

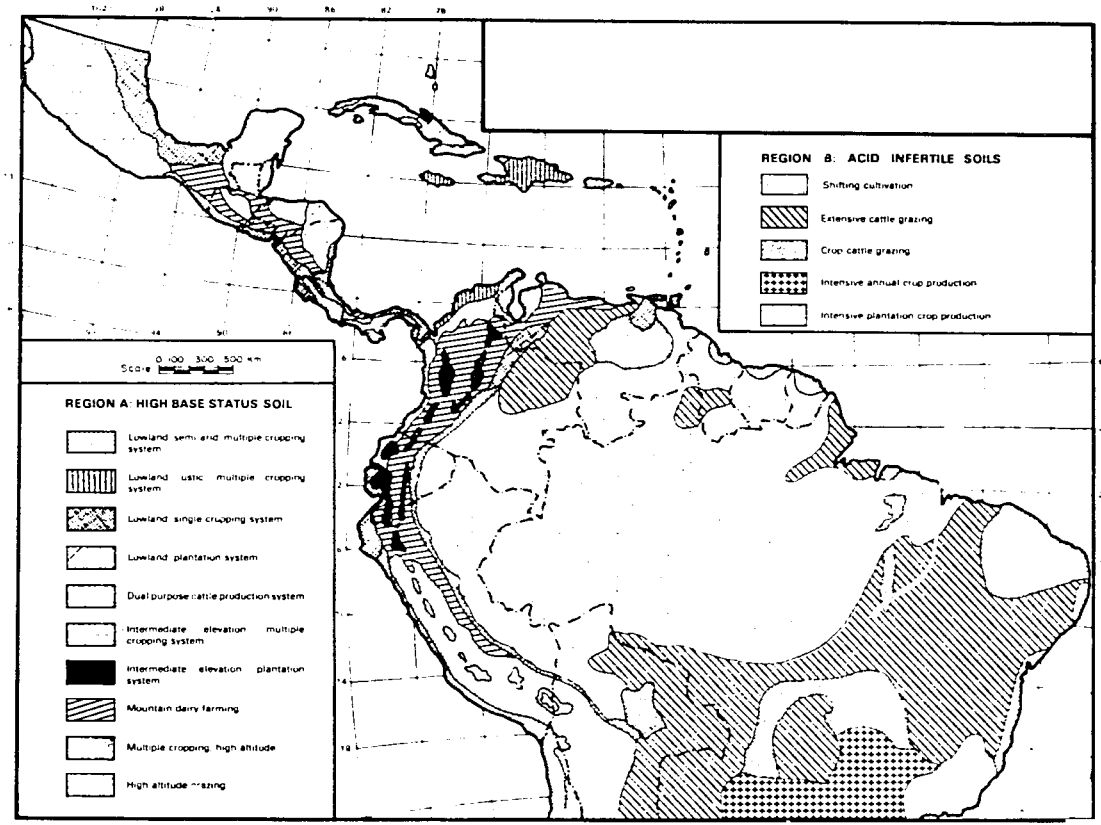
Major production systems	Elevation (m)	Dry season length (mo)	Purchased input use[a]	Labor input use[a]	Main products	Typical location	Main soils[b]
Region A: High base status soils							
1. Lowland, semiarid, multiple cropping system	0–900	7–9	L	L	Sorghum, corn, cowpea, cattle, goats, cotton	NE Brazil	AL, E
2. Lowland, ustic, multiple cropping system	0–900	4–6	L	L	Rice, corn, cowpea, sorghum, cassava, root crops	Dominican Republic	AL, I, V, M, E
3. Lowland, single cropping system	0–900	0–6	H	L	Corn, rice, soybean, cotton, cassava	Pacific coast of Guatemala	AL, I, V, M, E
4. Lowland, plantation system	0–900	0–6	M, H	H	Sugarcane, cacao, banana	Cuba, Central America	AL, I, V, M, E
5. Dual purpose cattle production system	0–900	0–6	L	H	Milk, beef	North coast of Colombia	AL, I, V, M, E
6. Intermediate elevation, multiple cropping system	900–1800		M	H	Corn, bean, plantain	Honduras	I, AL, V, M, E
7. Intermediate elevation, plantation system	900–1800	0–6	H	H	Coffee	Caldas, Colombia	I, AL, E, M,
8. Mountain dairy farming system	900–3000	0–6	M, H	H	Milk, cheese, beef	Sierra of Ecuador	I, AL
9. Multiple cropping, high altitude system	1800–3000	3–6	M, H	H	Wheat, barley, potato, pea, vegetables	Huancayo Valley, Peru	I, AL, M

continued on next page

Table 8 continued

Major production systems	Elevation (m)	Dry season length (mo)	Purchased input use[a]	Labor input use[a]	Main products	Typical location	Main soils[b]
10. High altitude grazing system	3000–5000	3–6	L	L	Sheep, llamas milk	Altiplano of Bolivia	I
Region B: Acid infertile soils							
11. Shifting cultivation system	0–900	0–4	L	H	Rice, cassava, corn	Selva of Peru	O, U
12. Extensive cattle grazing system	0–900	0–6	L	L	Beef	Colombian Llanos	O, U
13. Crop-cattle grazing system	0–900	0–6	M	M, H	Beef, rice, sorghum, peanut	Cerrado of Brazil	O, U
14. Intensive annual crop production system	0–900	3–6	H	M	Soybean, rice	Minas Gerais, Brazil	O, U
15. Intensive plantation crop production system	0–900	0–6	H	H	Coffee, sugarcane	São Paulo, Brazil	O, U

[a] L = low, M = medium, H = high. [b] Initials of soil orders, except AL = Alfisols.



2. Major production systems of tropical America. First approximation.

strategy appears to be the introduction of drought-tolerant crops, principally sorghum. The inability to improve the system gives rise to population stresses in adjacent areas: large-scale migration to less arid regions during drought years and large-scale return when rainfall improves.

2. Included in the *lowland, ustic multiple cropping system* are lowland areas with a reliable rainy season of 5 to 8 months. Soils of the area are Alfisols, Vertisols, Entisols, Mollisols, and Inceptisols. Multiple cropping combinations vary but generally include corn, cassava, upland rice, sorghum, and other grain and root crops. Cotton is important in the drier regions. Drought is a major crop production constraint, but in many cases it is overcome by small-scale supplementary irrigation. The most important constraint is soil erosion, primarily in sloping, densely populated areas. The universal solution to soil erosion is to keep the soil covered with a plant canopy at all times. The main way is to use improved, high yielding varieties of corn, cassava and sorghum, intercropped with cowpea, beans, and other soil-covering crops. Chemical constraints, principally nitrogen and phosphorus deficiency with localized secondary and micronutrient deficiencies, are also important, but their solution is limited by lack, not of soil fertility research, but of timely, site-specific, and profitable fertilizer recommendations, capital, management, and technical assistance. High population pressures make crop intensification necessary.

3. The *lowland, single-cropping system* encompasses commercial crop production with a large proportion of mechanization. Medium to large-scale fields of corn, soybean, lowland rice, cotton, sorghum, cassava, peanut, and other crops are grown with generally high levels of fertilizer inputs and, in some cases, excessive use of pesticides. Farmers generally have access to credit, technical assistance, producer associations, good infrastructure and better marketing than those engaged in the two previous systems. In effect, this system is most closely related to temperate region agriculture. The main soil constraints are soil compaction and, sometimes, erosion, caused by excessive tillage traffic, inadequate drainage systems leading to salinity, and difficulties in obtaining site-specific fertilizer recommendations in spite of a good data base for fertility requirements. The highest crop yields in tropical America are usually obtained in this system.

4. The *lowland plantation system* includes vast areas of sugarcane, banana, cacao, and other permanent crop systems mostly on high base status soils, with udic or ustic soil moisture regimes. Farms vary from small (less than 10 ha) holdings such as in the cacao-growing region of Ecuador to large-scale banana plantations in Central America and sugarcane farms in Cuba. Regardless of scale the main characteristic of the system is the vast support infrastructure of research, extension, marketing services, and even cradle-to-grave social services as in the CEPLAC (Comissão Executiva do Plano da Lavoura Cacaueria) region of Brazil (Fowler and Alvim 1977). Most soil constraints have been overcome. Other constraints are the results of excessive use of inputs. An example is use of copper-based fungicides, which caused copper toxicity in banana plantations in Costa Rica and Honduras (North Carolina State University 1973). Soil fertility

deficiencies are generally diagnosed and corrected at the field level because of more efficient soil testing and plant analysis laboratories.

5. In the *dual-purpose cattle production system,* cattle are grown for beef and milk production on farms of different sizes throughout the high base status soils of the lowland tropics of Latin America. The economic importance of milk and its by-products increases with decreasing scale of operation. The main soil-related constraint is probably drought, which results in low forage availability during parts of the year. In some areas, irrigated, nitrogen-fertilized grass pastures produce high yields of milk and beef. In many areas, the best soils are used for large-scale beef production, and intensive, small-scale cropping is pushed to marginal lands on slopes, because of land-tenure patterns. This system can seldom compete with either single cropping or plantation systems. When price increases make cropping more attractive only intensive milk production survives.

Intermediate elevation systems

Three systems are described for the isothermic altitudinal belt generally located at elevations between 900 and 1800 m. The isothermic belt is often described as the *eternal spring* climate, and is blessed with a large proportion of high base status soils, which support dense populations along the Central American highlands and in the lower Andes.

1. The *intermediate-elevation multiple cropping system* is best characterized by corn-bean intercropping and the presence of other crops such as plantain and banana. Farm size is generally small. The main constraint is probably phosphorus deficiency, particularly in volcanic ash soils, and erosion where population densities are extreme. In udic regions productivity is high and small farmers can afford to purchase large amounts of inputs because of low risk. In ustic areas input use and productivity are lower and soil services are usually not sufficiently responsive to solve farmers' needs. Nonsoil constraints such as bean diseases and lack of appropriate varieties of corn and beans for intercropping systems are perhaps more important than soil limitations.

2. The typical case of the *intermediate-elevation plantation system* is the coffee region of Colombia where favorable international prices and an all-encompassing support system by the Federación Nacional de Cafeteros have resulted in extremely productive small farmers who practice excellent soil conservation and intensive fertilization on farms of less than 30 ha. Soil constraints have been generally overcome, but erosion hazards are emerging where shade-grown coffee is replaced by sun-grown coffee planted in marginal soil areas.

3. In *intermediate and mountain dairy farming,* the climate is ideal for European breeds of dairy cattle and sheep. Many of the pastures are highly productive grass-legume mixtures, such as *Pennisetum clandestinum* and *Trifolium repens* especially in the udic regions, when well fertilized with phosphorus. In ustic regimes, feed supplementation during the dry season consists of forage, such as alfalfa, and crop residues. The system is not seriously affected by soil constraints, unless there is overgrazing. Overgrazing steep Alfisols and Inceptisols is

one of the main causes of soil erosion in the Andean region.

High elevation farming systems

Two main systems are identified for the isomesic regions above 1800 m – intensive multiple cropping and extensive grazing.

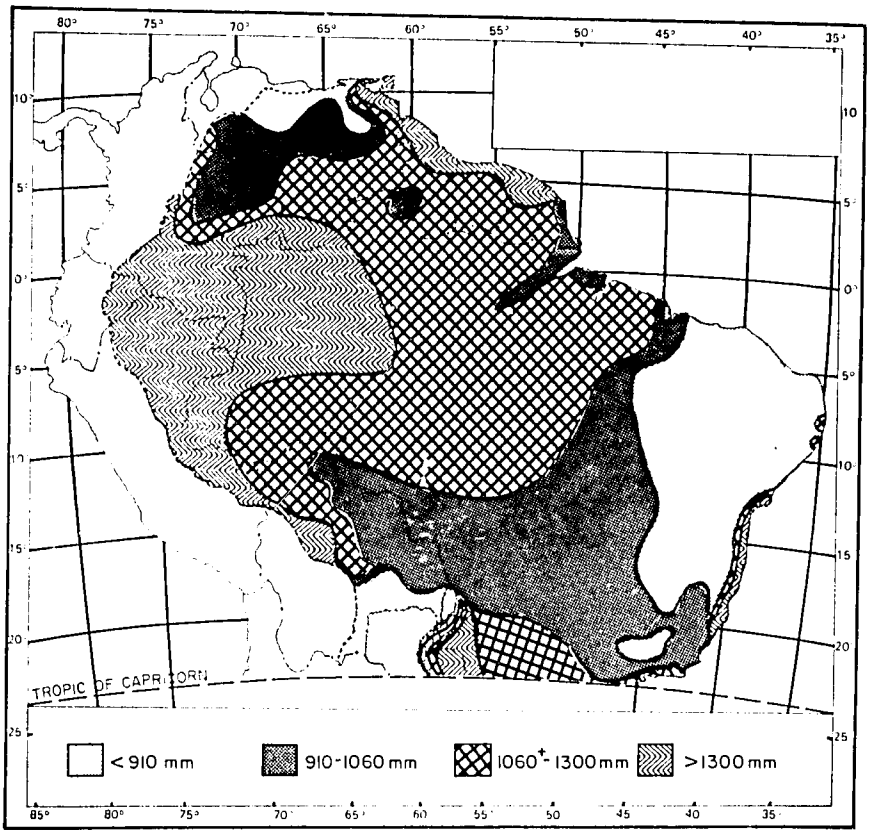
1. *High elevation intensive multiple cropping* involves sequential cropping of sole crops of wheat, potato, barley, and quinoa in small areas, as well as many intricate intercropping combinations. Low temperatures, drought, and shallow soils are the main constraints but one can still observe excellent soil conservation practices and irrigation systems developed by the Incas. Soil fertility constraints are mainly nitrogen and phosphorus deficiencies, but the intensive use of fertilizers is limited to seasons with reliable rainfall or to irrigated areas. Where population pressures are extreme there is decreasing farm size, abandonment of soil conservation practices, and erosion throughout entire valleys.

2. The high Andes have large areas of native pastures in the *high altitude grazing system.* These cover about 20 million ha in Peru alone. Too high for cattle, most of the areas are devoted to sheep, llama, and alpaca grazing. The constantly low temperatures and shallow soils limit the use of improved pastures to a few, small irrigated areas or to areas close to the small lakes that dot the Altiplano. Other soil-related constraints are drought, low cation exchange capacity, and nitrogen and phosphorus deficiency. Overgrazing causes widespread erosion.

Major farming systems in acid infertile soils regions

Five major farming systems are described in Table 8 for Region B. In order of increasing intensity they are shifting cultivation, extensive cattle grazing, crop-cattle grazing, intensive annual crop production, and intensive plantation crop production. Their occurrence in a vast area of acid infertile soils is mainly a function of climate, vegetation, parent materials, infrastructure, and economics. Tentative distribution of the systems is shown in Figure 2.

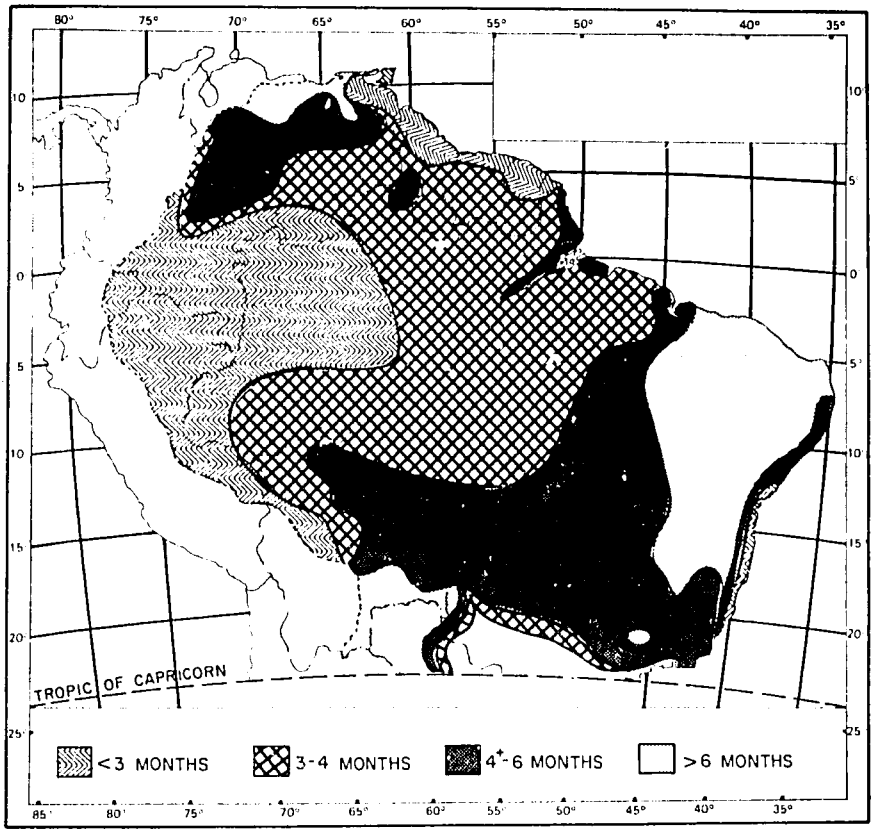
Figure 3 shows the total wet season evapotranspiration, which explains differences in native vegetation (CIAT 1978). Total wet season evapotranspiration (ET) provides an estimate of energy available for photosynthesis at a time that moisture is not limiting. The Figure 3 map correlates closely with the dry season map (Fig. 4) where a dry month has a moisture availability index of less than 0.33 according to Hargreaves' (1977) definition. Areas with wet season ET greater than 1,300 mm, and less than a 3-month dry season are covered by tropical rain forests where shifting cultivation predominates. Areas with wet season ET between 1,060 and 1,300 mm and with a stronger 3- to 4-month dry season are covered by semi-evergreen seasonal tropical forests. Shifting cultivation, extensive cattle grazing, and intensive plantation cropping are the main systems encountered. Areas with wet season ET between 900 and 1,060 mm and a dry season of 4 to 6 months outline the tropical savannas where shifting cultivation is essentially absent. The savannas are devoted mainly to extensive cattle grazing



3. Total wet season evapotranspiration (mm) map of tropical South America.

with increasing importance of crops in areas closer to markets. A fourth area, characterized by wet season ET lower than 900 mm and a dry season for longer than 6 months, has deciduous tropical forests including the Caatinga formations of northeast Brazil. Oxisol-Ultisol regions with this climate are devoted to extensive cattle grazing.

1. The *shifting cultivation* system is practiced in localized areas over the largest expanse of tropical America -- about 720 million ha of forested regions with mostly udic, but also ustic soil moisture regimes. Farming consists of annual clearing of less than 5 ha, usually by slash and burn, followed by planting of corn, upland rice, and cassava or plantain, which are usually intercropped. After 1 or 2 years the land is abandoned to forest regrowth or is planted to pastures. The main soil constraint is a sharp fertility decline within 1 or 2 years. This usually results in aluminum toxicity; nitrogen, phosphorus, and potassium deficiencies; and calcium or magnesium deficiencies, or both, or imbalances between these cations (Villachica 1978). Weeds and jungle regrowth are probably as constraining as reduced soil fertility, which appears in some areas to be primarily



4. Dry months (moisture availability index <.34) of tropical South America.

low phosphorus availability. Soil compaction and subsequent erosion are major constraints when mechanical land clearing is used (Seubert et al 1977). The solution is to slash and burn clearing and then to keep the soil covered by a crop or pasture canopy.

It is important to distinguish between two types of shifting cultivators. The traditional cultivators are native to the area and know when to abandon the land and therefore cause no erosion. The newcomers to the area expect more than the soil can give them and often cause severe soil erosion (Sánchez 1977a).

Traditional shifting cultivation is a sound stable system, but one that guarantees perennial poverty (Alvim 1977). Alternatives for improvement are intensive crop production with high fertilizer inputs, low input multiple cropping systems, crop-pasture or crop-pasture-permanent crop successions (Sánchez 1977a, b; Alvim 1977, 1978; Toledo and Morales 1979).

2. The *extensive cattle grazing system* is found in drier jungle and savanna areas farthest from the markets. When mechanical clearing of forests is avoided, the fertilizer value of the ash except for phosphorus lasts for as much as 10 years

in *Panicum maximum* pastures (Falesi 1976, Serrão et al 1979). The presence of a significant 3- to 4-month dry season plus nutrient recycling by the grazing animal provides for a much slower rate of fertility decline than in the true rain forest. Under these conditions phosphorus deficiency is the main soil constraint (Serrão et al 1979), probably followed by nitrogen, potassium, sulfur, zinc, copper, and molybdenum deficiencies and soil compaction by grazing animals. Erosion is surprisingly low in this system because degraded pastures are gradually transformed into secondary forest fallows, which provide a cover for the soil. The solution to the main constraints is to fertilize with modest amounts of P, Ca, S, K, and micronutrients plus the use of adapted and compatible grass-legume mixtures. The system is practiced on more than 2 million ha of cleared selva in the 1,060–1,300 mm wet season ET belt with a predegradation animal productivity of about 100 kg/ha per year of liveweight gains and carrying capacity of about 1 animal unit/ha.

Extensive cattle grazing occupies a much larger area – perhaps more than 200 million ha – in the least accessible savannas of the Llanos of Colombia, the Rupununi along the Guyana-Brazil border, and the Cerrado of Brazil and its extensions into Bolivia and Paraguay. Annual burning contributes only small quantities of phosphorus and other nutrients. Insufficient forage throughout the year causes cattle weight losses during the dry season, so that animals take more than 4 years to reach slaughter weight (Paladines and Leal 1979). Annual liveweight gains are in the order of 20 kg/ha with an average carrying capacity of 0.2 animal unit/ha. The main soil constraints are phosphorus deficiency and fixation, aluminum toxicity, and drought stress, followed by nitrogen, potassium, calcium, magnesium, sulfur, boron, and possibly molybdenum deficiencies (Spain 1975, 1978; Spain et al 1975). Erosion is a constraint only where there is overgrazing or loss of ash due to water or wind after annual burning. The existence of well-drained Oxisol and poorly drained Ultisol areas in close proximity provides for higher beef production because dry season grazing is possible in the poorly drained areas (Cochrane 1979a).

Improving the system consists of developing grass-legume mixtures using adapted species. An example is the combination of the grass *Andropogon gayanus* and the legumes *Stylosanthes capitata, Desmodium ovalifolium,* and *Zornia latifolia,* which are tolerant of drought, fire, and aluminum toxicity and require relatively low levels of available soil phosphorus. Fertility limitations are overcome by the direct use of rock phosphates and potassium, magnesium, and sulfur fertilizers (CIAT 1978, 1979). Improved pastures produce annual liveweight gains of 150 to 300 kg/ha and support year-round carrying capacities of 1 to 2 animal units/ha (Nores and Estrada 1979). The use of 10% of the grazing area on improved pastures and 90% of native savanna increased cow-calf production 2.5 times (CIAT 1979).

3. The *crop-cattle grazing system* in savanna regions with better infrastructure and located nearer to markets achieves intensification by growing one or more crops and interplanting grass pastures in the last crop. The main crop is upland

rice, and to a lesser degree, corn and soybean (Ferri 1977). Well-drained Oxisol and Ultisol savannas with topography appropriate for mechanization are cleared of scrub, burned, fertilized with 50 to 100 kg P_2O_5/ha, limed (1–2 t/ha), and planted to a crop. The resulting pastures are initially productive, but eventually suffer from deficiencies of nitrogen, potassium, sulfur, and other nutrients. The solution lies in the use of adapted grass-legume pastures, which could require somewhat higher fertility than the previous system, and the use of more drought-tolerant rice varieties.

A further intensification can be observed in areas with even better infrastructure and relatively low fertilizer costs. In the Llanos of Venezuela, the cycle starts with sorghum or peanut, which receive 2 t lime/ha and fairly high applications of nitrogen, phosphorus, and potassium. Pastures follow and many of them receive heavy nitrogen fertilization (Rodriguez 1976). The many constraints are severe erosion and compaction, particularly in sandy Ultisols, and zinc deficiency caused by the cumulative effect of annual lime applications. The solution to these constraints involves a more judicious use of lime and fertilization during the crop phase followed by the use of adapted grass-legume pastures to eliminate the need of costly nitrogen fertilization and assure pasture persistence for several years.

4. The *intensive annual crop production system,* or conventional, single stand crop production, is moving rapidly into Oxisol savannas of the Brazilian Cerrado where the topography favors mechanized agriculture. The move is generally from the southern states northward and westward and the principal crops are upland rice, soybean, coffee, and wheat, the latter in irrigated areas during the dry season. The various modalities are described in several chapters of the IV Cerrado Symposium (Ferri 1977). We estimate that about 5 million ha of extensive pastures have been transformed into cropland during the last 10 years in the Oxisol-Ultisol regions, mainly in Central Brazil. Commercial farmers select the areas with somewhat better fertility indicated by Cerradão or deciduous forest vegetation (Lopes and Cox 1977b), a shorter dry season, and in the case of wheat, those that can be irrigated by gravity systems.

A major soil constraint is drought due to limited root development in the subsoil, which is caused by aluminum toxicity (Gonzalez et al 1975, Bandy 1976). Liming to 30 cm helps alleviate this situation for crops like corn and sorghum, and downward movement of calcium and magnesium tends to reduce subsoil acidity after several years of cultivation (Ritchey et al 1978). The overriding constraint, however, is extreme phosphorus deficiency and high phosphorus fixation. The solution is based on 1) proper selection of rates, placement, and timing of phosphorus applications to provide long-term residual effect; 2) the use of phosphorus sources cheaper than superphosphate; 3) substitution of cheaper amendments to satisfy the soil's phosphorus fixation capacity; and 4) use of crop species and varieties tolerant of lower levels of available soil phosphorus (Salinas and Sánchez 1976). Other soil constraints include acute potassium, zinc, and sulfur deficiencies, which can be corrected economically, and

nitrogen deficiencies after 1 or 2 years (CPAC 1977, 1978; Lobato and Goedert 1977; Sánchez 1977b). Although these Oxisols are as resistant to soil erosion as any other soils in the world, poor management, such as downslope furrow irrigation, causes serious erosion losses.

Intensive cropping is also feasible in rain forest areas. During the past 5 years an annual rotation of upland rice, corn, and soybean has produced about 10 t of grain/ha a year in Yurimaguas, Peru, with heavy fertilization (Bandy 1977). Two crops a year of flooded rice in Jarilandia, Brazil, have produced 14 t/ha per year in commercial fields (Alvim 1977).

5. In *intensive plantation cropping systems,* permanent crops such as cacao, rubber, and oil palm have the advantage of deep roots, surface litter, and a permanent canopy, which favor nutrient cycling as in the native forest. After establishment, such crops also protect the soil against erosion. Cacao plantations are extensive in areas of better soils of the Amazon (Sánchez 1977a), but other crops and commercially planted timber are better adapted to acid infertile soils. Alvim (1977, 1978) reports impressive success stories of permanent crops under low fertilizer inputs in the Brazilian Amazon. In certain plantations, pasture legumes, e.g. *Pueraria phaseoloides,* are used as cover crops and are grazed by cattle. Soil constraints are the same as those listed before, but the use of acid-tolerant tree species capable of nutrient recycling minimizes purchased input use.

Areas planted to crops requiring high fertility, e.g. coffee and sugarcane, are rapidly increasing in the Cerrado.

EXPECTED DEVELOPMENTAL PATHWAY

The previous section indicates the diversity of farming systems and soil-related constraints in tropical America. That discussion consists largely of broad generalizations. The level of specificity of the prediction of a probable developmental pathway for a region with 28 countries of widely differing sizes and political, social, and economic systems is reduced by an additional order of magnitude.

The countries of tropical America have a combined population of 368 million as of 1979 and population increases at an average annual rate of 2.7% (USDA 1978). Most of the rural population is in the high base status soil region. Increases in population density reduce the size of the traditional multiple cropping system, break its equilibrium, cause erosion, and force large-scale migration to the major cities. The rapid growth in number of unemployed migrants has expanded the major cities beyond their capacity to support their population. Most new urban dwellers have little hope for gainful employment and little possibility of ever becoming farmers again. With the population doubling every 24 years, and with no significant decrease in population growth rates, food production will have to double in 24 years to maintain the present level of human nutrition in tropical America.

Exceptions to Sánchez and Buol's (1975) hypothesis that population density is correlated with high base status soils, where moisture is not a limiting factor,

are becoming more common as large cities like Brasilia, Goiania, Belém, Manaus, and Ciudad Guayana develop in the midst of acid infertile soil regions.

The most rational developmental strategy might be based on the following components:

1. Improved marketing infrastructure.
2. Increased yields in the favored high base status soil regions, i.e. those with a udic soil moisture regime or with irrigation potential, by the use of modern technology and intensive use of fertilizer, labor, and machinery.
3. Release of areas of favored high base status soils from extensive systems such as beef production or low yielding plantation crops, to intensive food production.
4. Development of improved crop and milk production technology for high base status soil areas with serious drought stress or erosion hazards.
5. Provision of opportunity to transfer excess population from the latter areas to regions of acid infertile soils.
6. Development of appropriate soil management technology for the acid infertile soil regions.

Foods consumed in tropical America in order of proportion of the total food budget are beef, rice, pork, milk, sugar, plantain, beans, corn, and eggs (Andersen 1977). Breakthroughs based on cultivars that respond to high input technology have been limited to lowland rice, irrigated wheat, grain sorghum, and sugarcane. Yield increases in corn have been disappointing, partly because soil constraints were ignored. Ongoing research to adapt these plants to the existing stresses may contribute significantly to yield increases in less favored lands. The strategy is used on sorghum for the Brazilian Sertão.

Developing effective pasture production technology for the acid infertile soils will contribute to the release of high base status soils for food production. The transfer of excess population from erosion-prone areas to new lands requires a viable alternative; an agronomically sound technology for the acid, infertile soil areas. Many colonization schemes fail for lack of marketing infrastructure and sound soil management despite government efforts to support such services. The exceptions, e.g. cacao in the Alfisol areas of the Amazon jungle, are precisely due to the existence of appropriate technology plus the required government backstopping. In essence, the danger of soil loss due to erosion of the best lands could be solved largely by effective soil management of the acid infertile soils.

Countries without significant areas of acid infertile soils are at a disadvantage in this sense. The worst cases are probably Haiti and El Salvador. Peru, Ecuador, Venezuela, Colombia, Bolivia, Panama, Nicaragua, and Honduras, with a mix of both high base status and acid infertile soils, have better possibilities. Brazil's current commitment to developing the Cerrado first and the Amazon later puts it in a good position to reap the benefits of such improved technology when it is developed.

RESEARCH PRIORITIES

To accomplish the above goals, many soil research areas need to be strengthened throughout tropical America. They are not listed in order of priority, but follow the sequence in the previous sections of this paper.

The exercise of determining the main soil constraints in the main farming systems has identified major weaknesses. The vagueness in the definition of soil constraints and their extension, and the major farming systems (Tables 4, 5, 6, and 8), are in themselves major constraints to our knowledge about soil management in tropical America. The need to make these broad generalizations site-specific will be discussed first:

1. Develop low-cost production technology for savanna and selva regions

In our opinion, this is by far the most important research priority because it tackles the critical issue of rational and efficient use of 70% of tropical America's land to meet growing food requirements and to provide land and employment for displaced rural dwellers. Significant advances have already been made in developing high input crop production technology for these regions. The general principles are fairly well established (Sánchez 1977b) but need to be validated in specific areas as the agricultural frontier moves forward. The main gap is in the development of low-cost technology based on the principle of adapting plants to acid soil infertility rather than eliminating these stresses by intensive use of lime and fertilizers (Spain et al 1975). An emerging strategy is the use of legume-based pastures in settling new areas (CIAT 1978, 1979). This type of technology now requires the large job of site-specific validation in both agronomic and economic terms.

But, pastures alone are not sufficient. What is sorely needed is an integrated approach for developing the full agricultural potential of these acid soil ecosystems at low cost. It includes the selection of areas suitable for annual crops, pastures, tree crops, and of those that should remain untouched. The components of this system, which may include intercropping of annual crops, pastures and tree crops, or rotations or successions must be developed and validated at specific sites. At present no center undertakes this integrated approach. Certain research stations concentrate separately on annual crops, livestock production, perennial crops, forestry, and ecological studies that recommend that no agriculture be [illegible]d in the region, particularly in the Amazon, thus raising exaggerated fear[illegible] ecological catastrophies. An integration of land resource evaluation specialists, soil scientists, agronomists, animal scientists, foresters, and ecologists is difficult, because traditionally they seldom have worked together. Their concerted efforts are indispensable to the development of agronomically, economically, and ecologically sound farming systems in the area of the world with the largest potential for expansion of cultivated land.

2. Develop a site-specific data base of land resources, farming systems and soil constraints

A geographically accurate synthesis of climate, landscape, vegetation, soils, and land use is the required first step in rationalizing research priorities at either the country or subcountry level. Much of the information is already available in many forms in the different countries. Its compilation would indicate the additional data needed. A synthesis based on land systems and land facets, as outlined by Cochrane (1979a) in a computerized form, can provide valuable data such as the extent of aluminum saturation in a specific area as illustrated in Table 9. The climatic compilation phase of this study has been completed (Hancock et al 1979). It is important to emphasize that soil surveyors and soil fertility specialists, along with climatologists and land use economists, have to develop the data base.

3. Provide more quantitative definitions of soil constraints

Table 4 is full of vague terms. The most obvious ones are the critical levels of nutrient deficiencies, aluminum toxicity, magnesium toxicity, salinity, and alkalinity. The differences among species and among cultivars of the same species result in different critical levels. Specific criteria, such as a formula for determining liming rates based on the critical levels of aluminum saturation for specific cultivars (Cochrane et al 1979), are needed to take the differences into account. For example, the general use of 60% aluminum saturation as the critical level for aluminum toxicity is adequate for many corn cultivars, but in two grain sorghum cultivars tested in an Oxisol from Brazil the aluminum saturation levels needed to decrease yields by half were 70 and 40% (Salinas 1978). The generally accepted critical level for soil salinity of 4 mmho/cm is too high for bean and cassava, which suffer from salinity stress at 0.8 and 0.4 mmho/cm (Leon and Medina 1977).

Likewise the definition of the ustic soil moisture regime is too broad to distinguish farming systems in semiarid regimes and those with a dry season of 3 to 6 months. The moisture availability index ranges shown in Figure 4 seem better related to the distribution of farming systems.

4. Reinforce soil fertility evaluation services

The keystone for site-specific, economically sound fertilizer recommendations is a functional soil and plant analysis laboratory either to back up field fertilizer experimentation in the way demonstrated by Cochrane (1979b), or to apply established critical nutrient levels for soil-crop combinations based on comprehensive field fertilizer experimentation. Tropical America is fortunate to have a well-developed network of such services (ISFEIP 1974). Since the discontinuation of international support in 1974, however, deterioration of such services in several countries, has been appreciable. Insufficient financing has resulted in serious delays in analysis due to lack of reagents and low personnel morale. The most adversely affected groups are the small-scale multiple cropping farmers; the

Table 9. Areal distribution of aluminum saturation in soils of West Central Brazil.[a]

Soil layer	Al saturation (%)	Land area	
		Million ha	%
Topsoil (0–15 cm)	0–10	95	39
	10–40	24	10
	40–70	44	18
	70–100	80	33
Subsoil	0–10	118	48
	10–40	38	16
	40–70	21	9
	70–100	66	27

[a]Source: CIAT Target Area Data Bank (on computer tape).

larger-scale, annual or plantation crop operators often rely on their own private laboratories. A boosting of this crucial service could have a major impact on the desired crop intensification of small-scale farming systems areas where low moisture stress risk permits fertilization.

5. **Develop soil management technology for erosive soils and drought stress areas** There is no need to do basic research on soil erosion because the solution to this problem is already well known: keep the soil surface covered at all times. Adaptive research is needed. In addition to relieving the population density, multiple cropping combinations, such as low-growing grain or forage legumes with cassava, can provide soil protection in cassava monocultures on sloping land. Also cultivar screening for deeper rooting and drought tolerance can reduce the risks of short-term droughts during the rainy season. Water conservation techniques practiced in semiarid areas of India and the United States should be tested and adapted for the Sertão of Northeast Brazil. The degree of purchased input use for these new technologies will increase in proportion to the reduction of risk due to drought stress.

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Production systems, soil-related constraints, and potentials in the semiarid tropics, with special reference to India

J. KAMPEN AND J. BURFORD

Existing production systems have not provided the food required by the people of the semiarid tropics (SAT) because of high, increasing population densities and lack of suitable soil-, water-, and crop-management technology for optimizing production under undependable rainfall. Development requires not only an assurance of increasing food production to match population growth but also an arrest of deterioration of the resource base. In the long run, production must be further increased to significantly improve the quality of life.

Alleviation of the main soil-related constraints on some of the deep Vertisols in India now appears feasible by implementation of *watershed-based* farming systems. This involves a synthesis of improved farming systems based on a combination of improved land, water, and crop management; genotypes; and cropping systems at medium-input levels.

Soil-related problems requiring primary attention are low fertility and limited water-holding capacity. Better resource-utilization systems are necessary, especially for the light-textured, easily erodable soils that dominate the SAT. The need for greater inputs of nitrogen by biological fixation is well recognized but the potentials of breeding genotypes for improved efficiency at low levels of available nutrients have not yet been sufficiently explored.

Systems analysis and process-based simulation techniques backed up by research at a few carefully selected *benchmark* locations provide the means for progress in agricultural research.

Principal scientists in Land and Water Management and Soil Fertility and Chemistry, respectively, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru P.O., Andhra Pradesh, India 502 324.

THE SEMIARID TROPICS (SAT) are mainly in developing countries of Africa (70% of the total) and Southeast Asia (mostly in India). Latin America and Australia each contain about 10%. Almost all of the 550 million people in the SAT live at nutritional levels barely sufficient for maintenance of life (Ryan and associates 1974). A shortfall in food production often causes serious hardship and starvation because subsistence farmers and landless laborers are unable to bridge the gap between years of low and high production. Thus, constraints to agricultural development must be immediately identified and overcome to improve per-capita consumption, to provide food for increasing populations, and to attain greater stability of production.

The dominant cause of low and variable crop yields is the frequent occurrence of unsatisfactory soil-moisture regimes. Erratic rainfall during and between rainy seasons is the most important characteristic of the SAT. Water (often too little and sometimes too much), a lack of suitable technology for better water utilization, and soil fertility limitations are primary constraints to higher and more stable production.

The need for dependable food supplies is especially critical because of the socioeconomic consequences of years with low or unevenly distributed rainfall. Increased yields in good rainfall years, improved grain storage, and easy access to cheap credit may have some impact. However, techniques to improve production in years of unfavorable rainfall are of vital importance to prevent the periodic catastrophic events that have resulted from 2 or 3 successive drought years. To obtain food at ever increasing prices during such periods farmers sold their assets, thus further depleting their resource base (Jodha 1977).

Recently, greatly increased population pressures have caused fundamental changes in agricultural production systems. Shifting cultivation has effectively disappeared from the Indian SAT, and is presently being replaced by semipermanent and permanent cultivation in Africa and Latin America. Farmers have attempted to increase production by extending annual cultivation to marginal lands, which are frequently subject to crop failure and erosion; increased animal numbers are changing the hydrologic characteristics of vast areas of grazing lands (FAO 1974). This intensification of land use can become self-defeating: it greatly increases runoff and soil erosion, which reduce groundwater recharge, increase the incidence of downstream flooding, and accelerate sedimentation of reservoirs, thus negating irrigation and power investments (Kampen and associates 1974). As a result, the land resource base shrinks and its productive capacity diminishes, which in turn increases the quest for more land. To break this vicious cycle, improved resource management to more effectively conserve and utilize rainfall and soil fertility and new crop production systems to maintain productivity and assure dependable harvests are urgently required.

THE SETTING

Substantial diversity exists within the resource environments of different regions in the SAT, but data collected so far are insufficient for well-defined classifica-

tion of the component subregions. Without the classifications, only restricted evaluations can be made of the constraints that have been identified. Progress has recently been made in India, both in more fully describing agroclimates and in identifying constraints. Because India contains the largest population among the SAT countries, major attention will be given to it.

Climate and precipitation

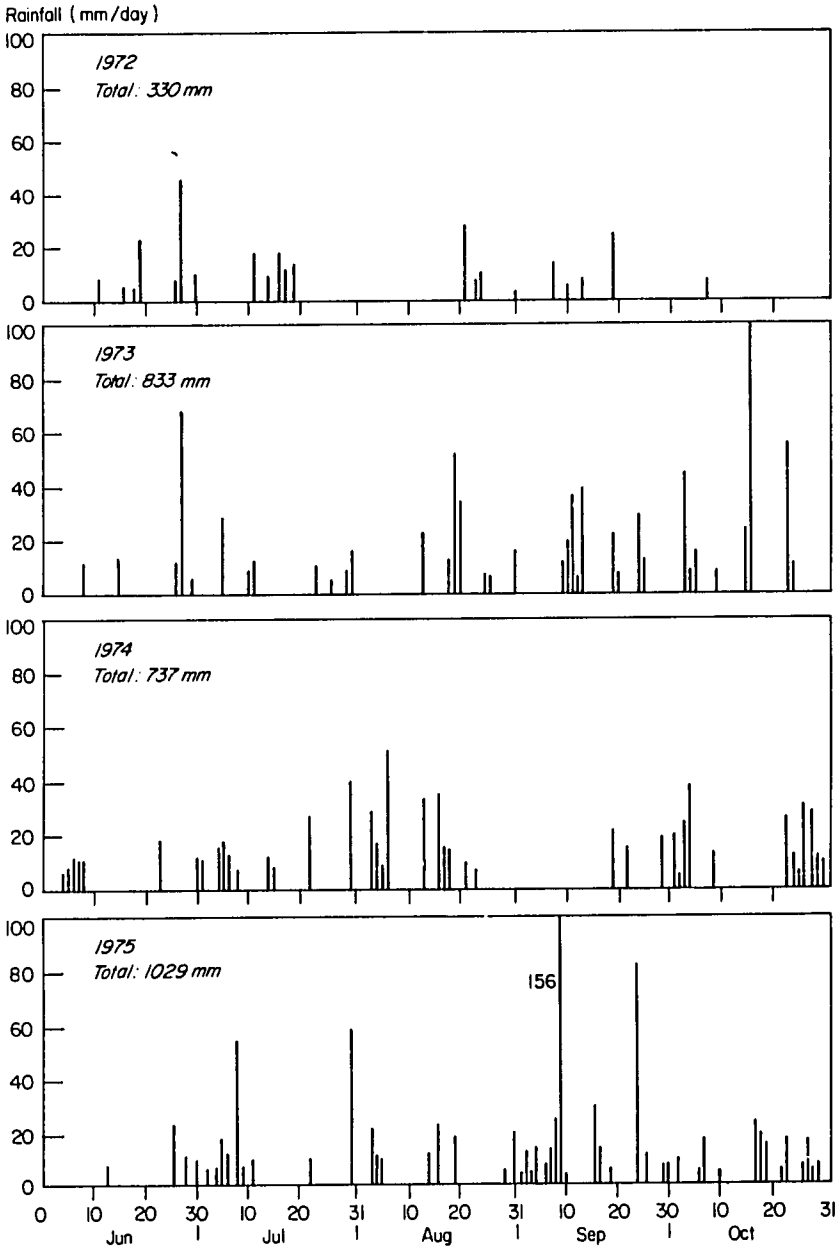
In the SAT the average monthly precipitation (P) exceeds the potential evapotranspiration (PE) for at least 2 and at most 7 months, and the mean annual temperature exceeds 18°C (Troll 1965, Virmani et al 1978). Three seasons can be distinguished (Krantz et al 1978): the humid monsoon or rainy season, the cool dry or posthumid season, and the hot dry season.

Precipitation variability. Rainfall varies widely from year to year and within the growing season. Because the potential evapotranspiration is high (often exceeding 1,750 mm) the SAT are characterized by a growing season in which neither moist nor dry periods are very predictable. The seasonal and annual variability of rainfall is exemplified by some data from Hyderabad (Fig. 1). The annual rainfall has varied from 330 mm in 1972 to 1,400 mm in 1977, and the coefficient of variation (CV) is 26% (Virmani et al 1978). High and low rainfall years, midseason droughts, and early and late terminations of the rainy season are all experienced within a few years.

Short-term rainfall probabilities. Assessment of rainfall variability improves understanding of the agroclimate. For this work, monthly rainfall data are not satisfactory; variability over shorter time periods is more important. This variability is quantified by assessing the probability of receiving certain amounts of rainfall during a given week; this is termed *initial probability* P(W). A logical extension is the determination of *conditional probabilities,* i.e. the probability of receiving rain next week if the current week is wet [P(W/W)] or dry [P(W/D)] (Virmani et al 1978). The following example shows the usefulness of this approach.

Hyderabad and Sholapur in India are about 500 km apart at similar latitudes and altitudes; they seem agroclimatologically, ecologically, and edaphically similar. The soils of both are mainly deep to medium-deep Vertisols. The mean annual rainfall is about the same – 764 mm at Hyderabad and 742 mm at Sholapur – and both receive more than 75% of their precipitation between June and September. Krishnan (1974) computed the mean annual PE at 1,757 mm for Hyderabad and 1,802 mm for Sholapur. The actual length of the growing season was estimated to be 130 and 148 days. The CV of the annual rainfall for Hyderabad and Sholapur are similar (26.1 and 28.6%). Rao et al (1971) computed Thornthwaite's moisture index at −56.4 and −58.7.

The information suggests similar agricultural potentials at two sites. On Vertisols at Hyderabad, however, yields in excess of 5,000 kg/ha are common for pigeonpea/maize intercropping and for maize/chickpea sequential cropping. At Sholapur, the success of a rainy season cropping with sorghum or maize is un-



1. Rainfall distribution during 1972–75 at ICRISAT Center, Hyderabad, India.

certain but a short-duration crop of pearl millet or a grain legume followed by sorghum grown on conserved moisture is sometimes successful. Furthermore, yields from year to year are highly variable and range from 1,000 to 2,000 kg/ha.

The undependable rainy season precipitation at Sholapur is probably the major environmental factor that causes a relatively low agricultural production efficiency (Virmani et al 1977); this is illustrated by an analysis for initial and conditional probabilities of P/PE ≤0.33 (Fig. 2). The rainfall distribution at Sholapur is erratic; few of the initial P(D/W) exceed 70%, and the P(W/W) follows a similar pattern. In comparison, the rainfall analysis for Hyderabad shows that rainfall is dependable (>70% probability) between mid-June and the end of July, and from about mid-August to mid-September. Rainfall characterization based on short-term periods can be particularly effective in describing differences in agricultural climate and yield potentials.

Soils and soil characteristics

The diversity of SAT soils is indicated in Table 1, which is based on soil maps and agroclimatology data (Aubert and Tavernier 1972, Virmani et al 1979). Alfisols cover about 32% of the African SAT and about 38% of the Asian SAT. The composition of the remaining area differs for the three continents, although each contains a substantial area of Aridisols.

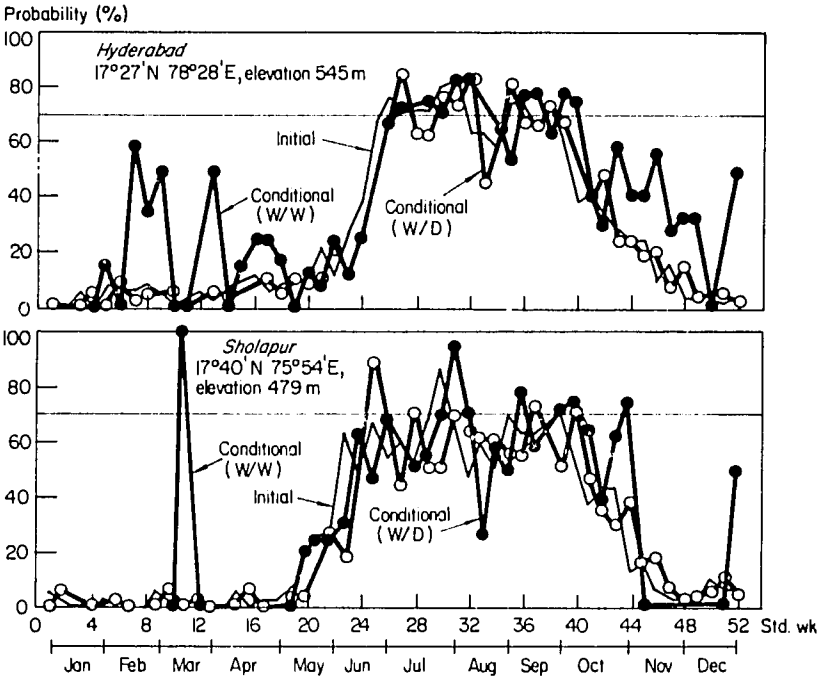
Soil moisture. Available soil water storage capacity and the likelihood of moisture stress are dominant factors affecting crop growth in the SAT. Thus, the soils are grouped in terms of their ability to store water. The Vertisols and Mollisols have a high content of 2:1 clay minerals and, therefore, a high water-holding capacity. Deep Vertisols in India may store as much as 250 mm plant-available water in a 2-m profile (ICRISAT 1977). Most of the other soils are light-textured so that even the deep phases rarely store more than 100 to 150 mm available water within the profile. These differences represent a crucial factor for crop survival and production in a region with undependable rainfall.

Soil depth. Shallow soil profiles are common. In India, for example, about 50% of the Vertisols are shallow or medium deep. Their lower available water capacity, compared with that of deep Vertisols, is sufficient to hold the present

Table 1. Soils of the semiarid tropics.[a]

Soil order	Area (million km^2)			
	Africa	Latin America	Asia	Total
Alfisols	4.66	1.07	1.21	6.94
Aridisols	4.40	0.33	0.47	5.20
Entisols	2.55	0.17		2.72
Inceptisols	0.38		0.28	0.66
Mollisols		0.78		0.78
Oxisols	1.88			1.88
Ultisols	0.24	0.08	0.20	0.52
Vertisols	0.51		0.80	1.31
Others		0.70	0.23	0.93
Total	14.62[b]	3.13	3.19	20.94

[a]The data in this table are derived from the map by Aubert and Tavernier (1972). [b]Excluding lakes, which occupy 0.13 million km^2.



2. Initial and conditional rainfall probabilities of P/PE≥0.33 at two selected Indian semiarid tropic locations (source: Virmani et al 1978). W/W = wet week, W/D = dry week, PE = evapotranspiration.

potential at one crop per year. Soils of very shallow effective rooting depth are frequently encountered, either due to their location on upper slopes and hilltops, or to a compact zone in the profile which impedes water and root penetration. Examples of the latter are the *murrum* layers in Alfisols in India and the *lateritic plinths* in Africa and Latin America.

Soil erosion. The high rainfall intensity experienced in the SAT is the prime cause of serious erosion (Greenland 1977). Soils are bare and dry when the rainy season commences. High-intensity rains then, and especially after cultivation but before there is appreciable plant cover to protect the soil, cause large soil losses. Overgrazed common lands also erode excessively. In Africa and Latin America, a major erosion threat is posed by the decreasing fallow period and the decreased protection of the soil surface.

The vast damage and the rapid decline in the productive potential of the land in the SAT that result from soil erosion have been well recognized. Heseltine (1961) points out a decreased productivity of land and water resources in tropical Africa due to inadequate management. Greenland and Lal (1977) describe soil erosion problems and potential remedies (e.g. mulching and minimum tillage) in the more moist tropical regions. Kampen (1974) reports on the serious losses due to soil erosion in India.

Soil fertility. Most SAT soils have low fertility (Jones and Wild 1975, Sanchez 1976, Kanwar 1976) because they are almost universally deficient in nitrogen and phosphorus. Sulfur deficiency is common in Africa where the annual rainfall exceeds 600 mm. Marginal zinc deficiency appears to be common over appreciable areas of India. The formation of most soils in a semiarid environment has resulted in their being reasonably well-endowed with bases, especially in respect to the low demands made by crops grown under traditional management practices. Extremes of acidity or alkalinity do not appear to be sufficiently serious to cause widespread problems at present; this contrasts with observations on soils of low base status, which have developed under more severe leaching – for example, the Oxisols of the humid tropics.

Land use and production systems in the Indian SAT

Ryan and associates (1974) discuss social and economic issues in relation to agricultural development in the SAT. Asia has by far the highest total population and population density among the major regions in the SAT (Table 2). It also has the lowest energy intake, protein intake, and income per capita. The statistics for Asia are dominated by data from India: total population and population density are greater there than anywhere else in the SAT; average landholdings, arable land per person, and fertilizer use are smallest. Because the problems now encountered in the Indian SAT may occur elsewhere when population pressures increase, emphasis is given to the Indian situation.

Three major agricultural production systems exist in the *dryland* regions of India. Often they are combined on the same farms: grazing on the upper slopes and hilltops, rainfed cropping on the intermediate slopes, and rice (or sugarcane) cultivation on the lowlands.

Grazing. The high and increasing grazing pressure on the skeletal soils of the uplands has resulted in serious erosion particularly early in the rainy season when the vegetative cover is limited. The water-holding capacity of the soils is so low that cultivation of food crops becomes extremely risky; the runoff and erosion danger is extreme under cropped conditions. Recent government policies to allot such land to previously landless labor have extended cultivation onto these marginal lands.

Rainfed crops. The range of crops grown in the Indian SAT is so extensive (Krantz and associates 1974) that detailed description is not possible. The main crops are sorghum (23% of the cropped area), millet (12%), groundnut and cotton (each 9%), wheat and chickpea (each 6%), and pigeonpea (2%). Wheat and chickpea, because of their need for a cool winter season, are planted in the northern areas. Cotton and groundnut are cash crops that require more assured soil moisture than sorghum and millet. Sorghum requires a better moisture environment than millet, which is grown under the most extreme dry conditions.

In addition to monoculture, various types of multiple cropping systems are used where the soil moisture status is favorable. A single crop of sorghum or millet may be grown on Alfisols and shallow to medium-deep Vertisols during

Table 2. Selected socioeconomic data on major regions in the semiarid tropics (SAT).

Data	Asia	Africa South of Sahara	South and Central America	Near East and NW Africa	Oceania (Australia)
Portion of component countries in SAT (%)	36.0	65.0	31.0	12.0	25.0
Total area in SAT (million km^2)	2.2	11.5	3.3	0.6	1.9
Population in SAT (million)	296.0	157.0	58.0	2.0	1.0
Population density in SAT (persons/ha)	1.33	0.13	0.17	0.03	0.01
Population growth rate (%)	2.4	2.5	2.7	2.9	1.9
Gross domestic product per head (US$)	106.0	123.0	469.0	303.0	3008.0
Domestic production relative to total food supplies:					
Cereals (%)	95.0	99.0	113.0	89.0	147.0
Pulses (%)	106.0	127.0	107.0	102.0	38.0
Net food supplies per capita per day:					
Energy (Kcal)	2013.0	2155.0	2670.0	1997.0	3160.0
Protein (g)	49.0	60.0	67.0	58.0	92.0
Per capita growth (%) of gross domestic product	2.3	2.6	2.1	6.4	3.4
Av size (ha) of agricultural holding	2.7	74.0	104.0	8.3	1842.0
Annual growth (%) of agricultural production 1961–71	2.6	2.6	3.4	1.7	n.a.[b]
Arable land (ha) per person active in agriculture	1.2	2.1	3.7	2.9	103.3
Fertilizer (NPK) consumption (kg/ha) on arable land	15.9	3.1	29.7	10.4	25.4
Cattle and buffaloes on arable land (no./ha)	1.36	0.89	2.30	0.42	0.62
Coefficient of variation of yields:					
Sorghum (%)	9.3	11.5	17.0	2.3	19.4
Millet (%)	14.1	14.9	12.4	11.6	14.3

[a]Adapted from Ryan and associates (1974). [b]Not available.

the rainy season. On Alfisols in seasons with late monsoon rains, a second rapid-maturing crop may be sown after an early-maturing monsoon crop, such as millet. On the deeper Vertisols, drainage problems and crop production risks during the rainy season have led to cropping only in postrainy season, often with disastrous effects due to runoff and erosion (Krantz and Kampen 1977). The

practice of growing two crops in succession, or as intercrops, is at present used on less than 20% of the deep Vertisols.

Combinations of crops, as mixed crops or intercrops, are utilized on all soils (Krantz and associates 1974) to optimize production and to reduce the risk of total crop failure. Common examples, particularly on Alfisols, are sorghum and pigeonpea, sorghum and millet, millet and pigeonpea; on Vertisols, postrainy season mixtures of cereals and oil seeds or legumes are found (sorghum and safflower, sorghum and chickpea). Other reasons for crop mixtures are to maintain soil fertility by growing legumes with cereals, to spread labor use, and to provide the subsistence farmer with several types of food grains. Certain intercrop combinations may produce superior yields across a wide range of agroclimatic conditions, with low as well as high levels of inputs and crop management (Spratt and Chowdhury 1978, Rao and Wiley 1979).

Rice cultivation. Either wetland rice or sugarcane is grown on the lower slopes and valley bottoms where more water is available and drainage is a frequent problem. Irrigation water is obtained from tanks (small reservoirs with water impounded by earthen dams) that store water from intermittently flowing drainage lines (Kampen 1977). Shallow wells are also common. The total rice production varies considerably from year to year because the area cropped is adjusted to allow for an adequate water supply; in wet years, sufficient water is stored for the total command area to be cropped once and a substantial portion to be cropped twice.

Rice and sugarcane production are not commonly included in the statistical summaries of the areas of dryland cropping patterns in the SAT; such data almost always describe upland crops only and effects of moisture unreliability on productivity. However, wetland rice and sugarcane are scattered throughout the Indian SAT, wherever the area favors water storage or groundwater use. Each village farmer may crop both dryland and wetland, but rice and sugarcane production is favored to the detriment of rainfed farming.

Production systems in the African and Latin American SAT

An important difference between India and other countries of the SAT is that continuous cultivation is normal in India, while shifting cultivation is still practiced across large areas of Africa and Latin America.

Two distinct types of vegetation were common in the African SAT in the past – the savanna zone in the drier, unimodal rainfall regions and the forest zone in the wetter, sometimes bimodal area (Cocheme and Franquin 1967). Under the bush fallow system, the soil is adequately protected because full surface exposure occurs only during the year of bush clearing and planting of the first crop. But in much of the African SAT where the fallow species are grasses, the soil is less well protected against erosion. The most common practice in the savanna zone (on soils that are often thin and gravelly) is to prepare the land with a hand hoe before planting the first crop. In northern Ivory Coast, Ghana, and Nigeria it is normal to scrape the soil into mounds on which various

crops are grown. Normal subsistence food crops are millet, sorghum, and groundnut in the drier zones, and maize, cassava, and various legumes in wetter regions. Intercropping is common and many crop combinations are used (Norman 1975).

In East and Central Africa, there is great variation in cultivation methods and cropping systems. In the *chitemene* system practiced in Zambia and Rhodesia, finger millet (*Eulisene corecana*) is planted without preparatory cultivation as a first crop; cropping may continue for 2 to 4 years with groundnut and beans in the second year, sorghum in the third, and cassava in the fourth. In parts of Malawi and Tanzania, beans or cowpea are planted on mounds, followed by finger millet or maize and beans (Krantz and associates 1974). Farmers often use the valleys for banana or sugarcane; the best upland soils are planted to cotton, maize, sorghum, or groundnut; and the poorer soils are planted to cassava.

The major food crops of the Latin American SAT are maize, dry beans, cassava, and banana (Patrick 1972). Most are grown with other crops. Some farmers include melon, castor, cassava, and palma (a cactus used for forage). Most mixtures are grown in the *slash-and-burn* areas of shifting cultivation. Increasing population pressure forces crop agriculture to steeper lands, where soil erosion and land degradation are serious problems.

THE CONSTRAINTS

The diversity of the resource base (climate, soil, people, etc.), cropping systems, and livestock management systems encountered in the SAT prevent a precise discussion of constraints and potential remedies. Nevertheless, some major restraints can be identified.

Soil physical factors

Crusting and drainage. High-intensity rainfall is common in the SAT. Surface soil of low water stability may suffer crusting and restricted infiltration; the result is reduced seedling emergence and increased runoff and erosion. Occasional periods of excess water also occur -- aeration may be restricted, especially on heavy soils. Waterlogging and nitrogen deficiencies are frequently observed.

Shallow soil profiles. Although deep plowing or chiseling of compact subsurface layers is sometimes beneficial (Nicou 1975), present draft power resources in the SAT pose a constraint to the practice. Once the surface soil is eroded, the subsoil matrix is often an especially poor medium for supporting plant growth.

Workability and timeliness of agricultural operations. Some heavy-textured soils, e.g. Vertisols, may be easily tilled only over a narrow range of soil water content. That limits the time available for tillage, and thus the area that can be cropped by draft animals. This constraint is even more serious where only manual labor is used.

Moisture storage. The drought sensitivity of light-textured soils – even if they are deep – is well recognized. Extensive areas of such soils occur in West Africa. Under normal rates of evapotranspiration, water on an Alfisol might be depleted

in only 1–3 weeks, but a deep Vertisol may continue to supply crops with water over a rainless period of as long as 4–6 weeks (ICRISAT 1975). These differences are often crucial for crop survival in dry periods.

The similar susceptibility to drought of some clayey Oxisols is less well known. In these soils the aggregates are particularly compact and the release of plant-available water may be similar to that of a sandy soil (Sanchez 1976). Susceptibility to drought limits the productivity of these soils under present management systems.

Soil fertility

Natural fertility. In India, data from many agronomic experiments show the need for fertilizer inputs, especially nitrogen and phosphorus. Surveys have been conducted to map the nutrient status of soils based on laboratory estimates. The soil test values have been compared with field responses only for irrigated soils.

Fertility constraints will certainly increase with time. Increased production, due to the use of improved varieties and improved land and water management, increases the demand on the soil pools of various nutrients. Additionally, exploitive practices cause a constant drain of nutrients. Increasing occurrence of potassium deficiency can be expected on Alfisols in India and on the light-textured soils of the West African savanna, which have low potassium (Wild 1971).

Loss of organic matter and nutrients. Increasing pressure for food production results in continuous cultivation of all arable soils, and continuous grazing on noncultivated soils. In India the pressure for immediate financial returns contributes to the low fertility of soils. After the removal of the grain, stalks and other residues are exported from the field and often from the farm; large quantities of sorghum and wheat straw are transported to the cities for use as animal feed. Dung is valued as fuel. Thus, nutrient return to the soil may be small. Nevertheless, farmers recognize the value of manure: small amounts of farmyard manure are applied to the land and itinerant herders are sometimes paid to herd sheep or goats on cultivated fields.

Fertilizer use. In rainfed agriculture in India, very little inorganic fertilizer is used; fertilizer is applied to about 30% of the dryland cropped to cotton or rice, and to about 15% of that cropped to wheat or sorghum (Tandon 1977). The average rate of application of elemental nutrients is 15 kg/ha (Ryan and associates 1974), representing mainly application to irrigated rice. Farmers apply fertilizer only when responses are assured.

In India, the almost complete lack of fertilizer application to crops such as sorghum appears to be a much more conservative policy than is warranted. Even in fairly dry years, economic responses can be obtained with applications of up to 40 kg N/ha (Spratt and Chowdhury 1978, Krishnamoorthy et al 1977).

Risks and uncertainty. The major constraint to wider use of fertilizers appears to be the uncertainty of responses because of uncertain soil moisture regimes. A secondary factor is socioeconomic. Most farmers in the SAT have limited means; a cash outlay for fertilizer must show an attractive return. The farmer

cannot risk even an occasional year's loss of return on the extra funds invested because interest rates are high and credit systems are rigid. Better water management, resulting in improved soil moisture, should considerably reduce the risk of losing fertilizer investment, particularly in drier years.

Biological nitrogen fixation. Under some of the drier regimes, the risks involved in fertilizer application may be so great (at least for nitrogen) that fertilizer will not be applied. Although the need to optimize biological nitrogen fixation by the use of suitable legumes is obvious, quantitative data on biological nitrogen fixation in the tropics are scarce. Some data are available for Africa (Nye and Greenland 1960, Jones and Wild 1975). In India, many authors have measured nitrogen removal by herbage and grain (Kanwar 1976), but none appear to have measured net accretion rates.

At the national planning level, there is a need to plan many years ahead for the capital and energy requirements for nitrogen fertilizer plants. This need will depend on the inputs to the soil from biological fixation and on the feasibility of its substantial improvement by current research.

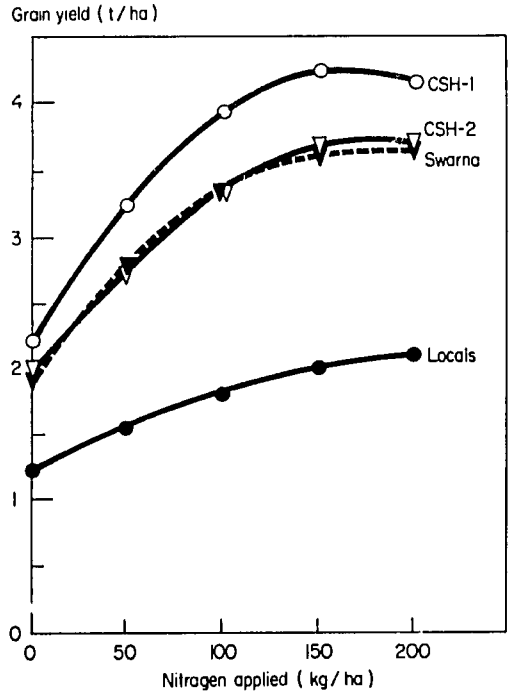
Biological constraints. The biological constraints have received relatively little attention. Legume growth may suffer because of inefficient rhizobial activity. There is increasing evidence of nonrhizobial nitrogen fixation (ICRISAT 1977); however, results are very variable, which suggests as yet unknown limitations to the bacterial association with the roots of some graminaceous species. Some cropping sequences appear to be unsatisfactory due to allelopathic agents. Examples are depressions in yields of maize after mung bean, cowpea, and sorghum (IRRI 1973, Herrera and Harwood 1975).

Salinity. Contrary to popular belief, there is at present little evidence of widespread serious salinity problems in upland soils of the SAT. For example, the total area of salinity-affected soils in India is only 7 million ha (Yadav 1976). However, the increasing use of irrigation (either with water from local aquifers or from general irrigation schemes) is expected to cause a considerable increase in salinity problems; with high potential evapotranspiration rates, accumulation of salts in surface soils appears inevitable unless adequate drainage is provided.

Production potentials of genotypes and cropping systems

Plant breeding experiments in the SAT are usually on soils of moderate to high fertility; one may therefore develop varieties that require fertile soils. Relatively little emphasis has been given to breeding or selecting for the ability of plants to produce on low fertility soils (Sanchez and Buol 1975). The desired characteristics are a combination of efficient extraction of nutrients from the soil by the plant and efficient utilization of the nutrients once absorbed. A successful example is sorghum variety CSH-1 (Fig. 3), which not only gives a much higher yield without fertilizer, but is also more responsive to applied nitrogen than the farmers' local varieties (Singh et al 1972).

Existing varieties of chickpea and pigeonpea require much lower added fertilizer phosphorus than do sorghum and millet (ICRISAT 1974, 1975). The need to preserve this characteristic, while improving yields, is obvious.



3. Comparative yield response of 4 sorghum cultivars to nitrogen application during the rainy season. Yield values represent the average of 25 experiments at various sites in the All India Coordinated Sorghum Improvement Project, 1965–70 (source: Singh et al 1972).

Population pressure and management skills

The increasing populations in the SAT cause difficult problems for resource management and utilization at the farmer's level. In the shifting cultivation systems of Africa and Latin America, production will support population densities of 0.01–0.3 person/ha. Greater densities are associated with continuous or semipermanent cultivation (Jones and Wild 1975).

The much higher population densities of India create other management problems. Prospective farming systems on Vertisols (discussed later) require some cultivation during the long dry season when animal feed is always in short supply. Can farmers be persuaded to keep more quality feed for draft animals so that they can perform the essential dry season cultivations? Group action and farmers' organizations may be required to ensure an equitable distribution of the benefits arising from the development of land and water resources. To be successful, such organizations will, in the long run, need to be supported by public laws.

Plow pans and compacted subsoil layers present another problem; if loosening of the subsoil is desirable, are there local power sources of sufficient strength to operate subsoiling equipment? Alternatively, can credit be arranged for farmers to pay for contracted subsoiling? Many similar questions will have to be answered to attain substantially more productive and stable farming systems in the SAT.

RESEARCH ON VERTISOLS AND ALFISOLS AT ICRISAT

Because the uncertainty of an assured supply of available soil water is a primary constraint to increased production in the SAT, improving the management and conservation of water and soil is an important goal. Resource management and use approaches pursued at ICRISAT show promising results with two of the major soils in India, the Alfisols and the Vertisols. The attributes of the local soils at ICRISAT have been listed by Krantz et al (1978).

The ICRISAT work entailed the development of new farming systems, which are based on the application of improved land, water, and crop management to watersheds or catchments. The components of these systems are described in the next section. The management systems are currently evaluated on national research stations and at the village level in India. These will eventually provide testing grounds for the full range of soils found in the Indian SAT.

Watershed-based systems for resource conservation, management, and use

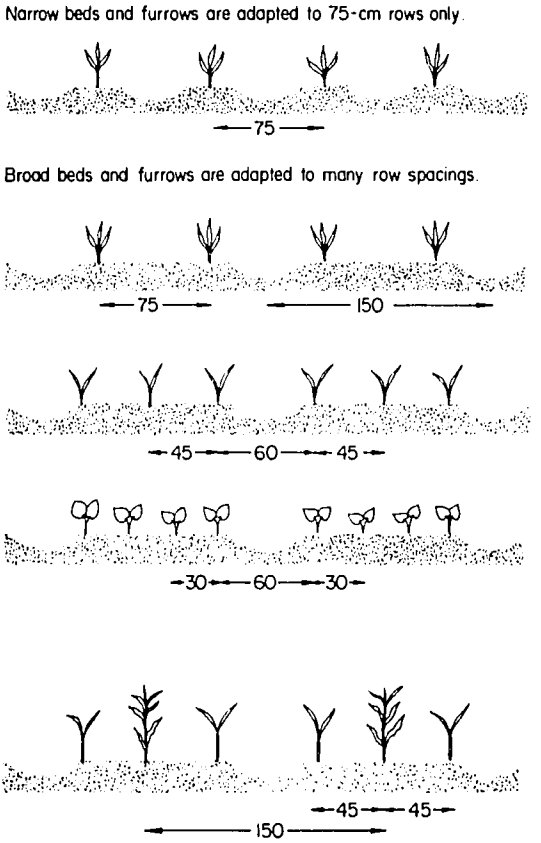
In rainfed agriculture the watershed is the natural unit for research on water management in relation to crop production systems and resource conservation and use. *Watershed-based resource utilization* involves the optimum use of precipitation through improved water, soil, and crop management for the improvement and stabilization of agriculture on the watershed. Utilization of water within a watershed can be improved by one or more of the following:

- directly by improving infiltration of rainfall into the soil,
- through runoff collection, storage, and use, or
- by recovery from wells after deep percolation.

Broad bed and furrow system. A broad bed and furrow system with an amplitude of 150 cm (Fig. 4) has been the most successful for facilitating cultural operations and for controlling excess water. Narrow graded ridges of 75-cm amplitude were not stable, particularly on Alfisols. The ridges were insufficiently wide to prevent *breaching*, which can be catastrophic for any soil and water conservation system (ICRISAT 1977). Furthermore, the 150-cm broad beds are more flexible; it is possible to plant two, three, or four rows at 75-, 45-, and 30-cm spacings, respectively (Fig. 4). Comparisons of flat planting with cultivation on narrow ridges and broad beds indicate substantial yield advantages of the graded broad-bed system on Vertisols. In 1976, values of crop yields in field-scale experiments were about Rs 800/ha (US$1 = Rs 7.95) higher on broad beds at a 0.4 to 0.6% slope than under flat cultivation at that slope (Table 3).

The broad bed system on deep Vertisols minimizes erosion and runoff because the excess water runs off at a controlled velocity in many furrows. Drainage during wet periods is also improved. The preliminary data obtained at ICRISAT indicate that the optimum slopes along the furrows on Vertisols are in the 0.4–0.8% range.

The broad beds and furrows are so arranged that water discharges into grassed waterways, which may lead to a dug tank or earth dam (Fig. 5). At ICRISAT,



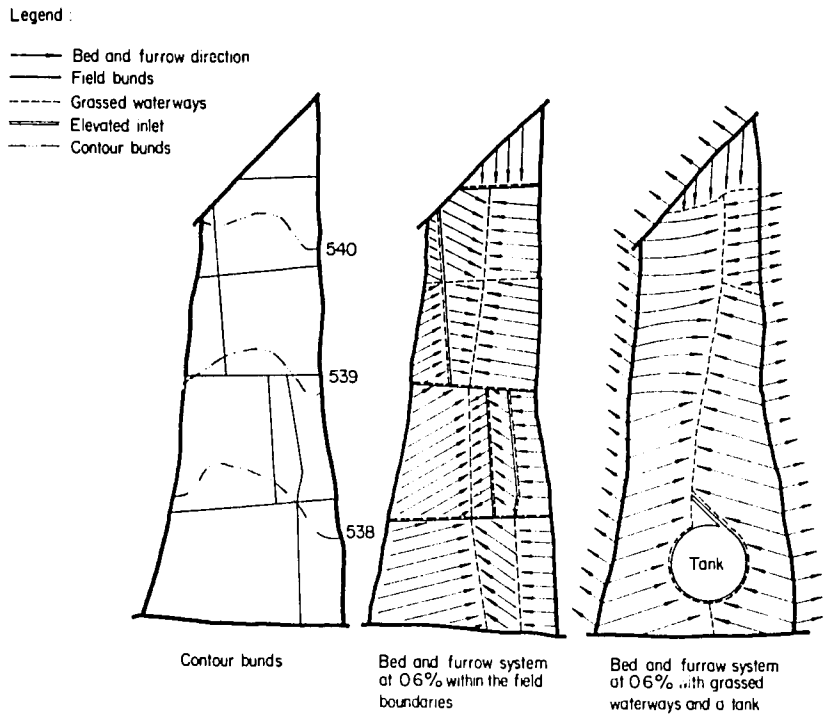
4. Cropping patterns and row arrangements on 75-cm ridges and 150-cm broad raised beds (source: Krantz et al 1978).

Table 3. Effect of land management[a] on runoff, erosion, and yields of sequential cropping of maize and chickpea on deep Vertisols, 1977.

Land treatment	Runoff (mm)	Erosion (kg/ha)	Yields (kg/ha)			Total value[b] (Rs/ha)	
			Maize	Chickpea			
				Nonirrigated	Irrigated	Nonirrigated	Irrigated
Flat planting	141	240	2740	490	610	3170	3360
Narrow ridges	77	110	3240	450	650	3540	3860
Broad beds	110	170	3170	740	940	3940	4260

[a]Furrows in the ridged and broad bed treatments were maintained at a 0.6% grade; the drill rows under flat planting had the same slope. [b]US$1 = Rs 7.95.

research on watershed-based resource utilization is on natural watersheds of a size similar to those of farmholdings. Several alternative resource-management methods and cropping systems are simulated on these watersheds under conditions (in terms of available labor and draft animals) similar to those on farms.



5. Vertical watershed with 3 possible soil and water conservation management practices. The broad bed and furrow (150 cm) system at 0.6% slope within field boundaries (center) was established 6 years ago. On the right is the watershed shown with field boundaries removed and a grassed waterway and tank in place. Contour bunds (left) are seldom tolerated by farmers, who do not want their fields bisected. It is for this reason that bunds are usually placed on field boundaries, with the resultant problems of water stagnation and breaching (source: Krantz et al 1978).

These systems are markedly different from the prevailing systems of contour bunds (large earthen embankments erected at vertical height intervals of 1–3 m); bunded land has no effective erosion control for the cultivated area and excess water is not collected but is led off or ponded on a small portion of the land (Fig. 5). Although some types of bunds may be useful with less intense rainstorms and on soils with high infiltration rates and large storage capacities, no positive effects of bunding have been found on Vertisols (ICRISAT 1977).

Runoff collection and use. The collection of surface runoff during periods of excess rainfall, and its subsequent use during dry periods in the dry season markedly decrease the risk involved in rainfed agriculture. This is particularly important on Alfisols and shallow Vertisols because of their limited water-retention capacity; one or more severe midseason droughts can be expected every 4 or 5 years in many areas of the SAT. A particular example is the response

observed in the rainy season of 1974, when a 30-day dry period coincided with the grain formation stage (ICRISAT 1975). An irrigation of only 5 cm to sorghum and maize in operational-research watersheds maintained yields near optimum levels, while yields of entirely rainfed crops decreased about 70%. The gross values of the average increase due to this water application in 2 watersheds were Rs 3,120/ha for maize, Rs 2,780/ha for sorghum, Rs 1,085/ha for pearl millet, and Rs 650/ha for sunflower.

The deep Vertisols rarely require supplemental water for the rainy season crop. However, supplemental water can always be used on a postrainy season crop; growing a second crop can sometimes be facilitated by a small initial quantity of water (Table 3).

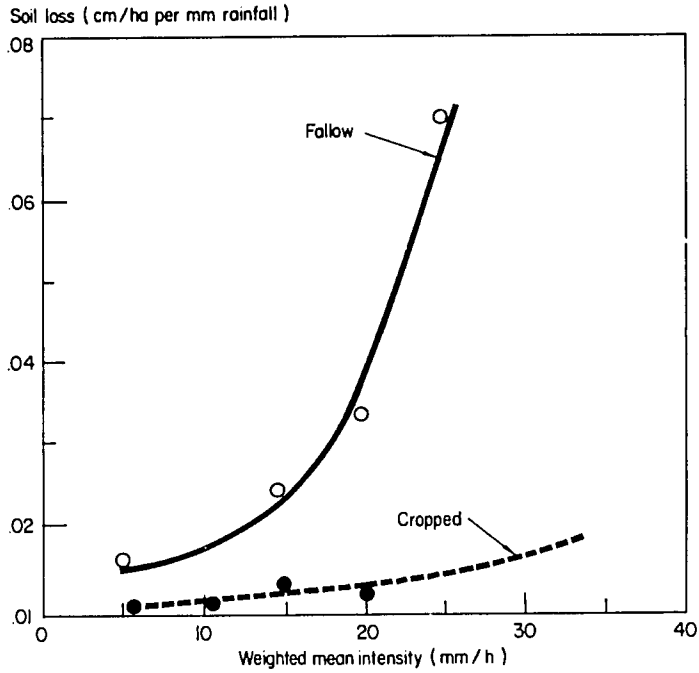
The potentials for use of collected surface water or groundwater as a backup resource need to be further explored. The direct effect of improved water-utilization technology appears substantial in years of ill-distributed rainfall. A similar effect may be expected in producing a second crop in the dry season. However, another consequence of decreased risk of production may be of even greater importance; the reduced uncertainty will provide the basis for greater assured responses to other inputs such as improved seeds and fertilizers in all years.

Infiltration and water balances. Provided that storage capacity is available in the soil, maximizing of infiltration is of the highest importance. This is especially relevant to the deep Vertisols, whose capacity to store up to 250 mm of plant-available moisture allows plants to survive mid- or late-season dry spells. However, improvement in infiltration may be needed on Alfisols. Although the infiltration rate on these soils may be 75 mm/hour shortly after cultivation, it can diminish to less than 10 mm/hour after surface crusting created by high intensity rainfall (Krantz et al 1978).

Investigations on runoff and soil loss during high intensity, long duration storms on operational-scale research watersheds at ICRISAT have shown that total runoff and peak runoff rates on watersheds using broad beds on Vertisols are much lower than those observed for other management. This is particularly true in relation to the traditional cultivation fallow treatment, which is presently practiced on almost 20 million ha in India (Fig. 6). Ellison (1944) and Hudson (1971) point to the danger of soil erosion on bare-fallow systems and the critical importance of vegetative cover during high intensity storms.

Although runoff is considerably reduced on cropped Vertisols using broad beds, the quantity of runoff is still considerable on both soils. The seasonal runoff on Vertisols exceeds 10% of the rainfall in many years. On Alfisols, 20% runoff is not unusual due to their surface-sealing character (Table 4); also large quantities of the rainfall may percolate beyond the root zone (ICRISAT 1976). Thus, the rainfall effectively used (that portion of the growing-season precipitation actually used for evapotranspiration) may remain relatively low, often in the 50–60% range (ICRISAT 1975, 1976).

Reappraisal of the cropping season. Only a small portion (20%) of the deep Vertisols in India are cropped during the rainy season (Krantz and associates



6. Effect of rainfall intensity on soil loss in a fallowed and a cropped watershed on a deep Vertisol (source: ICRISAT Annual Report 1976–77).

1974). In contrast, rainy season cropping is found on Alfisols and shallow and medium-deep Vertisols. The reason is largely the poor workability of these heavy soils once the rainy season starts, thus preventing land preparation and weed control. With these soils fallowed during the rainy season, the profile becomes saturated in midseason and considerable runoff occurs during the remaining part of the season (Table 4). However, if a crop can be established on these soils in the rainy season, the whole profile is usually near saturation only for short periods during the latter half of the season, water is more efficiently utilized, and there is less need for runoff collection and storage (Table 4). A possibility is also created for double-cropping because the high water storage capacity of these soils supports more growth during the subsequent dry (but cooler) post-rainy season.

The deep Vertisols can be cropped during the rainy season if crops are sown dry (shortly ahead of the rainy season) in areas where the rains commence fairly reliably and where there is a good probability of followup rains to ensure crop establishment. One problem is the difficulty of preparing a seedbed during the dry season. However, the development of new tillage techniques and equipment and the occurrence of 1 or 2 prerainy season rains in most years make adequate land preparation ahead of the rainy season feasible.

Table 4. Rainfall and runoff on a cropped Alfisol and a cropped deep Vertisol watershed with bed and furrow systems at 0.6% slope, and a rainy-season fallowed watershed at ICRISAT, 1976.

Date	Rainfall[a] (mm)	Runoff (mm)		
		Alfisol	Deep Vertisol	
		Cropped	Cropped	Fallow
23 Jun	23	1.8	0	0.5
2 Jul	24	3.0	1.7	0.2
21	89	25.2	16.9	49.4
3 Aug	26	0.8	0.2	1.6
4	32	8.5	2.3	21.4
19	105	77.5	27.0	95.4
20	39	16.5	19.5	37.1
21	10	0	4.2	8.5
26	8	0.5	0.1	3.2
3 Sep	8	0.2	0	2.9
4	20	2.3	0.4	11.1
Total for 11 larger storms	384	136.3	72.3	231.3
Total for 8 other smaller storms	115	4.3	0.7	6.9
Total	499	140.6	73.0	238.2

[a] Includes only rainfall from 19 runoff-producing storms. The total rainfall for the rainy season (Jun–Oct) was 679 mm.

Crop production and rainfall productivity

In operational-research watersheds on Vertisols at ICRISAT, three watersheds with broad beds were compared with two adjacent flat-planted watersheds. Each cropping system was replicated in each watershed unit, and yields and monetary values were calculated as means of the replicates (Table 5). The use of broad beds resulted in substantially increased yields. On Vertisol watersheds, with broad raised beds but without runoff collection, a much higher proportion of the rainfall was used for crop production than in most present systems; on these the effective rainfall under double-cropping was about 70% in 1974, 65% in 1975, and 65% in 1976, 2 to 3 times the effective rainfall utilized by existing rainy season-fallow systems (ICRISAT 1975, 1976, 1977).

Intercropping systems on broad beds usually resulted in a somewhat greater rainfall utilization than sequential cropping systems due to more continuous canopy development. The effective rainfall on Alfisols, even under improved systems of farming, was only about 55% in 1975 and 1976. Without technically appropriate and economically viable systems for runoff collection and use, large increases in effective rainfall appear difficult to achieve on these soils.

Preliminary estimates of the *rainfall productivity* (RP) – the agricultural production achieved by alternative systems of farming – show wide differences between various farming systems in 1975–76 and 1976–77 (Table 6). In 1975,

Table 5. Grain yields and values[a] of several double-cropped farming systems involving improved technologies on deep Vertisol watersheds at ICRISAT, 1976–77.

Landform	Slope (%)	Maize/pigeonpea intercropping[b]			Maize-chickpea sequential cropping[b]		
		Maize (kg/ha)	Pigeon-pea (kg/ha)	Gross value (Rs/ha)	Maize (kg/ha)	Cowpea (kg/ha)	Gross value (Rs/ha)
Raised bed	0.6	3260	720	4870	3310	600	3840
	0.6	2910	900	4960	3090	450	3410
	0.4	3590	670	4930	2970	760	3800
Mean		3290	760	4920	3120	600	3680
Flat		3030	620	4470	2350	440	2750
		2790	560	3940	2930	280	3000
Mean		2910	620	4210	2640	360	2870

[a]US$1 = Rs 7.95. [b]Intercrop varieties: maize, SB23; pigeonpea, ICP2. Sole crop: maize, Deccan Hybrid 101; chickpea, local.

sequential cropping of rainy season maize and supplementally irrigated postrainy season sorghum resulted in the highest RP value on deep Vertisols. RP increased from Rs 12/cm per ha in a traditional farming system of single postrainy season cropping on rainy season-fallowed land to Rs 58/cm per ha on double-cropped Vertisols, cultivated to graded ridges (ICRISAT 1976). A very high RP value (Rs 133/cm per ha) was obtained on an Alfisol watershed where pearl millet, grown on graded ridges in the rainy season, was followed by supplementally irrigated tomato in the postrainy season. The range of RP values obtained on deep Vertisols illustrates the production potential of this environment in the SAT if an improved system of farming can be developed and implemented. Such systems are now being further adapted and tested in on-farm research conducted cooperatively with national programs in India.

TARGETS FOR THE FUTURE

Since the gloomy predictions of Malthus that overpopulation would cause doom and starvation because food production could not increase correspondingly, there have been many such predictions. These have not been realized because an unexpected factor has resulted in increased production to satisfy, at least partly, the ever-increasing demand for food (Sanchez 1976). At this stage, we are similarly faced with difficulties in accurately predicting the future. The current rates of increases of population and food production are too closely matched – about 2.6 and 2.7% per annum compound growth (Ryan and associates 1974). Improved land- and water-management techniques, which strike at the most limiting constraints in the SAT, offer considerable promise, especially because they also promote better responses to fertilizer and improvements in

Table 6. Rainfall productivities (RP) for some alternative farming systems on Vertisols and Alfisols at ICRISAT, 1975–76 and 1976–77.[a]

Watershed number[b] and treatment	Cropping system and water use[c]	RP[d] (Rs/cm per ha)
1975–76 Vertisols		
BW1, narrow (75 cm), graded (0.6%) beds	Maize-chickpea	58
	Pigeonpea-setaria	34
BW3A, narrow (75 cm), graded (0.4%) beds	Maize-chickpea	52
	Pigeonpea-setaria	39
	Maize-sorghum S(5)	62
BW4C, flat, field bunded, traditional[e]	Fallow-sorghum	12
BW6B, flat, contour bunded	Fallow-sorghum	16
1976–77 Vertisols		
BW1, broad (150 cm), graded (0.6%) beds	Maize-chickpea	53
	Pigeonpea-maize	68
BW3A, broad (150 cm), graded (0.4%) beds	Maize-chickpea	53
	Maize-chickpea S(5)	63
	Pigeonpea maize	68
BW4C, flat, field bunded, traditional	Fallow-sorghum	9
BW6B, flat, contour bunded	Fallow-sorghum	17
1975–76 Alfisols		
RW1D, broad (150 cm), graded (0.4%) beds	Pigeonpea-sorghum	36
	Pearl millet-tomato	92
	Pearl millet-tomato S(5)	133
RW1E, flat, contour bunded	Pigeonpea-sorghum	31
	Pearl millet-tomato	77
	Pearl millet-tomato S(5)	100
1976–77 Alfisols		
RW1D, broad (150 cm), graded (0.4%) beds	Pigeonpea-setaria	36
	Groundnut-safflower	66
RW1E, flat, contour bunded	Pigeonpea-setaria	30
	Groundnut-safflower	43

[a]In 1975, the total seasonal rainfall in Vertisol watersheds was 1,040 mm and in Alfisols 1,100 mm; in 1976 the rainfall on Vertisols was 720 mm and on Alfisols 680 mm. [b]BW refers to Vertisol watersheds, RW to Alfisol watersheds. [c]The symbol "S" followed by a number indicates that supplemental water was provided at the given quantity in centimeters. [d]US$1 = Rs 7.95. [e]Those systems defined as traditional simulate local farming practices in terms of seed, fertilizer, farm equipment, etc.; in all other systems, optimum technology in terms of land and crop management is maintained.

genotype. However, a major unpredicted catastrophe (e.g. an exceptional series of drought years) may upset all calculations. Nevertheless, enough is known of the major constraints so that further efforts to overcome them may be envisaged to result in larger annual increases in production than previously. If there is a decrease in the rate of population growth, then a continuing increase in per capita food production within each country of the SAT may be expected.

RESEARCH STRATEGIES FOR THE FUTURE

The potential for improvement of some of the farming systems of the SAT has been established. However, land and water development and improved resource and crop management must fit the resource base of the farmer and result in immediate and visible benefits to provide for successful implementation. Deferred or small benefits will not capture the imagination of farmers. Although the long-term aim is to develop improved stable farming systems, the strategy required is detailed study on specific problems with concurrent studies to integrate the work on component disciplines.

Specific research problems

Several specific problems need to be examined. Water is the first key to crop growth in the SAT and emphasis must be given to improved land and water management systems especially for the light-textured soils, and also to the establishment of crops where surface crust can so drastically limit crop emergence and yields.

Under the assumption that improved moisture environments will provide greater potential for plant growth, attention must be focused on identifying the nutritional requirements of low-fertility soils with needs for low-cost inputs. Assessment of the risks attached to fertilizer inputs is a high priority; the use of existing records will assist early achievements. Longer-term efforts are needed to understand all aspects of nutrient cycling. There is a great need for more complete studies of the cycling of sulfur and nitrogen within the soil, and especially the movement of these nutrients in water, and for in situ measurement of nitrogen fixation rates and losses, to ultimately maximize accretion and utilization of nitrogen by plants. Some questions that need answers are:

- What are the inputs from legume crops?
- Can grain legumes improve the soil nitrogen levels under continuous cropping or alternatively, as suggested by Henzell and Vallis (1977), does the offtake of nitrogen by grain legume exceed the amount of nitrogen fixed by the legume?
- Can fixation by tropical cereals (e.g. sorghum and millet) be promoted to reliably satisfy a significant proportion of nitrogen requirement of these cereals?

The serious problems that develop under increasing population pressure in shifting cultivation systems in Africa and Latin America must be recognized. Ways must be found to minimize the fertility decline and soil erosion to a fraction of the current levels.

While most of the constraints can be alleviated at the farmer or village level, there is a need for direction at the national policy-making level. In India, for example, there is need for direction on land and water use. Shallow soils on hilltops should be used for permanent crops, and not overgrazed. Guidelines are needed for the control of the use and the management of stored water. While the present use is concentrated on crops with high water requirements, more economic returns (for society) may be obtained by the use of low rates of irriga-

tion on dryland crops (Kampen 1977). The social, organizational, and institutional problems involved need urgent research attention.

Simulation techniques based on mathematical modeling of the physical processes appear to have considerable potential in quantifying and predicting the effects of different environments on crop production, especially where there is large diversity in the environment. This technique may considerably reduce the need for detailed agricultural research at a large number of sites (Virmani et al 1978). To back up simulation techniques, it will be necessary to identify a limited number of *benchmark* locations. The diversity of the resources encountered in the seasonally dry tropics dictates associated and coordinated research efforts in a number of areas characterized by widely divergent agroclimatic, social, and economic conditions.

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Discussion summary

Session II.
C. Panabokke, chairman; D. Greenland, reporter.

Soil-related constraints, soil properties, and soil taxonomy: a terminology for exchange of scientific information, by W. Johnson

The general principles and the nomenclature system of *Soil taxonomy* were briefly outlined. It was stressed that the principal interaction between soil properties must never be forgotten. The inclusion of soil water and temperature regimes in the system was recognized, but more reliable measurements for the tropical regions and a consistent relationship between soil and air temperature were considered essential. Although *Soil taxonomy* is comprehensive and flexible, it is admittedly too complicated for general use. Interpretive groupings could simplify requirements. Further abridgment or simplification of *Soil taxonomy* was not considered feasible. However, the need to accommodate parameters for radiation regimes, and the creation of discrete categorical levels to accommodate *wetland soils* were accepted. Similarly, the need for modifying some of the presently used chemical criteria for purposes of soil fertility and for more stress on surface-soil characteristics, as in paddy soils, was highlighted.

Major production systems related to soil properties in humid tropical Africa, by F. R. Moormann and D. J. Greenland

The available body of research information for two broad soil groups – Alfisols and Ultisols-Oxisols – has clearly enabled a selective approach to research on the management problems of the soils of humid tropical Africa. Drought stress, restrictive rock layers, and erosion susceptibility are the major constraints on the Alfisols. High aluminum saturation at shallow depth of the Ultisols, and the low absorption capacity of the Oxisols are recognized as major constraints. The low retention of available water is recognized as a factor common to all groups. The existing information obtained from long soil-management experiments is applicable to specific agroecological regions within the humid tropics, and the need for further extending soil management research to well identified agroecological situations was stressed. The carrying capacities of the land and their interaction with the level of technology that would be relevant to the respective situation were discussed. It was recognized for example, that the Oxic Paleustalfs were capable of high sustained production if given the appropriate inputs and management compared with the Ultisols-Oxisols group. In attempting to correlate soil qualities with population density, other factors such as the hazards of the environment should also be considered. Reasons were also given for the growing period of 270 days as an appropriate boundary for the *humid tropics.*

Major production systems and soil-related constraints in Southeast Asia, by F. J. Dent

The major unexploited soil resource in the humid tropics of Asia consists of Acrisols of different makeup. They occur on a range of landforms, from rolling to very steep. Other than for export-oriented single-commodity plantation crops, little research information is available in respect to soil management for arable or permanent food crops. It was suggested that some experiences from the Ultisol region of the Amazon could be transferable to the Asian region. The hazards of indiscriminate and speedy jungle clearing with heavy bulldozers were highlighted by figures quoted for increase in bulk densities and striking reduction of infiltration rates. The need for safer indigenous techniques of land clearing and development was stressed. More research information on potential yield figures for different crops and their responses to lime, fertilizers, and micronutrients should be obtained. It was argued that low energy production systems, which involve high labor intensity, could be highly successful. Finally, it was recognized that coordinated interdisciplinary research efforts should be strengthened in the different agroecological regions of the Acrisols in Asia.

Soil constraints in relation to major farming systems of tropical America, by P. A. Sanchez and T. T. Cochrane

Two major production zones – with high base status soils and low base status soils – were recognized. Major constraints in the high base status (Alfisol) area relate to physical conditions, including erosion and dryness; those in the low base status areas pertain to nutrient management. Issues of general significance discussed were the reliability of the qualification of areas of different constraints, the problems and appropriateness of developing and extending *low output* strategies to increase production in the areas of low base status soils where difficult nutritional balance problems exist, and the problem of erosion control and its extension.

Production systems, soil-related constraints, and potentials in the semiarid tropics, with special reference to India, by J. Kampen and J. R. Burford

The paper stressed the problems of the variability of climate and rainfall incidence patterns in the semiarid tropics, and the need to improve food production systems by improving water management. The differences between the Sahelian zone and the Indian semiarid tropics in terms of soils and climate were discussed. The discussion centered on two general issues: the reliability of available information, and the problems of extending information from an international agricultural research center developed at a single site. The problems of evaluating needed fertilizer and other outputs for the semiarid tropics raised these general questions. What degree of risk was acceptable in relation to increased output in areas where water was likely to be the major limiting factor? Is soil testing feasible and reliable in such areas?

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Soil acidity in well-drained soils of the tropics as a constraint to food production

E. KAMPRATH

Many of the soils in humid regions are very acid (<pH 5) and crop growth is hindered by toxicities of aluminum or manganese or both. The major exchangeable cation in these acid soils is aluminum. Crop production is drastically reduced when aluminum saturation of the active cation exchange sites is greater than 60% and tends to be optimum when aluminum saturation is zero. Although base saturation is a criterion in soil taxonomy, it does not identify soils with acidity problems because the diagnostic horizon, except in one instance, is not the Ap. Soils with aluminum toxicity problems can be identified by extracting aluminum with potassium chloride and determining the proportion of the active cation exchange sites, sum of aluminum + calcium + magnesium + potassium, occupied by aluminum. Lime rates sufficient to neutralize exchangeable aluminum are considerably less than those required for pH 6.5. The amount of lime required to neutralize aluminum can be estimated by the equation meq $CaCO_3$/100 g = meq exchangeable Al x 2. Root growth into acid soil below the limed plow layer can be enhanced by use of aluminum-tolerant varieties, which thus increase utilization of soil moisture from below the limed zone.

MANY WELL-DRAINED soils in the humid tropics are acid and contain low amounts of basic cations. Early studies in which soils were limed to near neutrality often gave variable results (Pearson 1975). Many of the soils had high buffer capacities, and the amounts of lime required to raise the pH to neutrality were not economical. Liming practices that worked in temperate areas where 2:1 clays dominated were not applicable to highly weathered soils with 1:1 clays and 2:1 Al-interlayered clays.

Department of Soil Science, North Carolina State University, Raleigh, N.C. 27650, USA.

Ideas about soil acidity underwent drastic changes in the 1950s. The predominant cation in acid soils of less than pH 5 was shown to be aluminum rather than hydrogen (Coleman and Thomas 1967). The exchangeable acidity affecting plant growth was found to be that which could be extracted with a neutral unbuffered salt solution. At pH 5.5 and above, soils contained essentially no potassium chloride-exchangeable aluminum.

These findings resulted in a reexamination of the traditional concepts of base saturation developed with temperate soils. Soils with kaolinite and 2:1 Al-interlayered clays were found to be essentially 100% base saturated at pH 5.8 to 6 when the cation exchange capacity (CEC) was based on the sum of exchangeable bases and potassium chloride-extractable acidity (Coleman et al 1959).

No attempt is being made in this paper to document all of the liming studies in tropical regions. Pearson (1975) has made an excellent review of liming studies in the tropics and the reader is referred to that publication for documentation of response data for various crops. This paper examines the constraints of soil acidity on crop production in the tropics in the light of the modern concepts of soil acidity and shows how these concepts can be applied to liming practices.

SOIL ACIDITY PROBLEMS IN THE TROPICS

Use of base saturation as a criterion in soil taxonomy

Base saturation has been used as a criterion for classification at the great group level for Inceptisols and Oxisols and as one criterion of the Ultisol order. Examples of how base saturation is used in soil classification are given in Table 1. Base saturation of the surface soil is used only with the great group Eutrorthox. In all other instances the base saturation of a subsurface horizon is used. Thus, one cannot draw any specific conclusions as to the base saturation of the surface horizon except for one great group.

Some general conclusions, however, can be made. The great groups with the prefix *eutr* will generally have less acidity problems in subsurface horizons than those with the prefixes *dystr* and *hapl*. In many instances soils with the *eutr* prefix will probably have a better supply of calcium and magnesium in the surface horizon because of nutrient cycling than the other great groups. Great groups with the *dystr* and *hapl* prefixes can have soil acidity problems in subsurface horizons ranging from severe to slight because base saturations can range from 0 to 35 or 50 or 60%.

It must be kept in mind that the diagnostic horizons chosen for classification purposes are those which are not influenced by management practices, such as liming. Therefore, it is necessary to measure the pH and aluminum saturation to determine whether soil acidity will be a problem in surface soils.

Soil pH, exchangeable aluminum and aluminum saturation of soils

Major constraints to crop production in acid soils are toxicities of aluminum, manganese, and hydrogen and deficiencies of calcium (Jackson 1967). Research

Table 1. Use of soil acidity as diagnostic criterion in soil taxonomy.

Soil	Diagnostic criteria		
	CEC method	Base saturation (%)	Depth
Eutrochrepts	NH_4OAc	>60	In some part of 25 to 75 cm
Dystrochrepts	NH_4OAc	<60	25 to 75 cm
Eutropepts	NH_4OAc	>50	25 to 75 cm
Dystropepts	NH_4OAc	<50	In some part of 25 to 75 cm
Eutrorthox	NH_4OAc	>35	Epidedon and all subhorizons of the oxic horizon to a depth of 1.25 meters
Haplorthox	NH_4OAc	<35	In some part of the epipedon and subhorizons of the oxic horizon to 1.25 meters
Eutrustox	NH_4OAc	>50	In major part of the oxic horizon if clayey
		>35	In major part of the oxic horizon if loamy
Haplustox	NH_4OAc	<50	In the major part of the oxic horizon if clayey
		<35	In the major part of the oxic horizon if loamy
Ultisol	Bases + $BaCl_2$·T.E.A. acidity	<35	1.8 meters below surface or to 1.25 meters below upper boundary of argillic horizon or immediately above lithic contact or paralithic contact

in the 1950s with Ultisols showed that potassium chloride-exchangeable aluminum is the predominant cation in acid soils and that more meaningful values of cation saturation are obtained when CEC is based on the sum of exchangeable bases plus potassium chloride-exchangeable aluminum. The chemical properties of acid soils were evaluated with the use of the above concepts, and the data are presented in Table 2.

Exchangeable aluminum is a major cation in many of the acid soils, particularly at pH 4.5 and less. It occupies a large proportion of the effective CEC in these acid soils. Aluminum toxicity is definitely a problem in many soils in the tropics.

Several other important facts are brought out by the data in Table 2. The levels of exchangeable aluminum are relatively low (av 1 to 3 meq/100 g). As will be pointed out later this is an important factor when considering the soils, lime requirement. Another point is that the effective CEC is low, indicating that the clays have low activity.

Another factor affecting the exchangeable aluminum content of acid soils is the kind of clay minerals present (Juo and Kamprath 1979). Acid topsoils with

Table 2. Exchangeable aluminum, aluminum saturation, and pH of acid surface soils in tropical and temperate regions.

Region	Samples (no.)	Soils	pH range	Exchangeable aluminum (meq/100 g)		Aluminum saturation (%)	
				Range	Av	Range	Av
Australia[a]	7		4.5–5.2	0.6–3.2	1.6	32–97	72
Malaysia[b]	8		3.6–4.2	0.7–12.4	3.4	34–86	61
Brazil[c]	5	Red-Yellow Latosol	4.0–4.6	1.8–3.2	1.7	38–90	74
	3	Red Latosol	4.1–4.2	0.7–1.9	1.2	83–90	88
Colombia[d]	26	Oxisols	4.2–5.1	0.6–5.8	3.1	29–86	68
Panama[e]	6	Latosols	4.8–5.2	0.25–5.8	2.5	44–68	57
Puerto Rico[f]	5	Ultisols	3.9–4.6	4.5–9.9	6.6	36–70	57
	3	Oxisols	4.2–4.8	0.4–1.1	0.8	18–40	33
West Africa[g]		Ultisols					
	21		5.1–5.4	0–2.0	0.46	0–43	13
	26		4.5–5.0	0.05–3.7	1.34	2–69	41
	27		4.0–4.4	0.05–2.8	1.2	1–67	35
United States[h]	4	Ultisols	4.5–4.7	0.9–4.2	2.1	54–82	72

[a]Teitzel and Bruce 1972. [b]Singh and Talibudeen 1969. [c]Pratt and Alvahydo 1966. [d]Vargas 1964. [e]Mendez and Kamprath 1978. [f]Abruna et al 1975. [g]Juo 1977. [h]Kamprath 1970.

kaolinite and 2:1 clays with aluminum-interlayers had, on the average, 2½ times more exchangeable aluminum than those with only kaolinite even though the clay content was considerably less (Table 3). Subsoils with aluminum-interlayered clays also had much higher exchangeable aluminum contents even though their pH's were higher than subsoils with only kaolinite. The presence of Al-interlayered clays is the reason that certain Ultisols and Oxisols contain higher amounts of exchangeable aluminum than others even though clay contents and soil pH are similar.

Soil solution aluminum concentrations of acid surface soils (<pH 5) from temperate and tropical regions were at levels considered toxic for many crops (Table 4). Highest concentrations were in coarse-textured Ultisols from North Carolina, which contained 2:1 clays with Al-interlayers. The lowest concentration was in a clay-textured Oxisol from Brazil in which the clay mineral was kaolinite. The high concentration of soil solution aluminum in the Tropudult from West Africa with 3% carbon was attributed to organo-aluminum complexes (Juo 1977). The solution concentration of aluminum in surface soils from West Africa was supersaturated with respect to gibbsite. Solubility of aluminum was thought to be controlled by amorphous aluminum hydroxides, amorphous aluminum silicates, and organo-aluminum complexes. Concentrations of soil solution calcium would be considered adequate, except for the loamy sand, if aluminum were not at toxic levels.

Manganese levels in acid soils

Manganese toxicity is one of the possible constraints to crop production in acid soils. Morris (1948) found that the presence of 2 ppm of water-soluble manganese on a soil basis using a 1:2 soil-to-water ratio was sufficient to induce

Table 3. Effect of mineralogy on the exchangeable aluminum content of soils (data from Juo and Kamprath 1979).

Parameters	Clay mineralogy	
	Kaolinitic	Kaolinitic and 2:1 with Al-interlayers
	Topsoils	
Av potassium chloride-extractable aluminum (meq/100 g)	1.80	4.82
pH range	3.5–4.7	4.0–4.7
Av clay content (%)	31	17
	Subsoils	
Av potassium chloride-extractable aluminum (meq/100 g)	1.42	3.30
pH range	4.0–4.5	4.7–5.0
Av clay content (%)	45	36

Table 4. Exchangeable and percent saturation of calcium (Ca) and aluminum (Al) and soil solution concentration of Ca and Al of acid surface soils.

Area	Texture	pH	Exchangeable		Saturation (%)		Soil solution (meq/liter)	
			Ca (meq/100 g)	Al (meq/100 g)	Ca	Al	Ca	Al
North Carolina[a] (Ultisols)	Loamy	4.9	0.06	1.43	5	95	0.75	0.55
	Sandy loam	4.4	1.00	3.67	23	77	5.00	0.53
Brazil[b] (Oxisol)	Clay	4.5	0.45	1.15	26	70	1.14	0.16
Puerto Rico[c] (Ultisol)	Clay	4.1	0.44	5.35	6	77	3.24	0.31
West Africa[d]								
Paleudult	Sandy loam	4.2	0.26	1.83	9	64	–	0.30
Tropudult	Sandy loam	5.2	6.80	0.02	68	0.2	–	0.23

[a] Evans and Kamprath 1979. [b] Gonzales 1976. [c] Brenes and Pearson 1973. [d] Juo 1977.

manganese toxicity symptoms. The concentration in the soil solution of acid soils is dependent upon the amount of easily reducible manganese in the soil and the soil pH. Whether a soil has a low or high content of easily reducible manganese is dependent upon the type of parent material from which the soil is formed. In Puerto Rico clay-textured Oxisols had high contents (600–800 ppm) of easily reducible manganese while Ultisols had much lower (40–200 ppm) amounts (Pearson 1975). When soil solutions were at pH 5 (soil pH 5.5), concentrations of manganese were at very low levels (Pearson et al 1977).

MEASUREMENT OF SOIL ACIDITY AND INTERPRETATION

Extraction with unbuffered neutral salt solutions

"Probably the most significant single experiment which can be performed on an acid soil is to leach with a neutral salt solution such as 1 *N* KCl" (Coleman et al 1958). Unbuffered neutral salt solutions such as KCl replace cations which are bonded electrostatically to soil surfaces. In strongly acid mineral soils, Al^{+3} is the major cation countering active exchange sites, and exchangeable hydrogen is negligible (Coleman and Thomas 1967). Exchangeable Al^{+3} hydrolyzes to $Al(OH)^{+2}$ and $Al(OH)_2^{+1}$ and $Al(OH)_3$ as the pH is increased. Therefore to measure exchangeable aluminum present or active exchange sites, the extracting solution must assume the pH of the soil system.

One common procedure for determining exchangeable acidity is to extract 10 g soil with 50 ml of *N* KCl and wash with another 50 ml of *N* KCl (Lin and Coleman 1960). The extract is then titrated with 0.1 *N* NaOH to the phenolphthalein end point. To determine the relative proportions of hydrogen and aluminum in the leachate, two indicators, methyl orange and phenolphthalein, are used in the titration. Methyl orange has an end point which is close to pH 4. The titer to the methyl orange end point would be the acidity attributable to exchangeable hydrogen, and the difference between titer to the methyl orange end point and that to the phenolphthalein would be the exchangeable aluminum component. The rational for this is that a 10^{-3} *M* $AlCl_3$ solution has a pH of 4. Therefore, unless the KCl extracts have a pH of less than 4, there is essentially no exchangeable hydrogen present. Acid mineral soils extracted by the method described have not contained any exchangeable hydrogen (Evans and Kamprath 1970).

In a detailed study in which soils were leached with a large volume of *N* KCl, Bache and Sharp (1976) separated the extractable aluminum into exchangeable and nonexchangeable aluminum. A rapid estimate of exchangeable aluminum was obtained by shaking 4 g soil with 100 ml *N* KCl for 30 minutes. Exchangeable Al (Y) was related to the estimates of exchangeable aluminum (X) by the equation, $Y = -0.7 + 0.98X$. The correlation for this relationship was 0.973.

Another approach to estimate plant available aluminum is to shake soils for 5 minutes in 0.01 *M* $CaCl_2$ using a 1:2 soil-to-solution ratio (Hoyt and Webber 1974). The aluminum extracted by this procedure was correlated with exchangeable aluminum extracted with 2 *N* NaCl.

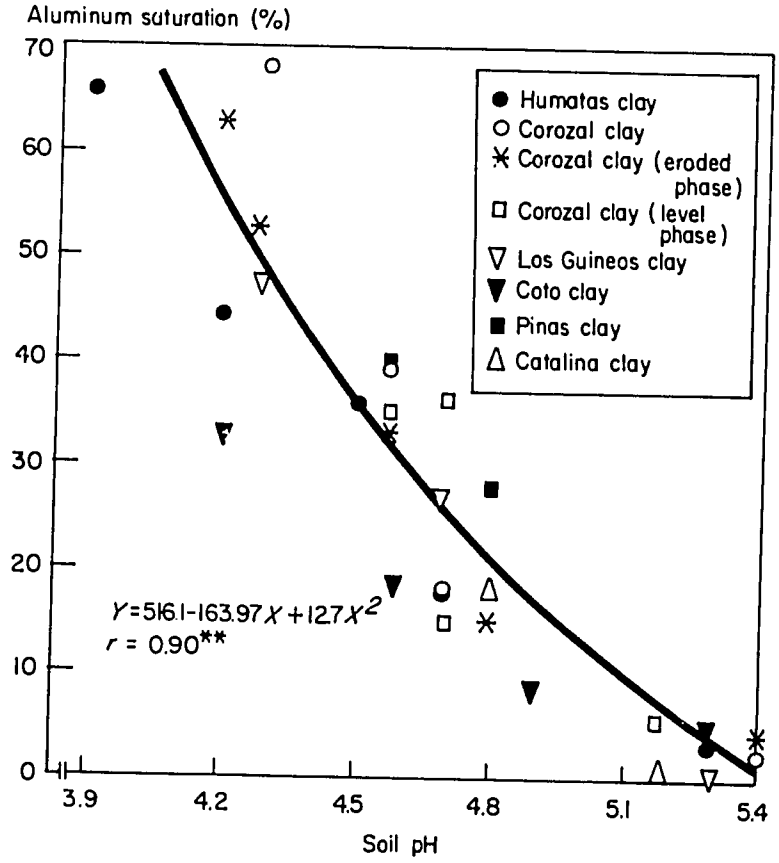
Relationship between soil pH and Al saturation

Soil pH is related to aluminum saturation. This relationship for Ultisols and Oxisols in Puerto Rico is shown in Figure 1. At pH 5.4 the aluminum saturation of the effective CEC (sum of exchangeable Al, Ca, Mg, and K) was essentially zero; at pH 4.2 it was approximately 60%.

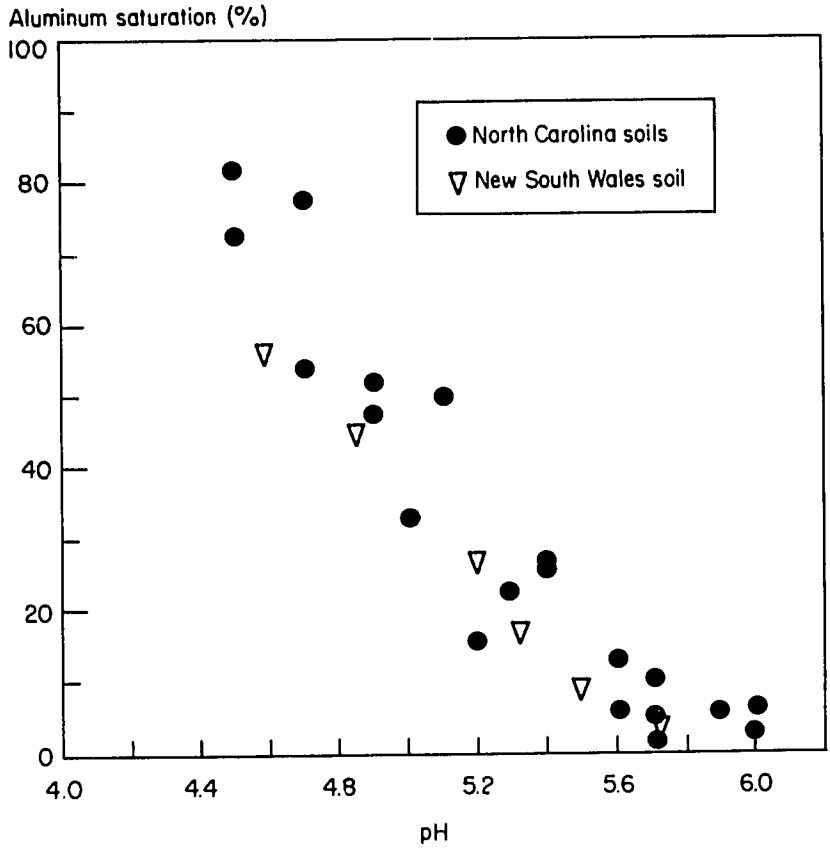
A good relationship also exists between soil pH and aluminum saturation for an Australian and four North Carolina Ultisols (Fig. 2). Aluminum saturation was essentially zero at pH 5.8 and 60% at pH 4.6

Juo (1977) found a high correlation ($r = -0.81$) between soil pH and aluminum saturation of subsoils from West Africa. The correlation for surface soils was only –0.50. When the pH of surface soils was measured in KCl the correlation increased to –0.63.

When soils from a given area are considered, the relationship between soil pH and exchangeable aluminum saturation provides a qualitative assessment of whether or not aluminum toxicity is likely to be a problem. It must be kept in



1. Relationship between pH and aluminum saturation for several Puerto Rican Ultisols and Oxisols (Abruna et al 1975).



2. Relationship between pH and aluminum saturation for 4 North Carolina Ultisols and 1 Australian soil (Kamprath 1978).

mind, however, that electrolyte concentration influences soil pH and amount of aluminum in the soil solution (Pearson 1975). Therefore, high rates of fertilization may intensify aluminum problems because the higher electrolyte concentration increases aluminum in the soil solution.

Crop growth as related to exchangeable aluminum saturation and soil pH

Toxic concentrations of aluminum in the soil solution limit crop growth on acid soils. Methods for determining soil solution aluminum are not suitable for rapid analysis of large numbers of samples. There is, however, a fairly good relationship between the percentage of aluminum saturation of the effective CEC and soil solution aluminum (Nye et al 1961, Evans and Kamprath 1970). Aluminum concentration in the soil solution increases rapidly when the percentage aluminum saturation is greater than 60%.

An example of the relationship between crop growth and percentage of aluminum saturation is given in Table 5. For eight Ultisols and Oxisols the relative

Table 5. Relationship between soil acidity parameters of Puerto Rican soils and relative yield of corn on nonlimed treatments as compared to that on limed treatments (Abruna et al 1975).

Soil order	Initial pH	Exchangeable aluminum (meq/100 g)	Aluminum saturation (%)	Relative yield (%)
Ultisol	4.3	9.9	68	10
Ultisol	3.9	6.3	66	22
Ultisol	4.2	6.9	63	18
Ultisol	4.3	4.5	47	47
Oxisol	4.6	0.9	40	61
Ultisol	4.6	5.5	35	62
Oxisol	4.2	1.1	33	85
Oxisol	4.8	0.4	18	85

Relative yield = 122.0 − 1.58 (% Al saturation); r = 0.97.
Relative yield = −222.0 + 62.1 (soil pH); r = 0.60.

yield of corn on nonlimed plots as compared to that in limed plots was highly correlated with percentage of aluminum saturation. Correlation of relative yields with soil pH, however, was not as good. Relative yields of corn on five acid soils in the Philippines are shown in Table 6. Only on the acid soil with a relatively high aluminum saturation was there a severe depression in yield. Responses to liming on the other soils, which had relatively low aluminum saturations, ranged from 10 to 22%. This suggests that the detrimental effect of pH per se or manganese toxicity on growth of corn was not as great as that of high aluminum saturation.

Critical values of aluminum saturation and pH for crop production

To use soil acidity parameters for predicting crop response to lime application, one must have information about critical values for a given parameter. The levels of aluminum saturation and soil pH at which yields are less than 50% and more than 90% of the maximum (Table 7) have been summarized with data from a number of liming studies with various crops. The critical levels at the 90% yield level are less than 20 to 10% aluminum saturation for maize and generally less than 10% aluminum saturation for soybean, green bean, sugarcane, and cotton; and soil pH values were in the range of 5–5.3 for corn, 5.6 for soybean, and

Table 6. Relative yield of maize on nonlimed soils in the Philippines.

Soil pH	Exchangeable aluminum (meq/100 g)	Aluminum saturation (%)	Relative yield (%)
4.4	2.5	46	49
4.8	0.9	22	90
4.7	0.8	8	87
4.7	0.7	3	80
4.8	0.2	2	78

5.3–6 for cotton. Critical levels at yields less than 50% of the maximum are a) aluminum saturations of more than 40 to 60% in most instances, and b) soil pH values of <4.5 for maize, and <5.0 for soybean and cotton.

When establishing critical levels, the wide differences in varietal tolerance for aluminum within a given plant species must be considered. Another factor is the sensitivity to soil acidity of the crops in the rotation. The liming practice used must provide a favorable environment to the most sensitive crop. For most crops a liming program should reduce aluminum saturation to near zero. This will generally provide a favorable pH and adequate calcium supply.

Measurement of manganese as a toxic factor in acid soil

Measurement of soil manganese has been concerned primarily with prediction of manganese deficiencies. Manganese toxicity symptoms were observed in legumes when 1:2 soil-water extracts contained more than 2 ppm Mn on a soil basis (Morris 1948). In a study with 20 acid soils at <pH 5.1, the manganese extracted with 0.01 *M* $CaCl_2$ gave the best correlation with the manganese concentration in barley and alfalfa (Hoyt and Nyborg 1971). The extraction procedure involved shaking of 150 g soil in 300 ml 0.01 *M* $CaCl_2$ for 16 hours. Further work indicated that equally good correlations could be obtained with 0.01 *M* $CaCl_2$ using 1:2 soil-water ratio and shaking for 5 minutes (Hoyt and Webber 1974). No critical values for toxicity were given.

MANAGEMENT TECHNIQUES FOR OVERCOMING SOIL ACIDITY PROBLEMS

Liming to correct soil acidity

Soil pH control. One approach to correcting soil acidity is to add an amount of lime that will raise the soil pH to a given level. Various buffer solutions for measuring the amount of acidity that has to be neutralized to bring the soil to a given pH have been developed. A given amount of soil is added to the buffer solution and the depression in pH of the buffer is measured. The pH of the commonly used buffer solutions is 7 for the SMP (Shoemaker et al 1961) and Woodruff (1948), 8 for the Adams and Evans (1962), and 6.6 for the Mehlich (1976). Because the solutions are buffered at pH 7 to 8 they measure not only exchangeable aluminum but also hydrogen associated with hydroxy aluminum, hydrated oxides of Fe and Al, and carboxyl groups. With the proportions of soil and buffer solution used in the various methods, a 0.1 pH depression is equal to 1 meq H/100 g with the Woodruff buffer, 0.8 meq H/100 g with the Adams and Evans buffer, and 0.4 meq H/100 g with the Mehlich buffer. Amounts of lime to raise the soil to pH 6.5 to 7 are considerably greater than those required to neutralize exchangeable aluminum (Reeve and Sumner 1970, Mendez and Kamprath 1978).

One potential problem of liming soils to a pH near neutrality is the possibility of inducing deficiencies of micronutrients particularly boron, zinc, and manga-

Table 7. Critical levels of aluminum saturation and soil pH for a number of crops.

Area	Crop	Critical level			
		<50% max yield		90% max yield	
		pH	Aluminum saturation (%)	pH	Aluminum saturation (%)
Brazil[a]	Maize	–	–	5.3–5.6	<10
Puerto Rico[b]	Maize	4.4	50	5.0	<15
United States[c]	Maize	4.5	60	5.1	<40
Philippines[d]	Maize	4.4	46	5.0	<20
Brazil[a]	Soybean	–	–	5.6	<10
Puerto Rico[e]	Soybean	5.0	20	5.6	<10
United States[c]	Soybean	4.9	40	5.6	<20
Puerto Rico[f]	Sugarcane	4.4	50	5.0	<10
United States[c]	Cotton	5.0	45	6.0	<7
Uganda[g]	Cotton	–	–	5.3	0
Puerto Rico[b]	Green bean	4.3	50	5.2	<10

[a]Soares et al 1975. [b]Abruna et al 1975. [c]Kamprath 1970. [d]Samonte and Ocampo 1977. [e]Abruna et al 1978. [f]Abruna and Vicente-Chandler 1967. [g]Foster 1970.

nese (Kamprath 1971, Pearson 1975). Liming to pH 7 has reportedly decreased phosphorus availability in a number of soils (Kamprath 1971). It has been the case with soils containing large amounts of exchangeable aluminum (Asmarasiri and Olsen 1973). It is presumed that formation of freshly precipitated aluminum hydroxides would provide very reactive surfaces for reaction with fertilizer phosphorus.

Liming rates based on exchangeable aluminum. The use of exchangeable aluminum as the criterion on which to base lime rates has been proposed for soils with a low permanent charge and a relatively high pH-dependent charge (Kamprath 1967, 1970; Reeve and Sumner 1970). The rationale was that aluminum is the toxic factor in many acid mineral soils, and one purpose of liming is to remove aluminum toxicity as a constraint to crop growth.

To determine how much lime has to be added to neutralize the exchangeable aluminum, lime rates on a chemically equivalent basis are added as multiples of the amount of exchangeable aluminum. After the lime has had sufficient time to react, the amount of exchangeable aluminum neutralized is determined (Kamprath 1970). Various studies have shown that lime rates chemically equivalent to 1.5 to 3 times the exchangeable aluminum must be added to neutralize the aluminum (Table 8). The greater lime rates can be explained by the buffering properties of acid soils. Exchangeable aluminum is responsible for buffering in the pH range 4.0 to 5.6, while hydroxy aluminum and aluminum-organo complexes control buffering mainly in the pH range 5.6 to 7.6 (Jackson 1963). Studies with Ultisols showed that when the pH was approximately 5.3, lime reacted with both exchangeable aluminum and pH-dependent sources of acidity (Kamprath 1970). To neutralize all of the aluminum, lime had to be added at rates chemically equivalent to twice the exchangeable Al.

The use of 0.02 *M* $CaCl_2$ has also been proposed for estimating the lime requirement of soils (Webber et al 1977). The tons of calcium carbonate per acre to reduce soluble aluminum to zero are given by the equation 0.1 + 0.23 (ppm aluminum extracted with 0.02 *M* $CaCl_2$). This relationship was found for Gray Luvisols and Solods, which varied from 2 to 10% in organic matter and 14 to 85% in clay content.

Exchangeable acidity extractable with potassium chloride, which in most instances is aluminum, is a valid criterion on which to base lime rates. As a general rule the meq KCl-extractable acidity/100 grams X2 will give the meq $CaCO_3$/100 g required to neutralize acidity. The amount of lime equal to 1 meq $CaCO_3$/100 g is 1 t $CaCO_3$/ha to a depth of 15 cm.

Use of varieties tolerant of aluminum and manganese

Another approach to overcoming soil acidity problems is to select varieties that are resistant to high concentrations of aluminum or manganese, or both. Interest in this approach has increased during the last decade. Some species have shown a wide variation in varietal tolerance for aluminum. Wheat varieties developed in acid soils of Brazil are highly tolerant compared to varieties developed on neutral to alkaline soils (Foy et al 1965). Similar differences exist with other species. At a recent workshop on plant adaptation to mineral stress in problem soils, work on tolerance of plants for aluminum and manganese was reviewed in detail (Wright 1976). (The reader is referred to these excellent reviews for in-depth treatment of the subject.)

Table 8. Liming factor (meq Al/100 g x factor) required to give equivalents of calcium carbonate to reduce aluminum saturation to less than 10%.

Area	Soil (Surface 15 cm)	pH	Aluminum (meq/100 g)	Aluminum saturation (%)	Factor	Final pH
Brazil[a]	Red-Yellow Latosol	4.0	0.7	70	3	4.9
	Red-Yellow Latosol	4.4	0.9	75	2	5.5
	Dark Red Latosol	4.0	1.9	86	2	5.0
Colombia[b]	Oxisol	4.3	3.5	78	2	5.3
Panama[c]	Latosol	5.1	1.2	53	1.5	5.9
	Latosol	5.0	3.0	64	1.5	6.0
United States[d]	Ultisol	4.5	0.9	82	2.0	5.9
	Ultisol	4.7	1.0	78	2.0	6.0
	Ultisol	4.5	2.3	73	1.5	5.7
	Ultisol	4.7	4.2	54	1.5	5.6
India[e]		<5.0	–	–	2.0	5.3
Natal[f]	Oxisol	<5.0	–	–	3.3	

[a]Soares et al 1975. [b]Spain et al 1975. [c]Mendez and Kamprath 1978. [d]Kamprath 1970. [e]Pradhan and Khera 1976. [f]Reeve and Sumner 1979.

Because liming can correct aluminum and manganese toxicities in the plow layer, the greatest benefit from the use of tolerant varieties is increased rooting in acid subsoils. Beneficial effects of increased rooting depth are primarily the use of subsoil moisture. In many regions of the humid tropics it is common to have periods of 1 to 2 weeks without rain. If toxicities below the limed plow layer restrict rooting depth, moisture stress can develop and limit crop yields.

Use of organic matter additions

Organic matter complexes aluminum and manganese and thereby decreases the amount of aluminum and manganese in the soil solution (Schnitzer and Skinner 1963). Where available, large amounts of organic matter, e.g. easily decomposable plant residues, could be incorporated into acid soils. The humified material should decrease the concentration of aluminum and manganese in the soil solution because of the formation of organocomplexes. Relatively high rates of organic matter additions would be required in order to have any beneficial effect in reducing toxicities in acid soils. This approach could be used on small farms where supplies of organic matter or crop residues are plentiful, labor is abundant, and lime is in limited supply and high priced. Where lime is readily available, and reasonably priced it is the preferred alternative.

FUTURE KNOWLEDGE NEEDS

It has been adequately demonstrated that the lime requirement of highly weathered acid soils should be based on the content of exchangeable aluminum. However, there have been few well-controlled studies to determine the factor by which the equivalents of exchangeable aluminum need to be multiplied to give the amount of lime required to neutralize aluminum. Such studies should be done with soils with a wide range in chemical properties in the root zone. Attention should also be given to determining the soil properties that might cause the factor to vary. Further information is needed as to the critical aluminum saturations for crop species adapted to the tropical environment.

Methods for identifying soils where manganese toxicities are likely to occur must be developed. Very little work has been done in this area. Information is needed as to critical soil manganese levels where toxicity will occur with important crops in tropical regions and the rates of lime needed to eliminate the toxicity.

Some acid soils have essentially no exchangeable aluminum or toxic levels of manganese, but are low in exchangeable calcium. In such instances information is needed as to the calcium levels and the pH level for optimum crop production.

Where liming practices have been based on exchangeable aluminum there is little information as to how long a given lime application will be effective. Long-term lime studies need to be started to measure the long-term effectiveness. The depth to which soils are limed is particularly important in areas where 1- to 2-week periods of moisture stress develop and root growth into the subsoil is

limited by high aluminum saturation.

When a given crop species is used in liming experiments, varieties with tolerance for aluminum should be included. This is particularly important in determining the effect of acidity below the zone of lime incorporation on crop yields.

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Acidity of wetland soils, including Histosols, as a constraint to food production

N. VAN BREEMEN

This paper discusses the growth-limiting factors for rice in three types of acid wetland soils: acid sulfate soils, peat soils, and ferrolysed soils.

Young acid sulfate soils (Sulfaquepts) are generally too acid for crop production, and their reclamation and improvement are uneconomic. Older acid sulfate soils (Sulfic Tropaquepts) are marginally suitable for wetland rice, but offer better prospects of improvement. Extremely low nutrient levels and adverse soil physical properties are more important than high acidity in limiting crop production in peat lands. Deep (>90 cm) ombrogenous peats should be left unreclaimed, but clayey peats and shallow (<50 cm) peats on mineral substrata can sometimes be made productive. Because periodic or permanent drainage appears invariably necessary for good crop growth, subsidence will always be a problem in peat lands.

Most strongly weathered acid wetland soils (pH 4.5–5) present no specific toxicities or deficiencies, but their productivity is low even at high management inputs. Further research is needed to find out if and how they can be improved.

Recommendations for further research are given. Such research can be effective only when carried out by crop scientists, agronomists, soil chemists, and soil evaluators working in close cooperation.

WETLAND SOILS are defined here as soils that are ponded or water saturated during most of the time that they are, or could be, used for food crop production. Most wetland soils are only seasonally flooded. If crops grown during inundation suffer from high soil acidity, dryland crops grown on the same land after drainage generally fare worse because of the increase in soil acidity after

Department of Soil Science and Geology, Agricultural University, Wageningen, The Netherlands.

aeration of the soil. Indeed, soils with harmful acidity for wetland rice are generally unsuitable for nonaquatic food crops. Certain tree and fruit crops, however, can be grown successfully on partially drained, strongly acid sulfate soils. Examples are oil palm and rubber in Malaysia, and pineapple and Eucalyptus sp. in Vietnam. Whenever acid or potentially acid wetlands are reclaimed for dryland food crop production, considerations similar to those for well-drained soils apply (Kamprath, this volume).

Because rice (*Oryza sativa* L.) is by far the most important food crop grown in wetland soils, this paper will focus on it. Locally, sago palm (*Metroxylon sagus* Rottb.) and taro (*Colocasia esculenta* L.) are important food crops on wetlands. Kang kong (*Ipomoea aquatica* Forsk) is an important vegetable that thrives better in ponded than in dryland fields. No direct information is available on the effects of wetland acidity on crops other than rice, but sago palm is sometimes cultivated on acid sulfate soils (Reijnders 1961) and perhaps can stand high soil acidity. In view of the high potential production of sago (Flach 1976) the use of wetland soils for production of sago starch for industrial purposes merits attention.

GROWTH-LIMITING FACTORS IN ACID WETLAND SOILS

The discussion of constraints to food production on acid wetland soils should distinguish between general soil fertility characteristics as a function of soil pH, and the specific toxicities or deficiencies induced at low pH. For example, the many soil fertility characteristics that are correlated with the degree of weathering and, hence indirectly, with soil pH are more or less invariant on a short time scale, but the concentrations of potentially toxic substances vary seasonally with the oxidation-reduction state of the soil. Unless specified otherwise, soil pH is the pH in a water extract of aerobic soil.

Fertility

In paddy soils of tropical Asia, soil pH shows significant positive correlations with cation exchange capacity, exchangeable and total bases, available silica, total phosphorus, and various forms of extractable phosphorus. At the same time soil pH shows a significant negative correlation with total carbon and total nitrogen (Kawaguchi and Kyuma 1977). In reduced mineral soils, a relatively high soil pH enhances the mineralization of organic matter to ammoniacal nitrogen, in proportion to soil nitrogen. This tends to offset the effect of higher nitrogen contents at lower pH, and no significant correlation exists between ammonification rate and soil pH (Kawaguchi and Kyuma 1977).

Generally speaking then, the nutrient status of acidic wetland rice soils is less favorable than that of near-neutral soils. The higher kaolinite content and lower smectite and vermiculite contents of acid soils further decrease their fertility, both chemically and physically (Moormann and van Breemen 1978). Because of the many interrelated factors involved, it is extremely difficult to assess the quantitative relationships between productivity for rice and chemical and physical

soil properties correlated with high soil acidity. Such properties could be responsible for differences in productivity among different soils with comparable and relatively high management levels. Clearly, much research is needed to sort out the causes of the differences and to determine measures, in addition to well-known sound agronomic practices, that could help raise productivity on such acidic soils of low fertility.

There is no direct causal relationship between low soil pH and the low productivity of acidic wetland soils: most of these soils are strongly weathered (or consist of sediments from strongly weathered soils) and hence are low in bases, and have a low CEC and a low pH. In most, the pH is probably not low enough to cause harmful toxicities. Low fertility, which is not easily corrected by fertilizer application, may be more important. Indications are that an unfavorable pattern of release of soil nitrogen is partly responsible for yield gaps of several tons per hectare between very good and poor soils both under optimal management (Moormann and van Breemen 1978).

In some cases, relatively fertile marine clay soils are more productive when limited acidification has taken place (*para acid sulfate soils*, Pons 1973). This may be due to better physical properties resulting from higher (but nontoxic) levels of exchangeable aluminum than in near-neutral soil. Scheltema and Boons (1973) obtained a marked increase in rice yield after lowering the pH of a fine mixed, acid Typic Tropaquept from 5.5 to 5.1 by adding strong acid (HCl) or aluminum sulfate. They attributed the yield increase to increased mechanical stability of the soil.

Specific toxicities and deficiencies

Poor rice growth on highly acid flooded soils has been ascribed to low pH per se; to toxicities from dissolved aluminum, iron, hydrogen sulfide, carbon dioxide, and organic acids released at low pH; and to phosphorus deficiency induced at low pH (Ponnamperuma et al 1973, Bloomfield and Coulter 1973). Toxicity of carbon dioxide and organic acids tend to be more pronounced at low than at high pH (Ponnamperuma 1977), but little is known about the practical importance of these toxicities.

Harmful concentrations of hydrogen sulfide, which is toxic at concentrations as low as 1 mg/liter, may be present in acid soils during the first weeks after flooding (Ponnamperuma 1977).

In nutrient solutions toxicity by H^+ occurs only at pH below 3.5–4 (Kanapathy 1973, Thawornwong and van Diest 1974), but in most soils, except peat soils, aluminum toxicity is more important in that pH range. Concentrations of dissolved aluminum increase with decreasing pH. On the basis of results from solution culture experiments and levels of dissolved aluminum in the soil, aluminum toxicity may be expected in acid soils at pH 4.5–5 for rice seedlings, and at pH below 3.5–4.2 for older plants (van Breemen and Pons 1978).

Stagnant floodwater above reduced acid sulfate soils may become very acid (van Breemen 1975). Intrusion by such water (pH 2.5–3.5) may affect rice on

adjacent good land because of the toxicity of both H^+ and Al^{3+} (Pham-Huu-Anh et al 1961).

Iron toxicity in rice may develop at dissolved ferrous iron concentrations as low as 30 mg/liter if the nutrient status of the plants is poor or if the plants are weakened by other toxins (hydrogen sulfide, harmful organic substances), or at concentrations above 300–400 ppm if plants are well supplied with nutrients (van Breemen and Moormann 1978). Iron toxicity at low iron concentrations seems to be typical for zones with upwelling groundwater (in inland valleys) in areas with strongly weathered soils very poor in bases, as in the low-country wet zone in Sri Lanka and in many West African countries. The causes of the problem are not well understood, and several hypotheses (van Breemen and Moormann 1978) must still be tested.

Although a low soil pH favors high levels of ferrous iron after flooding, in most flooded soils iron concentrations that are toxic to well-nourished rice plants are not reached or are short-lived. Exceptions are young acid sulfate soils, particularly Sulfaquepts, where toxic iron concentrations may persist for many months. In older acid sulfate soils, soil reduction tends to be slow and iron levels remain relatively low (van Breemen and Pons 1978).

Phosphorus availability increases upon flooding, but this increase is generally less in strongly acid than in weakly acidic or near-neutral soils (Ponnamperuma 1976). Depression of phosphorus uptake in rice by high concentrations of dissolved aluminum may further aggravate phosphorus deficiency in acid soils low in available phosphorus.

Seasonal variation in chemical characteristics

Flooding and soil reduction cause a decrease in redox potential and, in acid soils, an increase in pH to about 6.5. Drainage and aeration reverse these processes. Thus, the chemical conditions in periodically flooded soils fluctuate with flooding and drainage (Ponnamperuma 1972).

In aerated soils soluble and exchangeable aluminum are relatively high, and soluble ferrous iron and other potentially harmful reduced compounds (hydrogen sulfide, toxic organic substances) are low or absent. Flooding causes soluble and exchangeable aluminum to disappear, and iron and other reduced compounds in the soil solution to first increase to peak values and later decrease to relatively stable lower levels.

Unfortunately, this picture cannot always be used to predict processes in rice soils in the field. Because irregular flooding is the rule in many rice lands and even in so-called irrigated areas (IRRI 1975), the fluctuations in chemical conditions are often more complex than one would expect if the soil were ponded throughout the growing season of the rice crop. For instance, while toxic aluminum will disappear some time after flooding, its concentration will rise quickly again when the fields become dry temporarily. Little or no experimental work has been done to assess the importance of such drainage periods on toxicities in acid wetland soils.

In acid wetland soils the speed of soil reduction (and hence of the pH increase and the disappearance of aluminum) as well as the maximum levels of dissolved iron varies widely and the factors governing the differences in behavior are poorly understood. For instance, low contents of easily reducible ferric oxide, low contents of metabolizable organic matter, unfavorable nutrient conditions for anaerobic microorganisms, and a highly buffered pH in the acid range should, theoretically, contribute to a slow rate of soil reduction (Ponnamperuma et al 1973, van Breemen and Pons 1978). However, an analysis of relevant published data, mainly by Kawaguchi and Kyuma (1969), failed to show evidence for most of these theoretical expectations (van Breemen 1976).

TYPES OF ACID WETLAND SOILS AND LIMITING CONDITIONS FOR FOOD PRODUCTION

Soils in which acidity either directly or indirectly plays a role in limiting productivity of wetland rice can be subdivided into several groups (Table 1). Acid sulfate soils and peat soils stand out relatively clearly. The group of acidic soils that do not cause specific toxicities or deficiencies, but where low fertility in general poses a constraint is difficult to define. This last group includes alluvial soils from sediments derived from highly weathered older soil materials, as well as surface-water gley soils that have undergone acidification and *degradation* of the surface soil due to ferrolysis (Brinkman 1970, 1977). The ferrolysed soils, classified as Planosols and Gleyic Acrisols in the FAO classification (FAO 1974), and often as Aquults in *Soil taxonomy* (USDA 1975), probably make up the largest group of the acidic low-fertility wetland soils, at least in Southeast Asia, and will be discussed separately.

Ferrolysed soils

Ferrolysed soils occur in older alluvial terraces that are seasonally ponded by rainwater, but are not normally flooded by river water, nor influenced by laterally moving groundwater. They are found often in pluvial anthraquic rice lands (Moormann and van Breemen 1978). Ferrolysed soils are characterized by an acid (pH 4–5), pale colored, and relatively light-textured surface horizon (0.3–0.6 m thick) with an anomalously low cation exchange capacity, over a more clayey and strongly mottled B horizon. In Southeast Asia these surface-water gley soils have also been classified as low humic gley soils or *degraded* paddy soils (Brammer and Brinkman 1977). Their strongly weathered surface horizon is the result of a cyclic (seasonal) process of displacement of exchangeable bases by ferrous iron during flooding, and oxidation and acidification after drainage (Brinkman 1970). With the possible exception of salinized soils of the low terrace in northeastern Thailand, where aluminum toxicity in both dryland crops and wetland rice was suspected (Brinkman and Dieleman 1977), they normally present no acute toxicities or deficiencies. The generally low yields on these soils are probably due to low fertility and, in many areas, irregular water supply and frequent droughts.

Table 1. Approximate hectarage of acid wetland soil groups and of peat soils in the tropics.[a]

Soils	Extent (million ha)		
	South & Central America	Africa	South & Southeast Asia
Strongly weathered, acid hydromorphic soils[b]	20	9.5	>15[c]
Acid sulfate soils and potential acid sulfate soils	2.1	3.7	5.0
Peat soils	7.3	6.5	22

[a]Data adopted from FAO (1974), Brammer and Brinkman (1977), Driessen (1978), and van Breemen and Pons (1978). [b]Includes Planosols (dystric, solodic, humic) and Gleyic Acrisols. [c]The figure of 15 million ha is only for Bangladesh, Thailand, Cambodia, Laos, and Vietnam.

Irrigated dryland crops grown during the dry season often suffer from the poor physical soil conditions: limited rooting depth and risk of ponding due to a shallow traffic pan, rapid crust formation due to poor aggregate stability.

Acid sulfate soils

Actual and potential acid sulfate soils cover about 5 million ha in Southeast and South Asia, mainly in Thailand, Vietnam, and Indonesia; about 3.7 million ha in Africa; and about 2 million ha in Venezuela. Millions of hectares of peat in Indonesia and smaller areas in Malaysia, Vietnam, and Venezuela are underlain by potentially acid clay.

Potentially acid soil (Sulfaquents) from tidal lands, or from tidal sediments covered by good riverine soil, is often near-neutral or only slightly acid, but will become highly acid when drained. When fresh water is available to keep potentially acid soils or potentially acid substrata continuously submerged, or when tidal water is seasonally fresh, these soils can be very productive. Under those conditions the main constraints to food production are the risks of temporary water shortage leading to acidification and salinization, hazard of inundation by seawater during storms, and commonly poor trafficability of the land.

In *Soil taxonomy* (USDA 1975) two groups of acid sulfate soils are distinguished: Sulfaquepts and Sulfic subgroups. Acid sulfate soils that have been developed to a shallow depth are mostly Sulfaquepts, with a sulfuric horizon (characterized by a pH below 3.5 and the presence of jarosite mottles) within the 0.5-m depth. They can be found both in recently empoldered or drained tidal swamps and in much older, poorly drained inland swamps, as in the Mekong Delta of Vietnam. These soils are often highly toxic because of excess iron and aluminum, and invariably are potentially acid at shallow depth, i.e. between 0.5 and 1 m below the soil surface. In inland areas, highly acid surface water (Vietnam) or groundwater (Venezuela) often causes problems in neighboring better land.

In Sulfic subgroups, such as Sulfic Tropaquepts and Sulfic Haplaquepts, the surface soil is less acid (pH above 4), and the sulfuric horizon and potentially acid pyritic substratum occur at greater depth. Where these soils occur, as in the Bangkok Plain, they are normally used for wetland rice cultivation. Phosphorus deficiency and, in the first (dryland) stage of broadcast (*deepwater* or floating) rice cultivation, aluminum toxicity are partly responsible for relatively low yields (1–1.5 t/ha). Iron toxicity appears to be rare on these soils. With good management they can be very productive, but uncertain water supply makes high inputs too risky.

Histosols

Most of the tropical peats, which cover an estimated 32 million ha (Driessen 1978), are highly acid and have pH between 3.5 and 4.0 (Suhardjo and Widjaja-Adhi 1976). In most, the contents of aluminum silicate minerals and iron-containing minerals are very low, so sources for soluble aluminum and iron are essentially absent and toxicities of iron and aluminum do not occur. However, even if appreciable amounts of clay are present, aluminum toxicity may be less important in organic soils than in non-organic soils of the same pH because of the different nature of the exchange complex, and complexing of aluminum in Histosols (Buol et al 1973). In transitions from peats to acid sulfate soils, however, e.g. where peat domes wedge out over pyritic clays, or in soils developed from highly organic mangrove swamps (Sulfihemists and Sulfifibrists), iron and aluminum toxicity will probably occur (Sudjadi and Sediyarso 1973).

Generally speaking, peat lands, and especially the ombrogenous peat domes common in equatorial climates, are highly unsuitable for agriculture. The main constraints are unfavorable physical characteristics (irreversible drying, subsidence, poor accessibility due to low bearing capacity, poor anchorage of roots) and extremely low fertility due to deficiencies of practically all major and minor nutrients (IRRI 1976, Driessen 1978). If used at all for annual food crops, deep peats are generally occupied for one or two seasons and then abandoned. If rice is grown, surface drainage is usually necessary to ensure any yield at all. Drainage decreases toxicity due to dissolved organic substances and increases the availability of most nutrients, presumably as a result of increased mineralization of organic matter.

Histosols can be fairly productive if they are clayey and not strongly acid, or shallow (50 cm) on a mineral substratum, or if they are fed with groundwater rich in dissolved bases, as the many spring mires and peat-filled crater lakes in the volcanic areas of southern Luzon, the Philippines. Even then, however, periodic surface drainage is necessary to prevent mineral deficiencies. Surface drainage invariably leads to subsidence. If progressive lowering of the groundwater table is hydrologically possible, the peat will eventually disappear, leaving the mineral substratum at the soil surface. This prospect is not very desirable where peat is underlain by potentially acid sediments, as is probably the case with most of the extensive peats of Indonesia.

IDENTIFICATION OF PROBLEMS

Crop performance

Iron toxicity in rice causes purplish or reddish brown mottling (*bronzing*) or, in some cultivars, oranging or yellowing spreading downwards from the tips of the older leaves, followed by drying of the leaves. Roots are scanty, coarse, and often dark brown from coatings of ferric oxide (Ponnamperuma et al 1955). The root symptoms differentiate iron toxicity from zinc deficiency, which causes similar bronzing symptoms. The iron contents of rice leaves correlate well with the severity of the disorder, but vary widely with the cultivar and the environmental conditions (Jayawardena et al 1977, Tanaka and Yoshida 1970). The commonly cited limit of 300 ppm Fe in rice plants (Tanaka and Yoshida 1970) is probably on the low side for most rices; iron toxicity should certainly be suspected at iron contents exceeding 1000 ppm. Still higher values are frequently cited for apparently healthy rice. These are probably due to contaminations of ferric oxide coatings or soil adhering to plants and between leaf sheaths.

Phosphorus deficiency causes poor tillering and erect and often rolled leaves, which may range from dark green to orange yellow. Plants with phosphorus deficiency generally have phosphorus content below 0.1%. The symptoms of aluminum toxicity in rice have been described as an interveinal orange-yellow discoloration of the tips of older leaves, followed by brownish mottling (Tanaka and Navasero 1966). The symptoms have been observed in the field only occasionally (Jugsujinda et al 1978). Aluminum concentrations are harmful before they cause leaf symptoms, and high aluminum aggravates phosphorus deficiency; the disorder is easily overlooked.

Because different disorders often occur simultaneously and mutually influence each other, and because symptoms of toxicity by hydrogen sulfide and certain organic substances are not well defined, identifying a disorder in strongly acid soils by using visual symptoms alone is difficult, if not impossible. When a soil-related disorder is suspected, specific research – rather than a few tests and analyses – is necessary to clarify the nature of the problem.

Soil chemistry

The best indicator of soil acidity is the pH of a suspension of the air-dried soil in water. Generally speaking, acidity-related disorders in wetland rice are mild or absent at pH 4.5–5, moderate to mild at pH 4–4.5, severe at pH 3.5–4, and very severe at pH below 3.5. But because the pH changes with the redox state of the soil, the change in pH upon flooding is often more important than the pH of the air-dried soil. This is particularly so for the concentration of dissolved aluminum, which is directly regulated by pH.

The concentration of dissolved iron after the onset of soil reduction still reflects the initial aerobic pH: soils that are initially very acid generally show higher levels of dissolved iron (and lower final pH values of the reduced soil) than less acid soils (van Breemen and Moormann 1978). Although the overall

reduction processes leading to changes in pH and in concentrations of dissolved aluminum and iron are well understood, little is known about the factors responsible for differences in the kinetics of soil reduction. At present we cannot predict whether a given soil will exhibit slow or fast reduction, and whether aluminum toxicity will persist for a long time or if and to what extent iron toxicity will develop.

Soil morphology and classification

The groups of soils discussed in previous paragraphs can often be distinguished easily by inspection of soil profiles and a few chemical analyses. Potentially acid soils cannot be identified with certainty in the field, but their pH usually drops to below 3.5 within several weeks of moist, aerobic incubation. The conspicuous, yellow mottles of jarosite [$KFe_3(SO_4)_2(OH)_6$] indicate acid sulfate soils, but because jarosite is absent in some acid sulfate soils, particularly the highly organic ones, it is advisable to measure soil pH.

The distinction between Sulfaquepts (the young and shallow acid sulfate soils) and Sulfic Tropaquepts or Sulfic Haplaquepts (their more deeply developed counterparts) is agronomically useful: it differentiates soils where iron and aluminum toxicity can be expected from those where phosphorus deficiency is generally most important.

Strongly ferrolysed soils can also be identified readily by studying the soil profile in the field.

RECLAMATION OF ACID WETLAND SOILS AND THEIR POTENTIAL FOR FOOD PRODUCTION

Strategies for reclamation, improvement, and management of acid wetland soils depend on the soil type. They will be discussed separately for acid sulfate soils, peat soils, and other acid wetland soils.

Acid sulfate soils

Measures that counteract directly or indirectly the effects of adverse soil acidity include leaching, liming, application of fertilizers and organic manures, and improved water management. Growing of cultivars that have tolerance for certain adverse soil conditions may also increase productivity.

In principle, leaching is useful for acid sulfate soils with soluble acidity – aluminum sulfate or sulfuric acid – present at pH below 4. However, low hydraulic conductivity and high groundwater tables often preclude leaching as a practical way of removing subsoil acidity. Part of the soluble acidity in surface soils can be removed by lateral drainage of surface water after flooding and puddling. The beneficial effect of applying sodium chloride (a few 100 kg/ha) on acid sulfate soils before flooding, as reported by some Thai farmers, may be due to partial displacement of exchangeable aluminum. Leaching by seawater, which was partly successful in experiments on very young Sulfaquents in Sierra Leone

(Hart et al 1963), has the same effect, but can be applied only in specific conditions.

Liming is necessary for yields on acid sulfate soils with a pH below 4 in the surface soil, but it usually has little or no effect at pH above 4.5. Lime precipitates toxic aluminum, depresses dissolved iron concentrations after flooding, lowers the peak concentration of hydrogen sulfide, and presumably increases the availability of phosphate (Min Suk Yang 1974, Kabeerathumma and Money 1974, IRRI 1973). Even on soils with a pH of 3.5–4, optimum lime rates rarely exceed 3–6 t $CaCO_3$/ha, and higher rates are often harmful (van Breemen and Pons 1978). At still lower pH values, lime rates will be much higher, but no experimental data for such soils are available.

The residual effects of liming are small where subsoils are acid or potentially acid; thus applications must be repeated regularly. This is especially so when pyrite is present at shallow depths (within 50–100 cm) and oxidizes during a dry season.

Phosphorus is usually required to give reasonable or good yields. Rock phosphate is often effective and has a better residual effect than soluble sources of phosphorus.

In addition to the various amendments, good water supply and water management are very important. Leaching is only possible with good water management. Keeping the water table above the pyritic substratum prevents new acidification. Maintaining surface water on the field throughout the crop season prevents oxidation of the surface soil and reappearance of toxic aluminum, as well as the appearance of toxic iron after reflooding.

The various reclamation and management practices are usually economic on the moderately acid Sulfic Tropaquepts, but not on the more severely acid Sulfaquepts where good water management is a first requirement for successful crop production. Investments to achieve good water management of lands with such soils are rarely remunerative, and soil improvement is slow and usually takes many (5–10) years. In the Muda irrigation scheme in Malaysia, where Sulfaquepts occur in patches among better soils, the effects of improved water management and intensive irrigation are striking (van Breemen and Pons 1978). Cultivars tolerant of adverse acid soils can probably be used profitably, even without further soil amendment, on moderate acid sulfate soils such as the Sulfic Tropaquepts of the Bangkok Plain, provided they are adapted to drought in the early stages and to deep water later.

Peat soils

The deep (at least 0.9 m thick) ombrogenous peats of humid tropical Asia present such formidable difficulties that they should not be reclaimed for agriculture. When they are used at all, drainage and burning of the surface layer are usually necessary; thus, subsidence is unavoidable. If wetland rice could be grown on such soils, the problems associated with drainage would be avoided. It is unlikely, however, that an economic solution for the extremely poor per-

formance of rice on undrained peats will be found. Local rice varieties are not known to grow in deep peats and neither are other grasses (Anderson 1976), so there is no basis for breeding programs to produce rices suitable for deep peat lands.

Prospects are much more favorable on shallow peat soils (less than 0.5 m deep) and peats with appreciable amounts of mineral material, especially when they are only slightly acid or near neutral, as the spring peats and groundwater peats in southern Luzon, the Philippines. These, too, need to be drained periodically to increase the availability of many nutrients. Organic soils with acid sulfate characteristics are locally common in Indonesia (Driessen and Ismangun 1973). They may be similar to Sulfaquents and Sulfaquepts as regards their prospects for wetland rice cultivation, but more field experiments are necessary to evaluate their potential.

Other acid wetland soils

Other acid wetland soils, including ferrolysed soils, rarely present the extreme toxicities and deficiencies of acid sulfate soils and peat soils. Apart from irregular water supply in some cases, the reasons for their relatively low productivity are not well understood. Further research is needed to establish whether unfavorable supply of soil nitrogen and unfavorable soil physical characteristics due to low proportions of 2:1 clay minerals and high kaolinite contents are partially responsible, as suggested by Moormann and van Breemen (1978). If this is true, application of organic manures and the use of slow-release nitrogenous fertilizers should be helpful. It is unlikely, however that such measures will be economic unless the supply of irrigation water is assured.

RECOMMENDATIONS

In many areas there is need for increasing the production of many acid wetlands that are now used for agriculture. The question is whether we should extend cultivation to uncultivated, acid wetlands where the constraints are usually more severe than in existing marginal cropland. To answer that question, we must evaluate the agricultural potential of such lands as a function of costs of different degrees of land improvement, the benefits from other uses of the land (forestry, conservation), and the prospects and economics of increasing food production on existing cropland with fewer limitations.

In this paper we consider only the first part of that evaluation. We seek the boundary between acid wetlands that have potential for food production and those that have none under the present socioeconomic conditions. There can be little doubt that areas with severely acid sulfate soils and deep ombrogenous peats should be left untouched. Neither at present nor in the foreseeable future are there rice cultivars that can be grown in such soils in their original, unamended state; although often technically possible, land improvement is expensive. Only certain shallow peat soils with a mineral substratum, and certain

clayey peat soils could be made productive if they are not strongly acid or potentially acid. Present classification systems and standard laboratory procedures still cannot separate these soils from the peats that are useless for agriculture. The ranges of characteristics that occur over appreciable areas are not known, and the factors that are important for the production of rice and, e.g. taro and sago palm on these soils have yet to be identified.

In the case of acid sulfate soils, the distinction between Sulfaquepts and Sulfic Tropaquepts appears to be meaningful because the former are generally unsuitable and the latter suitable for rice. This conclusion is based on limited data, however, and does not take into consideration the effects of climate. Sulfaquepts, for example, may pose fewer problems in perhumid areas than in monsoonal areas. We do not know the factors that govern the kinetics of soil reduction and the changes in the concentrations of the most important toxins in acid sulfate soils, dissolved iron and aluminum. Virtually nothing is known about the effects of surface drainage and temporary oxidation and acidification on rice grown in iron-toxic and aluminum-toxic soils.

We know little about the reasons for lower productivity, even at presumably optimum soil and crop management, of rice grown on acid (but probably non-toxic) soils with low fertility levels. Research is needed to find out if and how we can improve the productivity of such soils.

Lastly, there is an appalling discrepancy between the attention paid to the statistical relevance of experiments in the field, greenhouse, and laboratory geared to increasing food production on problem soils, and the (lack of) attention to characterizing and defining the soil conditions and land qualities of the experiments. Only when agronomists, soil chemists, and soil evaluators cooperate on such research will it be possible to produce results that not only are relevant to the restricted areas studied, but also can be extrapolated to other environments.

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Soil salinity as a constraint on food production in the humid tropics

F. N. PONNAMPERUMA AND A. K. BANDYOPADHYA

In densely populated South and Southeast Asia, where both food and arable land are scarce, about 48 million ha climatically, physiographically, and hydrologically suited to rice cultivation lie idle or are cultivated with poor results, largely because of soil salinity. Reclaiming the coastal lands (about 30 million ha) for dryland crops will require costly inputs. Wetland rice is the crop of choice, but present yields are low because of soil toxicities, nutrient deficiencies, lack of water control, and the low yield potential of the varieties used by farmers.

The results of the Genetic Evaluation and Utilization Program and the International Rice Testing Program of the International Rice Research Institute indicate that areas where salinity and flooding are not severe can become productive rice lands without costly inputs if modern salt-tolerant varieties with insect and disease resistance and adaptation to adverse soils are grown.

There is a need to prepare accurate maps of saline soils in densely populated countries to demarcate those areas that can be used for rice growing without costly reclamation measures.

IN SOUTH AND SOUTHEAST ASIA where population pressure is high and arable land is scarce, about 100 million ha of land climatically, physiographically, and hydrologically suited to rice production lie idle largely because of soil toxicities (Table 1). About 48 million ha of this idle land are saline soils in humid parts of the region.

Recent developments focus attention on the problem lands of the region:

- the pressing need for more food for a rapidly expanding population;

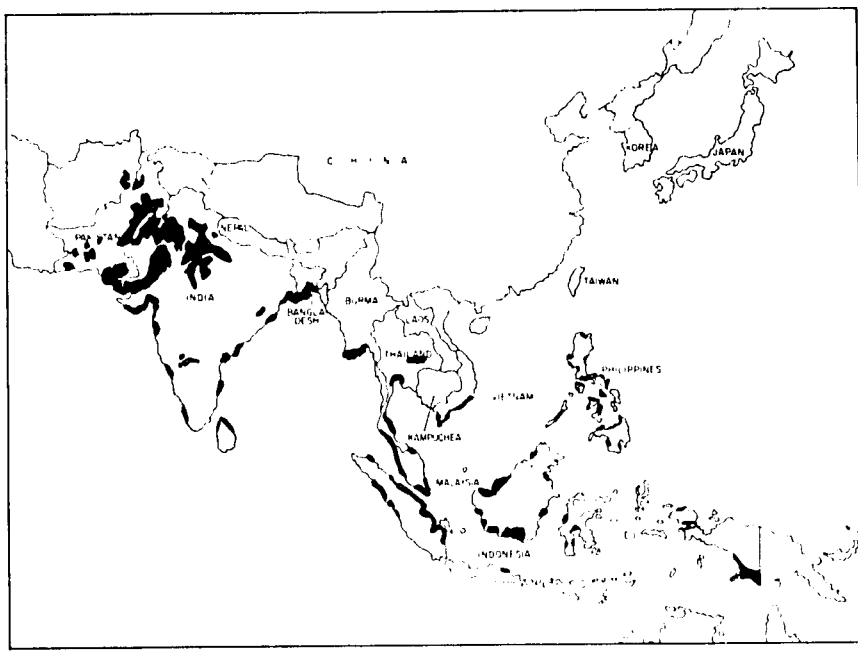
The International Rice Research Institute, Los Baños, Philippines; and Central Soil Salinity Research Institute, Canning Town, West Bengal, India.

- the failure of the modern varieties of the green revolution to deliver their potential; and
- the advent of rice varieties with tolerance for adverse soils.

Because salinity is a widespread soil problem in the region (Fig. 1) and because rice is the region's main food crop, this paper discusses soil salinity as a constraint on rice production, with special reference to South and Southeast Asia.

The estimated growth rate of Southeast Asia's population is 2.7%/year during the next two decades. Food production growth rates are insufficient to keep pace with population growth, especially in the poor populous countries (Allaby 1977, Asian Development Bank 1977, International Food Policy Research Institute 1977, Herdt et al 1977). Thus food importing countries will have to increase their imports, and exporting countries, such as Burma, may have to import food.

Small farmers lack the resources to provide the water control, soil amendments, fertilizers, and pesticides necessary to extract the potential of the modern varieties. In vast tracts with poor water control or toxic soils in India, Burma, and Thailand, farmers have not accepted the new varieties (Asian Development Bank 1977). Even where the new varieties are grown widely, national yields are about a third of experimental yields (Herdt and Barker 1979).



1. Saline soils (shaded areas) of South and Southeast Asia (sources: Chapman 1976, Collier 1979, FAO 1974, Sinanuwong and Takaya 1974).

Extending the area planted to rice faces obstacles. Arable land in the densely populated countries of Asia is limited. In Bangladesh and Indonesia the area of arable land per person is only 0.12 ha (Duncan 1977) and the percentage of farms that are less than 1 ha is 51 in Bangladesh and 71 in Indonesia (Wortman 1975). The Asian situation was summarized by Willett (1976):

> "The most crucial population problem is in Asia where population density is already extremely high, population growth is increasing, and underdeveloped land resources are limited."

Overcrowding, food shortages, and land scarcity are compelling Asian countries to crop land lying idle largely because of soil problems. The most common of the soil problems is salinity.

EXTENT, DISTRIBUTION, AND PRESENT USE OF SALINE SOILS

About 380 million ha of soils on the earth's land surface are saline. Of the 240 million ha that are not strongly saline (Massoud 1974), about 49 million ha are in the humid regions of South and Southeast Asia (Fig. 1, Table 1); 27 million ha of these are coastal saline soils. The actual area of saline soils in the regions may be considerably higher than estimated – vast areas of mangrove swamps have not been mapped, and about 1 million ha of saline soils reported in Northeast Thailand (Sinanuwong et al 1979) are not included in Table 1.

Most of the coastal saline soils are under mangrove vegetation. The trees are used for making pile stakes, as firewood, and as source of tannin. In Thailand mangrove areas are cleared for use as fishponds and salt pans, and for production of rice, coconut, and pineapple (Glopper and Poels 1972).

The Philippine archipelago has about 400,000 ha of coastal saline soils (Guerrero 1977). Of this area, about 100,000 ha are still under mangrove forests.

Table 1. Problem soils in South and Southeast Asia.

Country	Area (million ha)			
	Saline soils[a]	Alkali soils[a]	Acid sulfate soils[b]	Peat soils[c]
Bangladesh	2.5	0.5	0.7	0.8[d]
Burma	0.6	–	0.2	–
India	23.2	2.5	0.4	–
Indonesia	13.2	–	2.0	16.0
Kampuchea	1.3	–	0.2	–
Malaysia	4.6	–	0.2	2.4
Pakistan	1.1	9.4	–	–
Philippines	0.4[e]	–	–	–
Thailand	1.5	–	0.7	0.2
Vietnam	1.0	–	1.0	1.5
Total	49.4	12.4	5.4	20.9

[a]Massoud (1974). [b]van Breemen and Pons (1978). [c]Driessen (1978). [d]Authors' estimate. [e]Guerrero (1977).

About 175,000 ha of the cleared coastal saline land are used for fishponds, and about 125,000 ha are largely idle. The tracts where rice is grown have excessive flooding in the wet season and salinity due to the influx of brackish water at high tide in the dry season. Trials are under way to grow flood-tolerant varieties during the wet season and short-duration, salt-tolerant varieties soon after the wet season.

In Indonesia, about 558,000 ha of tidal swamps are planted to rice (Table 2). The total cropped area of tidal swamps and polders is 7% of the total rice area cropped per year. By June 1979, the government had opened 220,000 ha of tidal swamplands for rice in 1 transmigration project alone. It is one of the world's major experiments in the use of marginal land (Collier 1979). Rice yields are 0.8–2.2 t/ha. A vigorous breeding program to produce rice varieties suited to the tidal swamp areas is under way (Subiyanto et al 1977).

The saline soils of the humid region of South and Southeast Asia are economically important because:

- they are located in deltas, estuaries, coastal fringes, or river basins that are climatically, physiographically, and hydrologically suited to rice;
- rainfall is adequate for leaching the soil and growing at least 1 rice crop/year;
- the lands are close to densely populated areas, where the demand for both land and food is high; and
- labor for and know-how in rice cultivation are available.

Definition of saline soils

Saline soils are soils that contain sufficient salt to impair the growth of crop plants. But because salt injury depends on species, variety, growth stage, and environmental factors, it is difficult to define saline soils precisely. Current definitions are based on measures of salt content alone or salt content in conjunction with texture, morphology, or hydrology (FAO/Unesco 1973, FAO 1974, Northcote and Skene 1972, Soil Science Society of America 1978, US Salinity Laboratory Staff 1954).

For the purpose of this paper, we define a saline soil as one that has enough salt in the root zone of rice to give an electrical conductivity in the saturation

Table 2. Rice lands in Indonesia.[a]

Class	Area (thousand ha)	Rice crops per year	Rice area per year (thousand ha)
Dryland	1168	1	1168
Irrigated wetland	3893	1–2	6671
Rainfed wetland	1772	1–2	2216
Swamps (peat?)	254	1–2	317
Tidal swamps	558	1–2	697
Polder	10	1–2	12
Total	7704		9913

[a]Adapted from Collier (1979).

Table 3. Characteristics of some saline soils in India.

State	Texture	pH	EC_e[a] (mmho/cm)	Dominant salt
West Bengal	Silty clay-silty clay loam	5.5–7.0	4–35	Sodium chloride and sulfate
Orissa	Clay loam-clay	5.0–7.5	2–50	Sodium chloride
Andhra Pradesh	Sandy loam-clay loam	6.0–8.8	0.5- 17	Sodium chloride and sulfate
Pondicherry	Sandy loam-loam	6.5–8.5	1–50	Sodium chloride and sulfate
Tamil Nadu	Sandy loam-loam	6.0–8.2	2–10	Sodium chloride and sulfate
Kerala	Sandy loam-loam	3.5–5.5	1–20	Sodium sulfate
Karnataka	Sandy loam-loam	5.0–7.5	3–10	Sodium chloride
Maharashtra	Clay loam-clay	7.0–8.5	4–14	Sodium chloride
Goa	Silty clay-silty clay loam	5.0–6.0	4–15	Sodium chloride
Gujarat	Sandy loam	7.5–8.5	9–20	Sodium chloride

[a] Electrical conductivity in the saturation extract.

extract (EC_e) of more than 4 mmho/cm at 25°C. Four mmho/cm is the point beyond which rice yield declines appreciably as the salt content increases (Maas and Hoffman 1977).

Characteristics of saline soils

Saline soils vary widely in their chemical, physical, and hydrological properties. Some properties of some Indian coastal saline soils are given in Table 3.

Salt source. The salt source may be seawater, surface or underground saline water, or wind. In arid and semiarid areas salts brought by capillary action, surface runoff, or interflow accumulate in the soil profile. In coastal areas salinity is due to direct inundation by salt water or upward or lateral movement of saline groundwater. In northeast Thailand the source of salt is a geological stratum 1–2 m below the ground surface (Sinanuwong and Takaya 1974).

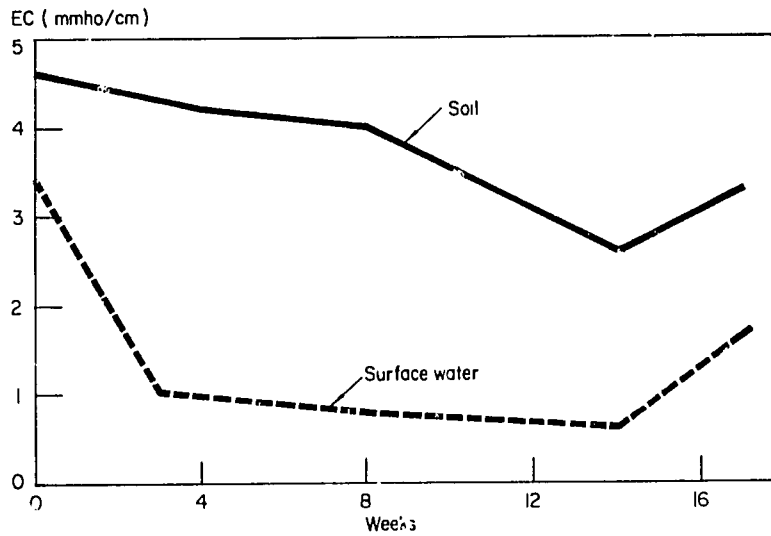
Content, nature, and distribution of salt. The dominant salts in coastal saline soils (and also in northeast Thailand) are chlorides, chiefly sodium chloride. In inland areas chloride-sulfates (FAO/Unesco 1973) may be prominent. Sulfates may constitute a high proportion of the electrolytes present in acid sulfate soils. In submerged calcareous soils, the bicarbonates of calcium and magnesium are important; strongly acid soils may have high concentrations of ferrous and manganous bicarbonates when submerged.

The salt content of a soil varies vertically, horizontally, and with season. Table 4 shows vertical variations in salinity in some coastal saline soils in India. Figures 2 and 3 show the seasonal changes in salinity in the soil and floodwater in experimental fields on two coastal saline soils in the Philippines.

Table 4. Vertical distribution of salt in coastal saline soils in India.

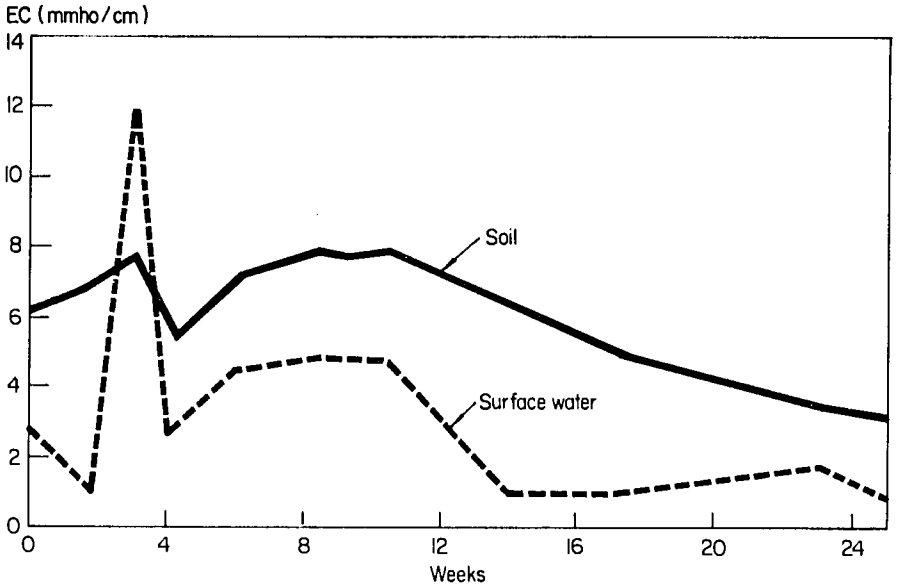
Approx depth (cm)	EC_e[a] (mmho/cm)				
	West Bengal	Orissa	Andhra Pradesh	Kerala	Tamil Nadu
0–15	14.7	5.6	31.3	29.4	31.6
15–30	12.8	6.4		12.6	25.6
30–45	15.1		19.6		
45–60	12.6	8.9		13.4	16.9
60–75	12.1		19.1	17.6	
75–100	34.4	9.1			13.4

[a]Electrical conductivity in the saturation extract.



2. Trend of EC in the experimental field, Sinacaban, Misamis Occidental, Philippines, 1978 dry season (source: International Rice Research Institute 1979).

pH, nature of clays, organic matter content, and nutrient status. The pH ranges from 2.5 for saline acid sulfate soils to 8.5 for saline alkali soils. The soil texture ranges from sandy to clayey and the composition of clay varies from predominantly kaolinitic to predominantly montmorillonitic. The organic matter



3. Trend of EC in an experimental field, Lubao, Pampanga, Philippines, starting 14 February 1978 (source: International Rice Research Institute 1979).

content ranges from 1 to 50%, and the nutrient status varies from very low to moderately high.

Inland saline soils have a pH >7. They are low in nitrogen and in available phosphorus, but are well supplied with potassium. Coastal saline soils may be eutric (fertile), dystric (infertile), calcaric (calcareous), thionic (sulfidic and sulfatic), or histic (organic). Saline alkali soils and calcaric saline soils are deficient in available zinc; thionic saline soils may have problems of aluminum toxicity and iron toxicity as well as phosphorus deficiency; histic saline soils are deficient in the major nutrients as well as in copper and zinc, and have other problems (Table 5).

Hydrology and relief. Hydrology and relief are important in determining the suitability of saline lands for rice production. The vast coastal saline tracts of South and Southeast Asia are in the deltas of big rivers. Most of them have an elevation 0–10 m above mean sea level. In the tidal area of the Bangkok Plain – as much as 54 km inland – the elevation is 1–1.5 m above mean sea level (Glopper 1971). The tracts are subject to flooding by fresh water during the wet season and submergence by salt water during the dry season when the discharge from the river system is low and seawater comes up the creeks and canals. The groundwater of the tracts is 1 to 2 m below the surface and is saline with an EC of 2 mmho in the wet season and 20 mmho/cm in the dry season (Central Soil Salinity Research Institute 1977).

Coastal saline soils are subject to tidal flooding. The amplitude of tides in India varies from 0 to 6 m (Rao and Dhruvanarayan 1978); in the Philippines, van Breemen (1979) reported tide levels ranging from 1 to 2 m above mean sea

Table 5. Some saline soil problems for rice.

Kinds	Accessory growth-limiting factors
Inland saline soils	High pH; deficiencies of zinc, nitrogen, and phosphorus
Acid saline soils	Aluminum toxicity, iron toxicity, phosphorus deficiency
Coastal acid sulfate soils	Iron and aluminum toxicities, phosphorus deficiency, deep water
Neutral and alkaline coastal soils	Zinc deficiency, deep water
Coastal organic soils	Deficiencies of nitrogen, phosphorus, zinc, copper, molybdenum; toxicities of iron, hydrogen sulfide, and organic substances; deep water; disease incidence (*Pyricularia oryzae, Helminthosporium oryzae*)

level for four saline tracts.

Coastal saline soils subject to tides fall into four main zones (FAO/Unesco 1973):

1. the strip nearest to the sea subject to daily tides,
2. a strip several kilometers wide subject to only exceptionally high tides,
3. an area where tides exercise their effect through rivers and creeks, and
4. a wide zone not influenced by tides but by the upward thrust of saline water.

Zones 3 and 4 are suited to rice production without high inputs on reclamation.

In the Philippines, coastal saline soils fall into four broad types (Fig. 4).

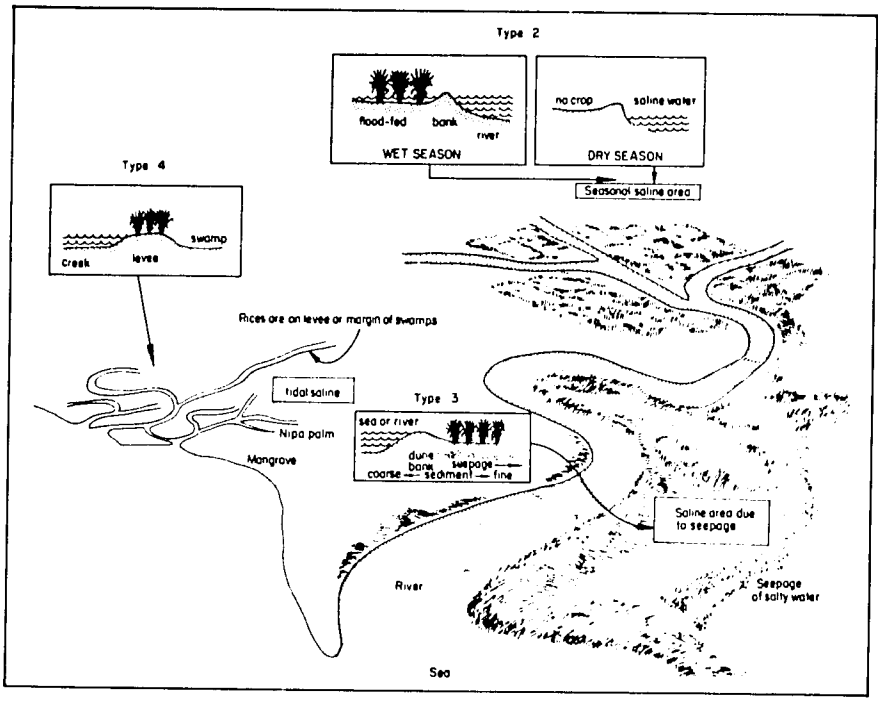
1. The first type (not shown in Fig. 4) is wet throughout the year, and is not excessively saline.
2. The second type is flooded with fresh water during the wet season and is saline in the dry season because of the intrusion of brackish creek water.
3. The third type is saline in the wet season because of upwelling or seepage of brackish water.
4. The fourth type derives its salinity directly from tides.

The first type can grow 2 salt-tolerant rice crops/year. The second type needs flood-tolerant varieties in the wet season and short-duration salt-tolerant varieties in the dry season. The third type is suited to the present salt-tolerant varieties. On the fourth type, salt injury can be severe and rice growing is risky (IRRI 1979). Some characteristics of the four types are summarized in Table 6.

Salinity and plant growth

Strongly saline soils are barren. Less strongly saline soils in arid areas are characterized by patchy growth of halophytic grasses and shrubs (FAO/Unesco 1973), whereas coastal saline soils of the humid tropics and subtropics are characterized by the presence of mangrove species (Chapman 1976).

Most plants suffer salt injury at EC values exceeding 4 mmho/cm at 25°C (US Salinity Laboratory Staff 1954). But Boyko (1966) states that many crops can stand much higher concentrations than generally supposed if the solution



4. Types of coastal saline soils (after H. Ikehashi; source: International Rice Research Institute 1979).

consists of physiographically balanced salts as in seawater. Epstein and Norlyn (1977) grew tomato in sand dunes irrigated by seawater. According to Maas and Hoffman (1977), crop yield decreases markedly with increase in salt concentration, but the threshold concentration and the rate of yield decrease vary with the species. They describe the effect of salt concentration on yield by the equation

$$Y = 100 - B(EC_e - A)$$

where Y is relative yield, A is the salinity threshold value, B is the yield decrease per unit of salinity increase.

Rice is moderately susceptible to salt injury (US Salinity Laboratory Staff 1954, Maas and Hoffman 1977). Susceptibility, however, depends on several plant and environmental factors (Ponnamperuma 1977). Salt injury may be due to osmotic stress, specific ion effects, ionic antagonisms, toxicities caused by ions released by cation exchange, and effects of ionic activities. In flooded soils, salt displaces K^+, NH_4^+, Fe^{2+}, Mn^{2+}, Ca^{2+}, Mg^{2+} from the exchange sites into the soil solution (IRRI 1973). If the salt concentration is not high, this is beneficial for rice (IRRI 1978); but in strongly acid soils iron toxicity may result.

Table 6. Some characteristics of six coastal saline soils in the Philippines.

Site	Salt source	Deep flooding	EC_e (mmho/cm)	pH	Organic matter (%)	Iron toxicity	Zinc deficiency	Highest yield (t/ha)
Sinacaban, Misamis Occidental	Seawater seepage	No	2–8	4.4	15.4	Yes	No	5.6
Calapan, Mindoro	Seawater	No	1–12	6.8	6.9	No	Yes	4.0
Lubao, Pampanga	Creek	Yes	6–12	6.9	2.0	No	No	1.0
Taal, Batangas	Creek	No	1–5	7.8	2.4	No	Yes	2.5
Aparri, Cagayan	Seawater	Yes	6	3.9	7.5	Yes	No	No experiment
Sabang, Camarines Sur	Groundwater	No	5–8	7.4	3.2	No	Yes	3.6

Most rices are severely injured in submerged soil cultures at an EC_e of 8–10 mmho/cm at 25°C. At an EC_e of 8–10 mmho/cm seawater is less injurious than sodium chloride, and injury is more severe on acid soils than on calcareous soils (IRRI 1975).

The symptoms of salt injury in rice are stunted growth, rolling of leaves, white leaf tips, white blotches in the leaves, and drying of the older leaves. Salt injury at the initiation of the reproductive phase causes severe sterility. In the field, salt injury may be in patches because of uneven salt and water distribution.

Reclaiming saline lands

To convert saline soils into productive agricultural land the following operations are necessary:

- prevention of the influx of salt water,
- leaching of salts from the root zone,
- surface drainage in areas prone to flooding,
- addition of soil amendments to correct soil toxicities such as strong acidity or strong alkalinity,
- correction of nutrient deficiencies, and
- growing of adapted, salt-tolerant crops.

Rice is the crop best suited to saline soils because standing water is necessary for reclamation. Standing water benefits rice by:

- diluting the salt;
- increasing the availability of iron, manganese, nitrogen, phosphorus, and silicon;
- conserving nitrogen and enhancing biological nitrogen fixation;
- eliminating water stress; and
- increasing the pH of acid soils and decreasing that of alkaline soils.

Bhumbla and Abrol (1978), Elgabaly (1975), Moormann and Pons (1974) and Van de Goor (1966) recommend rice as a desalinization crop.

Salt-tolerant rice varieties

For centuries, farmers have grown salt-tolerant rice varieties in the saline tracts in India, Burma, Thailand, Indonesia, and the Philippines. But yields were only about 1 t/ha. Varieties selected and bred for salt tolerance during the past few decades have not fared better. Recognition of the potential of saline lands for rice production has prompted an international effort to breed salt-tolerant varieties with disease and insect resistance and high yield potential (Ikehashi and Ponnamperuma 1978).

During 1975–78, the International Rice Research Institute (IRRI) screened 25,800 rices for salt tolerance: varieties from salt-affected regions in Asia, elite lines from the breeding program, and the progeny of the salt tolerance hybridization program. Of the total, 1,495 had an acceptable degree of salt tolerance.

In replicated field experiments on the coastal saline soils of the Philippines, the lines IR9884-54-3, IR4619-48-3, and IR4630-22-2 yielded 3.5, 3.2, and

2.6 t/ha, compared with 1.0–2.2 t/ha for three IR varieties. IR42, although not bred for salt tolerance, gave 5.6 t/ha on a moderately saline soil reclaimed from a coastal saline swamp only a year before.

On saline soils, rice is exposed to many hazards other than salinity. To sample the environments, IRRI has the International Salt and Alkali Tolerance Observational Nursery (IRSATON) within its International Rice Testing Program. In 1977 and 1978 IRSATON tests, the following performed well: IR4-11, IR2053-436-1-2, IR2058-78-1-3, IR4227-104-3, IR4630-22-2, IR4763-73-1, Getu, Nona Bokra, Nonasail (sel.), and Pokkali.

RECOMMENDATIONS

- The nearly 30 million ha of coastal saline soils in South and Southeast Asia offer promise as potential rice lands. But the distribution and area of saline soils in the regions are not accurately known. In densely populated countries where arable land is scarce, accurate maps of salt-affected lands should be made and their suitability for different crops indicated.
- Because saline soils vary widely in characteristics, accessory growth-limiting factors should be considered in preparing land suitability maps.
- Varietal tolerance for salinity and accessory growth-limiting factors should be exploited in bringing marginal land under rice. The use of improved, salt-tolerant, disease- and insect-resistant rice varieties, coupled with the correction of nutrient deficiencies, will enable farmers to double or triple their present yields on saline soils and also to expand rice growing into surrounding uncultivated land.

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Phosphorus deficiency in tropical soils as a constraint on agricultural output

B. DABIN

Highly weathered soils in the tropics, such as Ferralsols, Acrisols, and Luvisols are generally deficient in phosphorus. The amount of phosphorus adsorbed by soils is highly correlated with exchangeable aluminum, total iron, organic matter, and low pH. In highly weathered soils, the phosphorus is mainly in the organic and occluded forms. Iron-phosphorus is dominant in an active form.

Because the availability of phosphorus in soils is a function of the quantity-intensity relationship, estimates of the phosphorus requirement can be obtained from adsorption isotherms.

Various soil tests can be used to estimate phosphorus availability. Among ordinary chemical tests, the amended Olsen method has generally given high correlation with plant growth for drained soils as well as for flooded soils under acid or alkaline conditions. The critical limits of phosphorus availability are related to the total nitrogen content of the soil

$$\frac{P}{N} = \frac{1}{40}$$

and increases with high fixation capacity.

Recent trends in phosphorus fertilization are the conservation of excessively soluble phosphates by mixing them with rock phosphate and improving the technology of placement, additional amendments, and management practices. Research is needed to determine methods of more efficient application of fertilizer.

ABOUT 100 MILLION t of complete (NPK) fertilizers are used annually in the world – about 25 million t in developing countries (von Peter 1978). Of the constituents, phosphate accounts for 25%, potash 25%, and nitrogen 50%. Fer-

Office de la Recherche Scientifique et Technique Outre-Mer, France.

tilizer consumption figures vary considerably from one region to another. Some African countries use small amounts, but many Asian and Latin American countries have made substantial gains in fertilizer use and themselves produce fertilizers.

It is difficult to give a global assessment of phosphorus requirements because they depend on crop density and yield, and variable soil requirements. The requirements are also related to the type of soil, length of time and intensity of uptake, and to other inputs.

Tropical soils that have reached an advanced degree of development seem to have the highest phosphorus deficiency probability. A survey by IMPHOS and GERDAT (Roche et al 1978) shows that Ferralsols and Acrisols (FAO classification, ferrallitic soils in the French classification) and Luvisols (tropical ferruginous soils), as well as Gleysols and Vertisols, in most cases (about 66%) show serious to very serious phosphorus deficiencies. Cambisols (soils with inorganic reserves) show average phosphorus deficiency, and Fluvisols (alluvial soils) and Nitosols (well-structured clayey soils) often show low to no deficiency. The nature of the parent rock, pH, the presence of fixing compounds such as sesquioxides, and the organic reserve are essential factors in the phosphorus resources of soils. Over vast areas of the Sahel, soils low in organic matter content are also low in phosphorus, but this deficiency is often obscured by an even greater nitrogen deficiency. Large yield increases connected with nitrate fertilizer, manure, and organic amendments require the addition of phosphorus. Phosphorus contents of soils in moist regions, which are high in humus, are variable, and the N-P_2O_5 ratios and fixation capacity of those soils are predominant factors in phosphorus fertilizer requirements.

CHEMICAL FIXATION OF PHOSPHORUS

Buffer capacities of soils

The supply of phosphates to plants depends on the concentration of soluble phosphate ions in the soil solution, as well as on the soil's capacity to maintain this concentration. The *buffer capacity* of the soil is represented by the ratio of quantity (Q) to intensity (I) and is related to the soil's phosphorus fixing capacity (Schofield 1955).

A graph of adsorbed phosphorus (Q) against phosphorus in solution (I) provides isothermal curves. With it, Olsen and Watanabe (1970) showed that the buffer capacity affects phosphate supply to plants, and that for a proper supply to roots a low Q-I ratio requires a high concentration, and vice versa.

Phosphorus concentrations of the soil solution ranged from 0.3 to 3 ppm (Mengel and Kirkby 1978, Hossner et al 1973), but levels of 0.05 to 0.08 ppm frequently occur in tropical soils and are regarded as adequate for optimum growth of rice plants (Katyal 1978).

In most acid tropical soils with high levels of iron and aluminum oxides, phosphorus adsorption is high and the solution concentration is low. Conse-

quently, the quantity factor must play a major role in plant nutrition. In addition, the high temperature in tropical soils leads to a faster replacement of solutions, accompanied by a quicker decomposition of organic and inorganic reserves of low solubility. Measurement of the fixation capacity of soils remains an essential factor in evaluating the levels of exchangeable or assimilable phosphorus so as to ensure adequate phosphorus nutrition.

Not all measurements of fixation capacity are standardized. They depend on the ratio of soil to solution. Gachon (1969) defined this capacity as the quantity of phosphorus (P_2O_5) needed to obtain a 2 ppm concentration in equilibrium in a 1-4 soil-solution ratio. The percentage of phosphorus in solution can also be measured in a 1-4 ratio of soil to liquid. Examples of measurements (Oliver 1972, Le Buanec 1973) are shown in Table 1.

Fixation rates are more or less constant for solutions of between 200 and 1,000 ppm of an NH_4Cl extract on air-dried ferrallitic and ferruginous soils (Dabin 1970).

Juo and Fox (1977) determined the requirement as 0.2 ppm phosphorus in an equilibrium solution after 6 days.

Factors affecting phosphorus fixation capacity

Effect of oxides. Phosphate ions in the soil solution depend on pH:

- H_2PO_4 = for highly acid solution,
- HPO_4 = for medium-acid solution, and
- PO_4 = for alkaline solution.

The ions react with exchangeable aluminum or aluminum hydroxide in accordance with the following formulas:

$$Al^{+++} + H_2PO_4^- + 2_2H_2O \rightarrow Al(OH)_2H_2PO_4 \text{ (insoluble)} + H^+$$

$$Al\left\langle\begin{matrix}OH\\OH\\OH\end{matrix}\right. + H_2PO_4^- \rightarrow Al\left\langle\begin{matrix}OH\\OH\\H_2PO_4\end{matrix}\right. + OH^-$$

Table 1. Fixation of phosphorus by various soils based on an initial phosphorus concentration of 200 ppm.

Soil	Final conc after 24 hours (ppm P)	% remaining in solution
Hydromorphous soil, medium organic (Madagascar)	0.105	0.05
Ferrallitic soil on gneiss (Madagascar)	0.65	0.3
Ferrallitic soil in forest land (Ivory Coast)	20	10
Central grassland soil (Ivory Coast)	34	17
North grassland soil (Ivory Coast)	62	31

Fixation depends on the ratio of R_2O_3 to P_2O_5. Clay and allophanes fix PO_4. The 1:1 clays fix more than 2:1 clays via the hydroxy groups on the surface:

$$X\text{-}OH + H_2PO - X\text{-}H_2PO_4 + OH^-.$$

Similarly, in dilute solution PO_4 is fixed by goethite via reaction with FeOH groups on the iron oxide surfaces.

Phosphorus fixation is rapid at the start and then increases slowly with time. Physical fixation is distinguished from chemical fixation and can be determined by extracts using 0.1 N soda, citrate dithionine, or bicarbonate. Chemically fixed forms include those that diffuse through a porous material (Ryden et al 1977). Isotopic exchange tests with P-32 have shown that as the adsorption period lengthens, ease of desorption and the isotopic exchange capacity of adsorbed phosphorus decreases with time. The isotopic exchange capacity of physically fixed phosphorus is 10 times higher than for chemically fixed phosphorus. In Andosols, the complexes containing allophane and imogolite possess the highest fixation capacity (8,000 to 15,000 mg P_2O_5/1,000 g soil); similarly, iron and aluminum combined with humus, compounds related to allophane, and gel materials rich in alumina also contribute to phosphorus fixation.

Correlations established (Roche et al 1978) between the fixation capacity according to Gachon (1969) and other factors measured in 114 soils of various origins are as follows:

Fixation capacity with regard to phosphorus correlated with clay and fine silt (0.51), organic matter (0.7), total aluminum (0.63), exchangeable aluminum (0.86), total iron (0.55), all significant at 0.1%.

Presence of montmorillonite, vermiculite, illite, chlorite, $r = 0.31$, significant at 1%.

Presence of gibbsite, $r = 0.4$ significant at 1%.

Ferralsols-Acrisols have a correlation with fixation capacity, $r = 0.54$, significant at 1%.

Effect of pH-value on fixation capacity. The fixation capacity of iron and Al. hydroxides is greatest below pH 5.5; it decreases between pH 5.5 and 7, and is least at pH 7. Above pH 7.5, phosphorus is fixed by calcium and magnesium. Tests in Colombia (Gildardo Marin 1977) with 3 t lime/ha on soils of volcanic origin, with high fixation capacity, produced wheat yield increases equivalent to those obtained by 160 kg P_2O_5/ha.

Fixation of soluble phosphorus by the solid soil phase

Chang and Jackson's (1957) fractionation method has been used for studies of fixation of soluble phosphorus by the solid soil phase.

Phosphorus is extracted by means of various successive reagents. The quantities of PO_4^{-3} in the various extracts represent soluble phosphorus and fractions linked to aluminum, iron, and calcium, which are shown conventionally as soluble P, Al P, Fe F, and Ca P, although these are not clearly defined chemical or mineralogical species. Many analyses of widely differing soils show a good

relationship between the distribution of soluble phosphorus fractions and soil physical and chemical properties. In acid, oxide-rich soils, the Fe P and Al P forms predominate. The proportion of Ca P is greatest in calcareous soils.

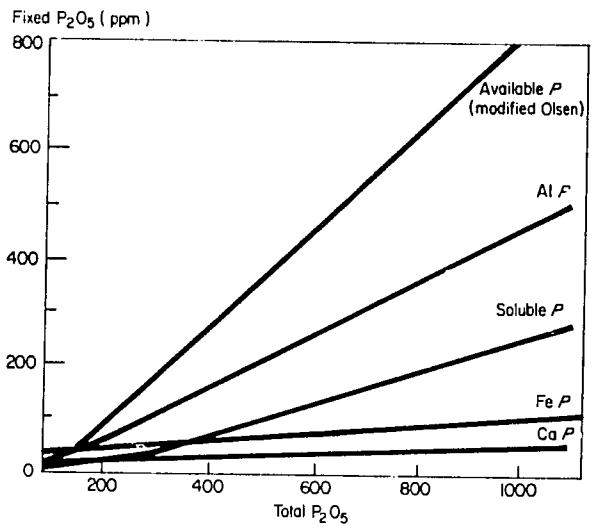
Distribution among active forms, occluded forms, and organic forms of phosphorus in the solid soil phase depends on the degree of evolution of the soil.

In young soils and in calcareous or calcic soils, apatite (Ca P) predominates. As the original materials weather, a large quantity of phosphorus dissolves and is lost; another part is fixed in an adsorbed or active inorganic form (non-occluded), and a large fraction evolves toward occluded forms (occluded P) and the organic form.

In a tropical soil at a medium stage of evolution, organic, occluded inorganic, and adsorbed inorganic forms of phosphorus each account for about one-third of the total. In highly evolved soils, adsorbed active forms diminish in favor of organic and occluded forms. For example, in acid Nigerian soils (Alfisols, Ultisols, Oxisols, Vertisols; pH 4.5 to 6), Fe P represents 60% of the active form when the Fe_2O_3 content ranges from 2–7%. Ca P is the lowest, and Al P is less than 1% (Udo and Ogunwale 1977) occupies an intermediate position except when Fe_2O_3 is less than 1%.

Short-term and long-term phosphorus fixation

Chang and Chu (1961) have shown that when a soluble phosphate is added to soils of average moisture content and pH values from 5.3 to 7.5, fixation after 3 days is mainly in the form of Al P or Ca P depending on the pH value. In a



1. Chang and Jackson fractionation on enriched soil Sandy hydromorphic soil, Chad. 3 days contact – soluble phosphate.

soil suspension the form Fe P may predominate even in a short time. After 100 days, Al P and Ca P decrease and Fe P increases. The increase is particularly rapid in a very moist soil.

In short-term (3 days) fixation test with soils with medium to high fixation capacity, Dabin (1970) found that the quantities of phosphorus fixed between 0 and 1,000 ppm P_2O_5 in various forms (soluble P, Al P, Ca P, Fe P) increased linearly in relation to the quantity added. The slope of the lines measured the reactivity of each form.

In most acid soils with sesquioxides, it is Al P (Fig. 1) that shows the highest reactivity; Fe P has a slightly less steep slope, and Ca P a very slight slope. In moist goethite-rich forest soils (Fig. 2), it is the Fe P fixation slope that is steepest, because of its reactivity in the surface horizon. In soils with a pH value of less than 5.5, soluble phosphorus is very slight; between pH 5.5 and 7.5, soluble phosphorus increases steadily. In humus-bearing calcic soils of pH 7.5, soluble phosphorus is extensive, and the Ca P is greater than Al P or Fe P.

Biological phosphorus fixation

In soils with high organic content and a high carbon-phosphorus ratio, biological fixation of phosphorus in microbial bodies may occur. This fixation is reversible.

Phosphorus fixation in the case of submerged soils

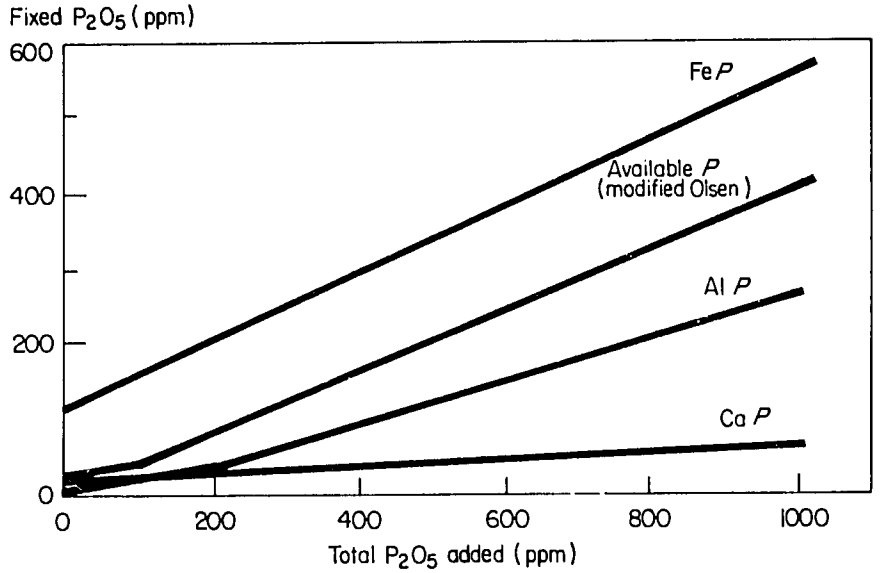
Fixation of phosphorus in submerged soils depends on alterations in the forms of fixing compounds caused by the drop in Eh (redox potential).

Ponnamperuma (1972) showed that the pH in acid soils grows steadily, and tends asymptotically toward pH 6.7 to 7.2 in high humus, iron-rich soils; in low humus, iron-poor soils, it levels out at less than pH 6.5. In calcareous and sodic soils, on the other hand, the pH tends to decrease because of accumulation of the carbon dioxide ions.

In submerged soils, iron as ferric oxide is reduced to the ferrous form, making it more soluble and likely to migrate. Similarly, Mn^{++++} is reduced to soluble Mn^{++}. Soluble iron and manganese move toward oxygenated surfaces where they precipitate again in oxidized form. Iron reduction is greatest below pH 6, and slows considerably at pH 7 and above. Because of the reducing substances that organic matter contains, its presence contributes to solubilization of the iron.

In an acid medium-moist soil (pH of 5.4), iron phosphate is insoluble. Under flooding the solubility of Fe P (60 kg P_2O_5/ha) increases from 4 to 12 ppm after 10 to 75 days flooding; it reaches a maximum on the 75th day, then decreases between 75 and 105 days (Kar et al 1977). The pH may reach 6.1 at the end of the period. The solubility of superphosphate alone is very soluble (16 ppm) at the beginning of flooding, decreases rapidly with time and becomes less than that of iron phosphate after 45 days. The solubility curve of Fe P is parallel to that of iron.

In slightly calcareous soils, submersion decreases phosphorus fixation and the addition of organic matter increases phosphorus solubility after 32 days. In



2. Chang and Jackson fractionation on enriched soil. Ferrallitic soil, Cameroun. 3 days contact, soluble phosphate.

calcareous soils a drop in pH from 7.4 to 7.1 was probably due to the effect of carbon dioxide on calcium carbonate (Shantamallaiah 1976). Ca P is released as the pH drops, and Fe P and Al P are released when it rises.

Moisture conditions altered phosphorus fixation (Mandal and Khan 1975). The increase of Fe P in acid soils submerged for 30 days was lower than in soils kept at field capacity. In neutral soils, on the other hand, phosphorus fixation at various sites remained high regardless of moisture conditions.

Black clayey calcic soils (Vertisols) present a special case. When they are adequately drained (e.g. as for a cotton crop), no serious phosphorus deficiency occurs. When flooded (rice paddy), however, phosphorus deficiency is frequent. These calcium-rich soils of neutral pH contain fairly large quantities of iron and manganese in the clay.

Fixation capacity, which is not very high in a dry soil because of the neutral pH and favorable structure, increases under flooding through an increase of contact surfaces with clay and oxides.

METHODS OF MEASURING AVAILABLE PHOSPHORUS IN SOIL

There are many methods of measuring available or assimilable phosphorus. (Actually, use of the term *labile P* is preferred.) Different methods give variable

results, according to the type and concentration of extraction reagents, the soil-solution ratio, agitation time, and temperature. Consequently, the results must be accompanied by the name of the method used. In addition, the data must be calibrated with crop tests.

The best measurement methods are those that give the highest correlations with plant growth and yields. Historically, the different methods developed in different countries have been found most suitable for conditions (soil, climate, plants) in the area where they were developed. Many authors have tried to compare the methods and define their conditions of use more clearly. Others have done more fundamental research on phosphorus dynamics in soils, using the isotope ^{32}P.

Commonly used techniques

The traditional techniques using chemical reagents are listed:

- *Organic extracting solutions*
  - Dyer – 2% citric acid
  - Joret Hebert – 0.2 N ammonium oxalate
  - Morgan – 0.75 N sodium acetate in 0.5 N acetic acid, pH 4.8
  - Egner – 0.1 ammonium lactate in 0.4 N acetic acid, pH 4.
- *Acid inorganic extracting solutions*
  - Truog – 0.002 N H_2SO_4 buffered to pH 4.8 with ammonium acetate
  - Mehlich or North Carolina method
  - 0.025 N H_2SO_4 in 0.5 N HCl
  - Other methods using H_2SO_4 or HCl at higher concentrations, 0.2 N or 0.5 N.
  - Bray 1 – 0.03 N NH_4F in 0.02 N HCl
  - Bray 2 – 0.03 N NH_4F in 0.1 N HCl
- *Alkaline reagents*
  - Olsen – 0.5 N $NaHCO_3$ at pH 8.5
  - Saunder – 0.1 N NaOH
  - Modified Olsen – 0.5 N $NaHCO_3$ + 0.5 N NH_4F buffered to pH 8.5 by NaOH (Dabin 1967)
  - 0.5 N $NaHCO_3$ + EDTA
- *Water and very dilute saline solution*
  - Distilled water
  - 0.01 M $CaCl_2$ Schofield – equilibrium potential (Aslyng 1964)
  - Anionic resin and soil suspension in water
- *Isotopic methods*
  - E value – Isotopic exchange with P-32 without using plants (MacAuliffe)
  - L value – Isotopic exchange with P-32 using plants (Larsen)

Many scientists have adopted the isotopic techniques. The traditional techniques are most often used as routine laboratory methods. Other methods are research tools for learning more about phosphorus dynamics, particularly its rate of desorption in relation to time. This is the case with Fardeau's isotopic methods and also the use of adsorption isotherms. Phosphorus extracted by a

strong acid (concentrated nitric acid or perchloric acid) is routinely used for tropical soils.

Comparison of methods

Many reports provide comparison among methods. Soils in 43 different regions on all 5 continents have been tested by 43 authors using the techniques mentioned earlier. Recent studies of soils of both temperate and tropical regions include van Raij's comparison (1978) of 12 different methods. The selection criterion is restricted to results of pot tests with measurement of the phosphorus extracted by test plants in the absence of phosphate fertilizers but with all other conditions for plant development.

The Olsen and Bray methods are frequently used and show fairly consistent correlations with pot results; the results of other chemical methods vary more from one region to another. Of all chemical methods Olsen's appears to give the best results. One reason for its overall superiority is that, unlike other methods, it gives good correlations for both submerged and aerobic soils, even with air-dried soils.

Acid reagents appear to be less effective for tropical soils high in sesquioxides, where labile phosphorus consists mainly of Al P and Fe P. Better extraction is obtained by Olsen, Bray, and resin methods. The Olsen method is also effective for acid and saline soils.

Roche et al (1978) used 168 different soils, graded according to the FAO/UNESCO classification, to show correlations between phosphorus uptake in pot tests and the results of analyses of soil phosphorus using a number of methods. The best correlations for all soils (0.884) were by the Gachon (1969) index. The L value (0.796), Dabin-modified Olsen method (0.633), and the Saunder method (0.613) are all significant at 1%.

Other methods are more difficult to use. Anionic resin gives the best results; isotopic techniques (*E* and *L* values) give satisfactory results but they are slightly inferior to those using resin.

Relations between assimilable phosphorus methods and Chang and Jackson fractions

Chang and Juo (1963) correlated results obtained by routine assimilable phosphorus analysis techniques with forms of phosphorus. Acid extracts represent assimilable phosphorus better when Ca P predominates; alkaline extractants are better when Fe P and Al P predominate; mixed extractants (Bray, amended Olsen), which contains NH_4F, are better when the different forms are balanced.

For rice grown in pots with soils where Fe P predominates, alkaline extracts give the best correlation with the response to phosphate fertilizers; the correlation is not so good with acid-fluoride extract, and poor with an acid extract.

Alban et al (1964) investigated the reduction in certain fractions in pot tests in correlation with uptake of phosphorus by plants in reddish-brown lateritic soils in Oregon. The quantity of Al P (NH_4F extraction) lost during crop growth

showed the closest correlation with phosphorus taken up by oats and clover.

Maida (1978) made a recent comparison of nine methods on Malawi soils. These methods correlate significantly with one another. Aslyng P and Morgan P variations correlate with the phosphorus fraction related to soluble phosphorus; Al P is in correlation with Dyer, North Carolina, Olsen, Bray 1, resin and acetic acid. Fe P is the second variable contributing to total variation of phosphorus extracted by 0.1 N NaOH, Olsen P, North Carolina P, resin, and Dyer, in decreasing order of importance. Fuleky (1977) shows that lactate solutions mainly dissolve Ca P, and alkaline solutions to a lesser degree dissolve Al P and Fe P. Using 73 Indian soil samples, Kanwar and Tripathi (1977) compared Bray, Olsen and Morgan, and forms of phosphorus extracted by Chang and Jackson. Ca P forms have little effect on Olsen and Bray 1, but partly explain results with Morgan; Al P, and Fe P fractions contribute significantly to Bray 1 and Olsen extractions, which are similar in their phosphorus form extraction diagrams.

Some characteristic levels of phosphorus in soils

Total phosphorus in tropical soils ranges from 50 to 2,000 ppm P_2O_5. The poorest are the sandy savannah soils in arid regions, and the richest are those formed from volcanic rocks in humid regions.

In 1956 a relationship between the total nitrogen (Kjeldahl) and total phosphorus content was established (Dabin 1950) in the upper horizon of numerous tropical African soils. A linear relationship exists between nitrogen and phosphorus, between 0.02 and 0.1% N and 0.01 and 0.05% of total P_2O_5, with a N-P_2O_5 ratio of about 2. Above 0.1% N and 0.05% P_2O_5, the increase in phosphorus is less than proportional. The N-P_2O_5 ratio can reach 4 for 0.8% N. Empirically, the average representative curve of N against P_2O_5 corresponds approximately to critical levels of P_2O_5 below which phosphorus deficiency begins to appear.

These results have been confirmed for a number of crops: with nitrogen levels of 0.025, 0.045, and 0.1 to 0.14%, P_2O_5 was 0.012% for peanut in Senegal (aridic sandy soils), 0.02 to 0.025% for cotton or rice in the Niger Delta (alluvial soils, Gleysols, Vertisols), and 0.05 to 0.07% for cotton or corn in the Ivory coast (Alfisols, Luvisols, Acrisols).

In 2 soils in rice in Madagascar, total P_2O_5 ranged from 0.075 to 0.17% for respective nitrogen contents of 0.15 to 0.46% (Pichot et al 1976). The first soil responds to 100 kg P_2O_5/ha, but the second reacts only to larger amounts because of its high fixation capacity. This relationship between total phosphorus and plant response may be due to the fairly constant percentages among the various forms of phosphorus in highly weathered tropical soils:

- Active forms (Soil P, Al P, Fe P, Ca P) 10 to 20% of total
- Organic forms 10 to 30% of total
- Occluded and residual forms 50 to 80% of total

Soils formed from basalt rocks are often richest in phosphorus because of the phosphorus content of such rocks, and also mainly because of the high iron and organic matter content in soils formed from basic rocks.

Available phosphorus. Critical levels of available phosphorus are the amounts in the soils when the ratio of the yield from complete fertilizer minus phosphorus to the yield with complete fertilizer exceeds 80% of maximum yield. This value depends on the method of measurement, sometimes on the crop, but mainly on the absorbing capacity of the soil; it also depends on other conditions such as physical properties.

When measured by the amended Olsen method (0.5 $NaHCO_3$ + 0.5 N NH_4F) with cotton on ferruginous soils in the Ivory Coast, 48 to 60 ppm P_2O_5 (25 ppm P) gave 86 to 89% of maximum yield and a level of 0.36% P in leaves (Dabin 1970). The figures were confirmed by Fritz and Vallerie (1973) for cotton on various soils in northern Cameroon.

Working with corn in northern Ivory Coast, Le Buanec (1973) reported a critical level of 26 to 32 ppm P in low-fixing soils, and 72 ppm P in a ferrallitic soil with high fixation capacity. Pichot and Le Buanec (1978), working with ferrallitic soils derived from gabbros in the Ivory Coast, calculated correlations of 0.2 to 0.35% (r = 0.778) between corn yield (2–6 t/ha) and phosphorus content in leaves: for the Saunder method (r = 0.799), amended Olsen (r = 0.739), total phosphorus (r = 0.473), and L value (r = 0.786). Critical levels were leaf P, 280 ppm; L (Larsen), 30 to 35 ppm P; amended Olsen, 60 ppm P; Saunder, 120 to 135 ppm P.

Pichot et al (1976) studied two Madagascar rice-growing soils with nitrogen contents of 1.5% and 4.6%, Gachon fixation levels of 485 ppm and 1,050 ppm P, total P of 377 and 875 ppm, Olsen 25 and 268 ppm, Saunder 166 and 402 ppm, Truog 0 and 5 ppm, Larsen 33 and 69 ppm. One soil produced an additional 1 t/ha with 100 kg P_2O_5; the other soil responded only to higher amounts.

In fertilized plots, correlations between yields and all analytical methods, except Truog and Saunder, are highly significant; modified Olsen and total phosphorus are more suitable for rice (Gleysols).

Synthetic data relating to critical phosphorus levels. Roche et al (1978) provide critical levels for different methods for a large group of soils. The levels range from 250 to 450 ppm for total P, 70 to 780 ppm for Saunder, 10 to 17 ppm for Bray 2, 30 to 70 ppm for amended Olsen, 50 to 140 ppm for carbonate (Dalal), 15 to 40 ppm for L value, and 4 to 9 ppm for Gachon index. The levels are lowest for Luvisols and highest for Gleysols, which correspond to the group with high fixation capacity.

For modified Olsen P, the following empirical rule is generally given: for average to low fixation capacity, the minimum critical phosphorus level is estimated at 2.5% of the total nitrogen rate; for a high fixation capacity that level can be doubled. For a very high fixation capacity the level can be increased even further.

Using NH_4Cl extract of air-dried soil after the addition of 100 ppm of soluble phosphate, an average fixation capacity is less than 10% of the phosphorus remaining in the extract; a high fixation capacity is less than 1% and very high is less than 0.1%.

PHOSPHATE FERTILIZATION

A large number of experiments have illustrated the effectiveness of phosphorus fertilizers, particularly in combination with nitrogen fertilizers. The main problems involved are diagnosis of fertilizer requirements and quantities to be used; determination of most efficient forms of fertilizers, placement, and application dates; and economic factors.

Deficiencies can be diagnosed by soil analysis, or by subtractive pot and field tests. The effect of fertilizers on increasing or decreasing nutrient levels can also be determined by analysis.

The quantity of phosphorus needed depends on the kind of plant and the desired yield. One ton of wheat takes up 20 kg P_2O_5, and a ton of rice takes up 25% of that. Crop composition at harvest can provide a basis for estimating annual fertilizer needs, but tests with tracers have shown that about 20% of phosphorus fertilizer is used by the plant and about 80% remains in the soil. Forms of fertilizers have variable levels of solubility, and give different reaction products with the soil.

In flooded soils with a high active iron content, 86% of the phosphorus in superphosphate was converted in 15 days to a low available form, but natural phosphates or basic slag maintained a higher availability level. Most quantitative fertilizer tests have been done using soluble forms such as ammonium phosphates or superphosphates, with the initial objective the determination of quantities that gave the highest yields. The response curve method (Chaminade 1964) consists initially of determining the quantity of nitrogen providing maximum yield in the presence of excess phosphorus and potassium, then investigating the effect of increasing amounts of phosphorus in the presence of the optimum amount of nitrogen, etc.

The amount of phosphorus corresponding to the maximum yield or *potential fertility* of the soil can be the basis for a corrective application, after which fertility can be maintained by minimum applications based on yields. This method, which has given spectacular results in Madagascar, involves high investment costs and is not always suitable for small holdings.

Methods that determine previously maximum quantities of fertilizers to be applied involve investigating the best balances among elements. Examples are the *systematic variant* method applied by Braud et al (1959) to cotton crops, and the so-called *factorial methods,* which are still used. These methods, applied in experimental centers, have facilitated the establishment of fertilizer formulas for various crops throughout large regions.

In many developing countries local products are used with techniques that will ensure maximum efficiency in the use of expensive imported fertilizers. There has been progress in research into methods of application, placement, date of application, position in crop rotation, and the use of supplementary products.

Maertens' (1978) investigations of fertilizer placement have shown that roots can absorb 15 to 20 times the plant's needs, but placement must not slow down

the development of other roots and adequate water supply must be ensured. Absorption increases in relation to the concentration of soluble phosphorus in the soil and proper placement increases fertilizer efficiency in a soil with high fixation capacity. A small number of roots in a rich soil can feed a whole plant. Another factor is the level of absorption of phosphorus by young roots at the beginning of growth, on which complete nutrition of the plant may depend. Finally, by reducing contact between soluble phosphate fertilizers and the mass of soil, fixation is reduced.

Submerged soils

In connection with soluble superphosphates for rice crops, Katyal (1978) noted that fertilizer broadcast on the soil surface is more efficient than the same fertilizer placed at 15-cm depth. Fertilizer applied in one operation (50 kg P_2O_5/ha) at the beginning of cultivation is more effective than that applied late or in split applications (60 kg P_2O_5/ha in three 20-kg applications).

Dipping the rice roots before planting in a mixture of soil and superphosphate reduces by 50% the quantity of phosphorus needed for the same increase in yield (Katyal 1978). The dip mixture can be made with superphosphate or nitrophosphate.

Placement is different if rock phosphate of low solubility is used. The effectiveness of rock phosphate depends on its fineness and solubility in citrate (Hammond et al 1977). The effectiveness increases as the amount applied increases and is incorporated in the soil.

Absorption by plant roots of phosphorus from fairly insoluble phosphorus sources depends partly on the probability of the roots' growing near enough to phosphorus particles to absorb them from the surrounding solution. According to Blanchet (1978) the effective distance is only 1 mm for phosphorus compared to 5–10 mm for potassium.

Comparison of soluble phosphates and rock phosphates

Superphosphates and hyperphosphates, like ammonium phosphate, are used widely throughout the world. In most soils, particularly those with low pH, crop response is better than with most rock phosphates, mainly in short-term tests. Over longer periods, for example after 14 years' application, the increase in labile phosphorus is higher for rock phosphate and residual effects on crops are high (Mandal 1975). In a soil of pH 5 after 8 years of fertilization, superphosphate increased Fe P, but rock phosphate increased all fractions. In lateritic and acid soils in India, citrate-soluble phosphate fertilizers and rock phosphates can replace water-soluble phosphates, but applications have to be at least twice the amount of superphosphate on the basis of P_2O_5 content.

In flooded rice soils, where the phosphate is incorporated into a humid soil 3 weeks before flooding, Ca P (citrate-soluble and slowly-soluble) is converted into Al P, thus increasing P availability by hydrolysis and solubilizing Fe P by reduction. These changes do not occur in neutral or calcareous soils and in this

case the addition of organic matter may have a beneficial effect.

For many crops, rock phosphate may be as effective as superphosphate in quantities of 100 kg/ha after *3 years' application.* For higher levels of natural phosphate, the available phosphorus is significantly higher. Another series of experiments has shown that it may be better to apply a certain quantity of superphosphate in addition to rock phosphate, e.g. 33% the first year, 25% the second year, and none the third and fourth years. Rock phosphate may also be partly acidified with H_2SO_4, H_3PO_4, or HNO_3. Phosphoric acid is best but 20% HNO_3 is also effective. In general, phosphate fertilizers containing 20 to 50% soluble phosphorus were as effective as those completely soluble.

Amendments improving the effectiveness of phosphate fertilizers

It has been found that liming acid ferrallitic soils improves phosphate uptake by plants. Organic matter encourages plant growth and rooting, thus causing greater phosphorus mobility. It may, however, increase the phosphorus fixation capacity of oxide-rich soils, which become more reactive in the presence of organic matter. Loss of organic matter in the surface horizon of soils causes loss of phosphorus. In calcic or calcareous soils, organic matter increases phosphorus solubility.

CONCLUSION

Tropical soils usually possess limited phosphorus reserves and have high absorbing capacity. Economic application of fertilizers should allow these reserves to be increased economically and gradually to improve general soil fertility. Future research could cover better integration of the results of analysis of phosphorus with other soil properties – morphological, physical, and chemical. Because phosphorus fertilization depends on general plant-rooting conditions related to multiple factors as well as to phosphorus content, computer models may help. Regarding laboratory research, the dynamics of phosphorus desorption in tropical soils must be defined. More sensitive techniques for measuring phosphorus in solution should be developed.

The action, as well as the residual effects, of organic matter and of phosphate fertilizers must be defined in long-term experiments.

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Sulfur deficiency in soils in the tropics as a constraint to food production

G. J. BLAIR, C. P. MAMARIL, AND M. ISMUNADJI

Soils of the tropics generally have low levels of organic sulfur, and adsorbed sulfur is often the major reserve of this element. The addition of lime or phosphate to soils decreases sulfate adsorption and may significantly reduce their sulfur status.

Responses to sulfur are widespread in the tropics and have been recorded in 40 tropical countries with 23 different crops. Suggested reasons for the widespread nature of the deficiency are presented.

Published information indicates no association between sulfur deficiency and soil or climatic factors that would be useful for predicting areas of likely deficiency.

The major problem encountered in examining published data on soil and tissue tests was that of chemical methodology. Although soil and tissue tests for sulfur have been extensively used in temperate areas and on some tropical crops care is needed in deriving acceptable criteria for diagnostic purposes, and a suggested approach to this problem is presented.

There is an urgent need for experiments that examine the effects of sulfur fertilization on the yield and quality of tropical crops and pastures if this constraint to food production is to be reduced. The experiments must examine sulfur in its own right and not simply as a secondary component of other fertilizers.

ALTHOUGH THE ESSENTIALITY of sulfur as a plant nutrient has been known for more than 100 years, the element has received relatively less attention in laboratory, greenhouse, and field research than that received by the *big three* – nitrogen,

Department of Agronomy and Soil Science, University of New England, Armidale, N.S.W., 2351, Australia; Cooperative CRIA-IRRI Program, P.O. Box 38, Ujung Pandang, Indonesia; and Central Research Institute of Agriculture, Bogor, Indonesia.

phosphorus, and potassium. This is explained in part by the fact that, in many instances, the use of nitrogen and potassium fertilizers containing sulfur has masked a deficiency of sulfur. Moreover, given the current state of the art, sulfur analysis in biological material is difficult.

In general, plants contain as much sulfur as potassium (av of about 0.25%). The ratio of nitrogen-sulfur in plant protein is generally considered relatively constant at 15:1.

Sulfur deficiency affects not only plant yield but also protein quality through its effects on the synthesis of the amino acids cystine, cysteine, and methionine. Since methionine is an essential amino acid for humans, decreases in grain methionine levels as a result of sulfur deficiency may have serious implications for human nutrition and health. Zake (1972) found that sulfur fertilization increased the methionine level of finger millet such that the quantity needed to meet the daily sulfur amino acid requirement of an adult was reduced from 1,325 g/day to 725 g/day.

Sulfur present in soils as the anion sulfate undergoes many reactions, similar to those of nitrate and phosphate, and its strength of adsorption to surfaces is intermediate between that of the two ions.

While some complete studies of sulfur have been conducted in temperate areas of the world, little research on sulfur in the tropics is available.

SOILS OF THE HUMID TROPICS

The great variation in the age and character of soil parent materials in the tropics gives rise to a wide range of soil types. The intensity of weathering is generally high because of the high-intensity rainfall and high relatively constant soil temperatures.

The highly weathered soils from the tropics contain mostly 1:1-type clays (kaolinite and halloysite), which have a low cation exchange capacity and generally high oxide content. Most of these soils are the Oxisols and Ultisols which cover large areas of the humid tropics. The pH is generally acid with the most acid soils found in the rainy regions of the area. Acid soils of comparable age and parent material of the low rainfall or wet-dry areas, in general, have higher pH than those in wet areas partly because the organic matter is generally higher in soils from the latter area, and the bases from this source help to maintain soil pH levels. As cropping depletes the level of soil organic matter, the supply of bases declines as does the soil pH.

Soils of the humid tropics are formed under conditions of high moisture percolation, and removal of bases from the profile is rapid. As the bases are leached from the profile, they carry with them the anions of chlorine, nitrate, and sulfate. In experiments by Pearson et al (1962), 90% of the water-soluble bases were leached as sulfates from the acid Latosol and Ultisol profiles; chlorides and nitrates accounted for only about 6% and 1%.

Soil sulfur

Tropical and temperate soils differ in both the total amount of sulfur and its form. As with phosphorus, soils of the temperate region show a decline in total sulfur content with the degree of weathering. Jordan and Reisenauer (1957) report average values of 540 ppm sulfur for Mollisol and 210 ppm for Alfisol surface soils from the temperate areas. Generally, the total sulfur content of tropical soils is lower because of their lower organic matter content. A summary of data on total sulfur contents of topsoils from tropical areas is given in Table 1. Although the range is great, the mean (106 ppm) is well below the average values for temperate soils given by Jordan and Reisenauer (1957).

Sulfur is found in soils as a variable mixture of primary minerals, sulfate ions in solution, adsorbed sulfate, organically bound ester sulfates, and organic sulfur compounds.

Although sulfur data on tropical soils are limited, those available suggest some important differences between the forms of sulfur present in tropical and temperate soils. These may be summarized as follows:

1. Adsorbed sulfur is generally higher in tropical soils (Fig. 1). In this state it cannot be leached from the profile.

2. Organic sulfur and ester sulfate, which may be thought of as *reserve S*, are generally lower in tropical soils.

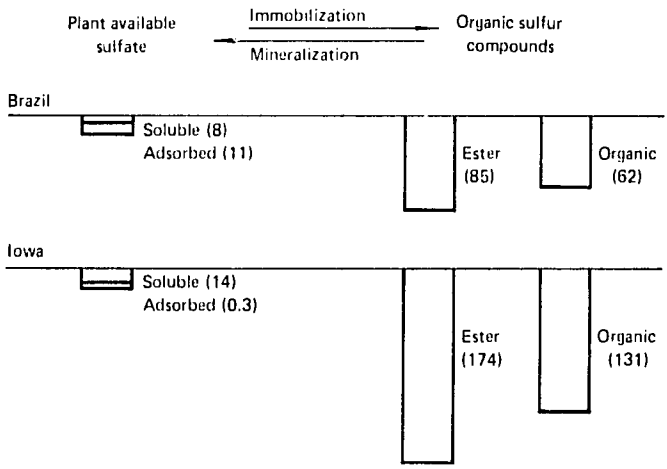
3. Environmental conditions in the tropics are generally conducive to a rapid mineralization of organic matter, which leads to high turnover rates of sulfur. An exception is the volcanic soils (Andepts) in which adsorption of organic matter on the particles of allophane retards mineralization.

SULFUR DEFICIENCY IN THE TROPICS

In his review of sulfur in world crop production, Coleman (1966) reported sulfur deficiency in 12 tropical countries. He noted that the number of reports of

Table 1. Total sulfur values for a range of soils from tropical regions.

Location	Soils (no.)	Total S (ppm)		Reference
		Mean	Range	
Malawi	14	66	35–139	Laurence et al (1976)
Nigeria	3	43	38–52	Bromfield (1972)
W. Indies	8	248	110–510	Haque and Walmsley (1973)
N. Cameron, Chad, Ivory Coast	31	70	20–300	Dabin (1972)
Brazil (virgin)	4	103	40–251	McClung et al (1959)
Brazil (cropped)	6	49	27–67	McClung et al (1959)
Nigeria	–	–	18–132	Watson (1964)
Zambia and Rhodesia	–	–	60–100	Grant et al (1964)
Brazil	6	166	43–298	Neptune et al (1975)
Mean		106		



1. Soil sulfur pools in samples from Iowa (USA) and Brazil. The numbers in brackets represent ppm (drawn from the data of Neptune et al 1975).

sulfur deficiency was increasing because of:

1. the increasing use of high-analysis, low-sulfur fertilizers; and
2. the increased sulfur demand brought about by increases in yields obtained as a result of other technological advances.

A greater number of experiments have been conducted where sulfur has been studied as a nutrient in its own right. In many early experiments, responses to fertilizers such as ammonium sulfate, potassium sulfate, zinc sulfate, and single superphosphate have been attributed to the nitrogen, potassium, zinc, and phosphorus components of the fertilizer, and the potential response to sulfur has been ignored.

Response to sulfur has been reported in 40 countries of the tropics (Fig. 2). Figure 2 reflects the availability of published information rather than the limitation of the deficiency to those countries.

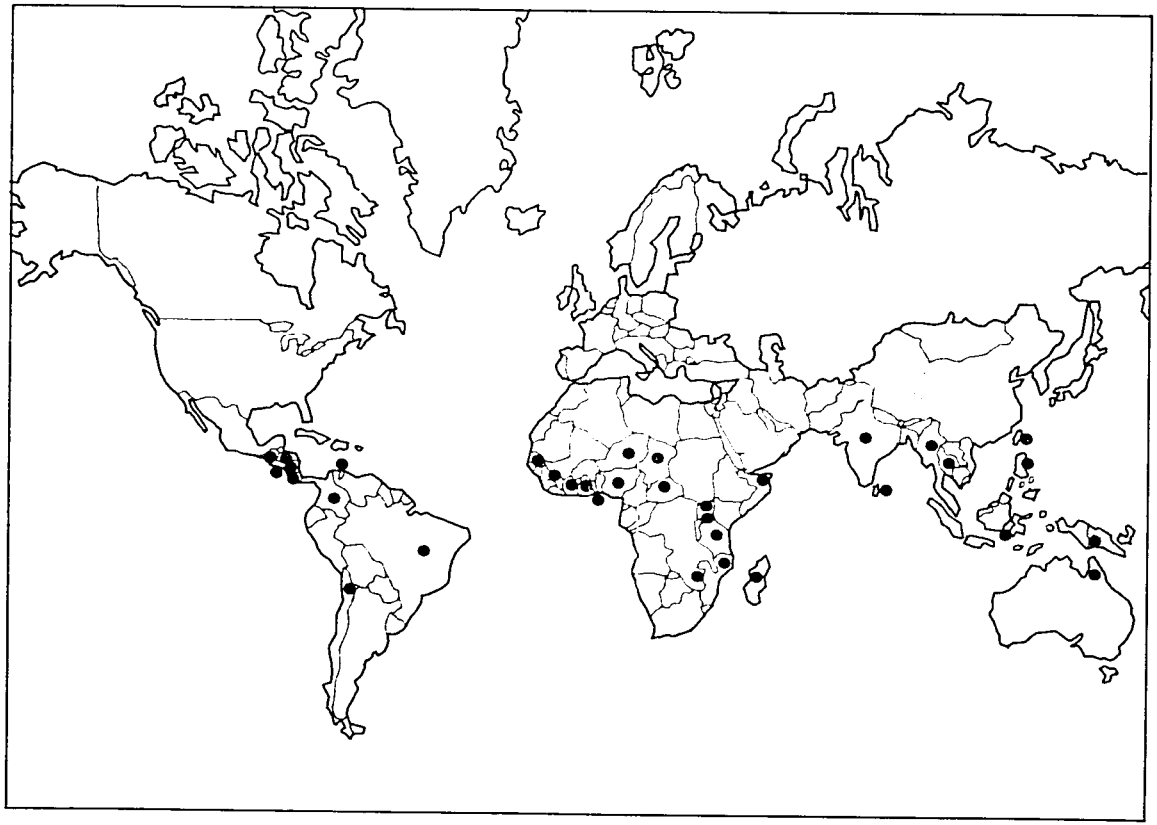
The available data are insufficient to permit an estimate of the actual area that may be sulfur deficient in the tropics or of the expected magnitude of sulfur response. The small amount of published data, however, suggests that the problem is widespread and severe. A summary of these data follows.

Kenya – 133 pot trials; 71% showed yield depressions of >20% without sulfur (Mehlich 1970).

East Africa – 202 field trials; 18% showed yield depressions of >30% without sulfur (Braud 1970).

Brazil – 21 pot trials; 81% showed yield depressions of >25% without sulfur (McClung et al 1959).

Nigeria – 45 pot trials; 17% showed yield depressions of >20% without sulfur (Enwezor 1976).



2. Countries marked with a dot are those where sulfur deficiency has been recorded (Blair 1979).

Senegal – 29 field experiments showed an average sulfur response of 71 kg peanut yield/ha in a total fertilizer response of 522 kg/ha (Brockelee-Morvan and Martin 1966).

Indonesia – 28 field trials with rice; yield responses >20% at 77% of sites (Blair et al 1979a).

The reasons for a soil's deficiency in sulfur can be grouped broadly into three areas: 1) inherently low initial sulfur status, 2) low availability of sulfur-containing soil organic matter, and 3) the result of agricultural practices.

Inherent sulfur status

As indicated earlier, the highly weathered soils that occupy large areas of the tropics have low total sulfur contents because of low sulfur in the parent materials or to extreme weathering and leaching losses, or to both.

Few data are available on the sulfur status of virgin tropical soils. McClung et al (1959) found that all five soils collected from under virgin hardwood forests were responsive to sulfur and that the deficiency became severe after cropping. In contrast, Enwezor (1976) found that two soils collected from virgin lowland rain forests in southeastern Nigeria were nonresponsive to sulfur.

Low availability of sulfur-containing soil organic matter

Sulfur deficiency frequently occurs in soils derived from volcanic parent-materials. In such soils, which are common in Central America (Fitts 1970), the organic matter is closely associated with allophane and the mineralization of the allophane-bound organic matter, i.e. the rate of release of sulfate S is very low. Plants on such soils are often sulfur deficient despite the fact that the soil is high in organic sulfur.

Agricultural practice

Sulfur deficiency often develops in the tropics after a period of agricultural exploitation. The major factors that contribute to its onset are crop removal, organic matter losses, leaching and erosion losses, and fertilizer use and management.

Crop removal. Cropping intensity affects the amount of a product or products removed in a cropping system; the more intensive the cropping system, the greater the product removal and sulfur demand.

The type of crop grown (annual or perennial) and its total sulfur requirement will govern the total amount of soil sulfur utilized. The net requirement is governed by the amount of sulfur removed in the product and the fate of the plant residue.

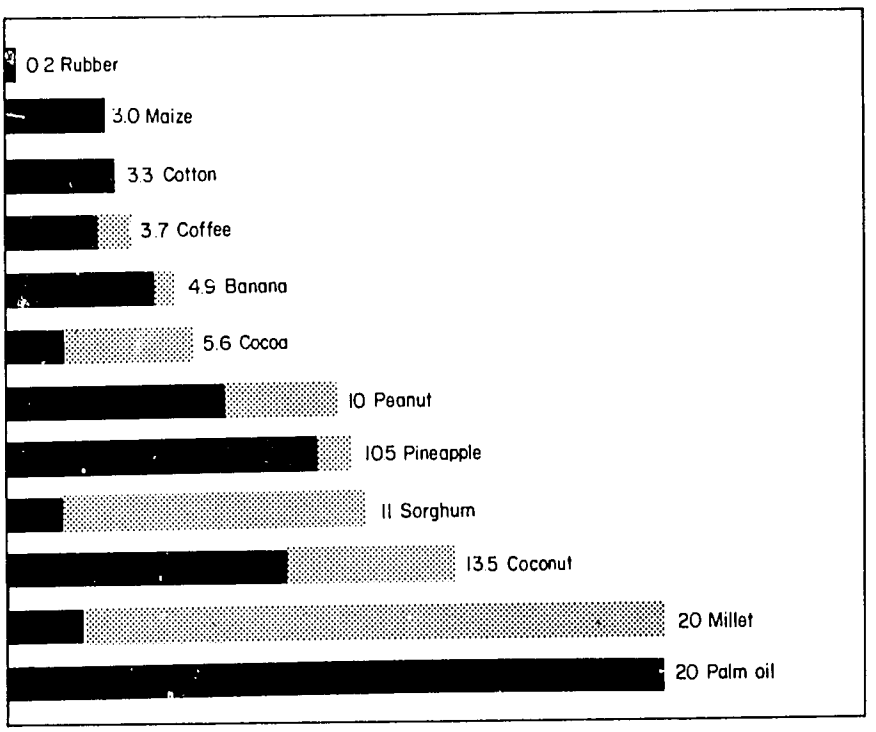
In a natural bush ecosystem the sulfur demand is low because of the low growth rates and the efficient cycling of sulfur in the system. When this vegetation is replaced by an agricultural crop, the sulfur demand increases considerably. The magnitude of the increase will depend on both the sulfur content of the product and its yield, and the fate of crop residues.

An example of variable crop removal is found in published data for rice. Sulfur contents of the rice grain vary from 0.034% under deficiency conditions to 0.16% in a nonresponsive situation, and rice grain yields may vary from 0.75 to 8 t/ha. The sulfur demand thus ranges from 0.26 to 12.8 kg/ha.

A further factor to take into account when considering the effect of crop removal on sulfur demand is the zone of removal in the soil. The generally deeper pattern of rooting of perennial crops enables them to utilize sulfur that has been leached into lower soil zones, particularly on soils with a clay or oxide layer at depth within the rooting zone.

The values in Figure 3 are for average crop yields; they represent the material actually exported from the field and include residue that may or may not be returned to the field. The removal of the residue contributes significantly to losses in some situations (sorghum, millet).

Incorporation of crop residues back into the soil may, in some instances, decrease plant-available sulfur. Stewart et al (1960) found a net immobilization of soil sulfur when wheat straw with less than 0.15% sulfur was added to the



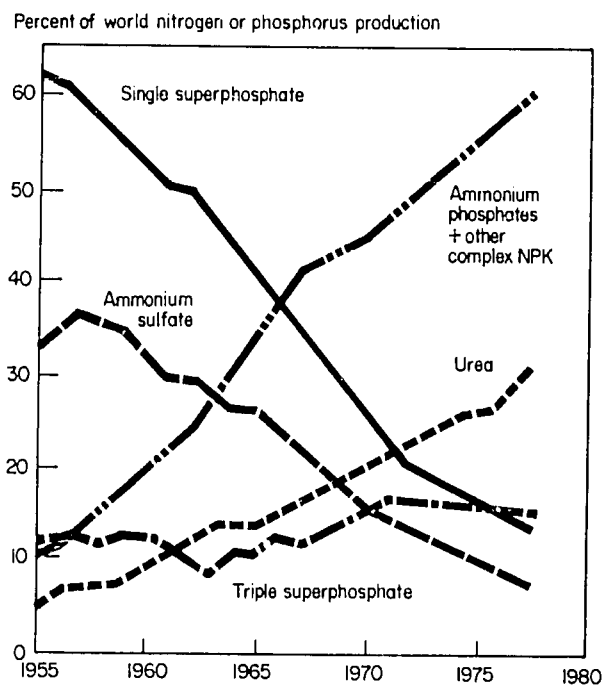
3. Sulfur uptake by different crops of average yields. Hatched areas represent product that may or may not be returned to the field. The number before the crop name is total removal in kg/ha (Martin-Prével 1972).

soil. In a review of published literature, Blair et al (1978) found only two cases where the sulfur content of rice straw was above that level. This aspect of straw management requires further study.

The recycling of sulfur in crop residues is important in livestock systems where the residue material is used as an animal feed or bedding. Decau (1972) presented returns from various straw management systems that varied from 70% from grazed forage down to 50% where grain was sold and straw used as a manure.

Organic matter losses. One major consequence of cropping a tropical soil is the loss of organic matter. Since organic matter acts as a reserve of sulfur in soils, the losses have serious implications for the soils' sulfur-supplying power. Experiments by McClung et al (1959) showed that cropping reduced the organic sulfur levels in four Brazilian Ultisols from 115 to 42 ppm.

In many parts of the tropics, burning of plant matter, which is an integral part of farming, can be an avenue for sulfur loss. When carbon is burned off by combustion, there is a concentration o sulfur in the ash. Bromfield (1974) has shown that the sulfur content of ash can be 2 to 10 times higher than that in dried plant material. The actual values depend on the ignition conditions and plant species. In sulfur studies in northern Nigeria, Bromfield (1974) found in-



4. Fertilizer product consumption patterns, 1955–80 (after Hignett 1971).

puts of 0.05 to 0.25 kg/ha from ash during the dry season. In areas of prevailing winds, sulfur loss may be high, but in regions of variable winds the gains may equal the losses. One additional consequence of burning is that organic forms of sulfur are converted to inorganic forms which, at the beginning of the rainy season when fields are bare, are susceptible to leaching losses. No data are available on this form of loss.

Sulfate in readily soluble fertilizers and produced by the mineralization of organic matter enters the soil solution where it is leached if it is not taken up or adsorbed. In Nigerian field studies, Bromfield (1972) observed sulfate movements in soil. Sulfate that was mineralized from organic matter moved down the profile and accumulated at depth.

Losses from leaching and erosion. Data on losses of sulfur due to erosion are not readily available. Since a large proportion of the sulfur present in the soil is in the organic matter and this is often accumulated on the soil surface, losses from wind and water erosion may be high in some circumstances.

Fertilizer use and management. Direct inputs from sulfur-containing fertilizers are major sulfur sources in agriculture. Fertilizer sulfur additions are generally made as a secondary component of ammonium sulfate, single superphosphate, potassium sulfate, or compound NPK fertilizers, but in some places sulfur is applied as a primary fertilizer. The declining use of conventional sulfur-containing fertilizers is a major concern in the tropics (Fig. 4).

Since adsorbed sulfur is a major source for plants in weathered tropical soils, the use of nonsulfur-containing phosphatic fertilizers may aggravate the sulfur problem by replacing adsorbed sulfate with phosphate. In this regard two aspects of sulfate adsorption are important.

First, phosphate ions will replace sulfate ions on charged surfaces. This effect is shown in the work of Barrow (1969); in the soil used in his experiment, sulfate adsorption showed an almost linear decline with added phosphate, i.e. where phosphatic fertilizers are added to a soil, the phosphate ions would be expected to remove sulfate ions from the clay, oxide, or organic surfaces. The displaced ions are then free in the soil solution and can be leached into the profile and either lost in percolating water or readsorbed at a lower depth. This appeared to be the case in the experiments of Bromfield (1972) where the sulfate level in the 0 to 7.5-cm layer declined from 10 ppm where ammonium sulfate and single superphosphate had been applied. The reduction occurred despite the addition of an extra 277 kg of S in superphosphate/ha over the 19-year period of the experiment. In this work most of the applied sulfur was retained in the top 180 cm of the profile, but the zone of major accumulation was below 20 cm.

The second major effect of other fertilizers on sulfur nutrition is that brought about by pH changes. The adsorption of sulfate depends on concentration and pH (Kamprath et al 1956), i.e. the application of fertilizer materials (rock phosphate) or soil amendments (lime) that increase soil pH may decrease sulfate retention.

ENVIRONMENTAL FACTORS AND SOIL AND PLANT ANALYSIS IN DIAGNOSIS OF AREAS DEFICIENT IN SULFUR

In attempts to identify areas that may be sulfur deficient or to indicate areas where the problem may arise, an association between sulfur status and some factor in the environment would be extremely useful. Alternatively, the analysis of soil or plant samples may be useful. The discovery of such relationships could obviate or reduce the necessity of conducting costly field experiments and lead to an earlier recognition of problem areas.

Environmental factors and sulfur status

Rainfall. In northern New South Wales, Australia, McArthur and Spencer (1970) found that sulfur responses were lowest on soils from areas of highest rainfall. Soils from such areas also had the greatest sulfur adsorption capacity and retained sulfate against leaching. Although rainfall and sulfate adsorption capacity have been related, the relationship varied between soil types (Barrow 1970).

The relationship between adsorption capacity and rainfall can be complicated by other factors. Negative correlations between rainfall and pH and rainfall and sulfur response and a positive correlation between rainfall and sulfate adsorption were found on the Dorrigo soils used by McArthur and Spencer (1970). They may not indicate a cause-and-effect relationship between sulfur responsiveness and the measured parameter. Sulfate adsorption occurs by reaction with surface aluminum and iron. In some soils the amount of reactive aluminum is closely related to pH and both have been related to rainfall (Barrow 1970).

Rainfall is a major source of sulfur in industrialized temperate and tropical areas; the annual accessions are often in excess of 20 kg S/ha (Coleman 1966). In such areas sulfur deficiency is unlikely. Few data are available on the amount of sulfur in rainfall in tropical areas, but indications are it is low. Bromfield (1974) estimated that the mean annual sulfur input from rainfall was only 1.14 kg/ha in Nigeria.

Sulfur inputs from rainfall are generally higher near the sea than inland. Fox et al (1965) recorded 5 ppm S in rainwater 0.5 km from the sea on the island of Kauai, Hawaii, but only 0.8 ppm 8 km inland. Probert (1976) measured annual inputs of 6.0 kg/ha 9 km away from the sea near Townsville, Australia, and 3.2 kg/ha 40 km inland.

The insufficient data available for establishing a direct relationship between rainfall and sulfur status suggest that it may be dangerous to generalize, as is often done in temperate areas, that areas near the sea in the tropics may be free of sulfur deficiency.

Irrigation water. Irrigation water is a source of sulfur for crops. Yoshida and Chaudhry (1972) suggest that irrigation water with a sulfur content of 2.7 ppm would supply the needs of a rice crop. But Wang et al (1976) suggest a value of 6 ppm. Severe sulfur deficiencies in South Sulawesi, Indonesia, in rice paddies supplied with water containing 2.8 ppm S suggest that the sulfur contribution

from irrigation water needs reassessment.

Soil factors. Little work has been done in the tropics to relate sulfur deficiency to soil factors. A survey of information from Australia was made by Blair and Nicolson (1975), and much of the discussion that follows comes from that source.

An early attempt to relate sulfur responses to various measurable factors was carried out on 32 virgin soils collected from eastern temperate Australia (McLachlan 1955). No relationship was found between responses and climatic and soil factors apart from pH. In an examination of 40 Northern Tableland soils from New South Wales (Spencer and Barrow 1963), no relationship was found between pH and sulfur response. The pH range was narrower than that of soils tested in the previous survey, and the pH relationship noted earlier may have been unduly influenced by a small number of soils of high pH (>8.0).

The color of basaltic sedentary soils in northern New South Wales was found to be significantly correlated with sulfur status ($r = 0.92$), the reddest soils being the most deficient (Spencer 1966). There was no relationship between soil pH or redox potential. The red soils were probably high in exposed iron oxide, reflecting better aeration and drainage and greater sulfur leaching. The comparative nature of such an assessment gives it limited value in delineating sulfur responsive areas.

The lack of success in establishing a meaningful relationship between the occurrence of sulfur deficiency and some predictable factor in the soil or climatic environment means that we must either conduct more studies of associations in various areas, or revert to agronomic response data of soil and plant tissue testing, or do both, to delineate areas of sulfur deficiency.

Soil testing for sulfur status

The major problem encountered in studies of soil sulfur in temperate areas is the variability in size of soil sulfur pools over short periods of time. This is brought about by the nature of the sulfur sources present. Since such a large proportion of the sulfur is in organic form or associated with organic matter (ester S), it can undergo rapid mineralization or splitting to plant-available forms or both. This is a major problem in areas with marked short-term fluctuations in moisture and large seasonal temperature differences. In those areas of the tropics where short-term temperature and soil moisture fluctuations are not as great, soil testing may be of more use.

Sulfur extraction. The methods used to extract sulfur from soil can be grouped into four basic categories: soluble sulfates, soluble and adsorbed sulfate, total and organic sulfur, and microbiological methods.

The first two categories involve the removal of sulfur by one of several chemical extractants. Not all extractants perform equally well on all soils. Those that remove soluble-plus portions of adsorbed sulfate tend to be better correlated with sulfur status than those removing only readily soluble sulfate. Adsorbed sulfate is removed by neutral and slightly alkaline extracts and by extractants

containing a strong replacing ion such as phosphate. Excellent prediction of response in field trials in isolated areas of the temperate zone has been reported for extractants that remove soluble, adsorbed, and portions of the organic sulfur. Included are the acetic acid-phosphate solutions employed by Cooper (1968) and Hoeft et al (1973) and the pH 8.5 sodium bicarbonate solution used by Bardsley and Kilmer (1963), which is commonly used as an extractant for *available phosphorus.*

Solutions containing phosphate are most commonly used as sulfate extractants because the phosphate effectively replaces sulfate on the adsorption complex. Of the phosphate extractants calcium phosphate is generally the most acceptable because the divalent calcium does not cause dispersion of the clay and organic matter, which may occur when potassium or sodium is used. For these reasons, calcium phosphate (500 ppm P) should be one of the extractants in any proposed testing program.

Relationships between total sulfur or organic sulfur and plant response have generally been poor or nonexistent in soils from the temperate areas. However, one study of tropical soils, where the sulfur released on incubation (organic S) was related to plant response, should be noted. In a study of 45 soils from Nigeria, Enwezor (1976) found that soils mineralizing <6 ppm of sulfur (extracted by sodium acetate) gave responses to sulfur in a pot trial with corn grown for only 45 days. More field work using the method with crops grown to maturity is needed. Perhaps in areas with marked wet-dry seasons this method, applied to samples taken toward the end of the dry season, would be useful.

Microbiological methods have never really gained much acceptance, because they allegedly are impractical and time-consuming. This may be a bias on the part of soil chemists rather than a true indication of the worth of the tests. In one study of 28 topsoils from Kenya, Mehlich (1970) compared the response to sulfur of greenhouse tomatoes and *Cunninghamella* and found good agreement in their growth. The method requires minimal equipment and is worthy of further investigation in the tropics.

Once the sulfate has been extracted from the soil and all the sulfur in the plant sample has been oxidized to sulfate, the sulfur content of the sample must then be determined. Beaton et al (1968) list some 107 methods of extraction and analysis of soil sulfur and 66 combinations of ashing and analytical methods for plant material. The most accurate and sensitive method for determining sulfate – that of Johnson and Nishita (1952) – involves its reduction to hydrogen sulfide and its adsorption in zinc-sodium acetate. This method is accurate, but time-consuming and costly. The equipment required is specialized, and the availability of chemicals and nitrogen gas limits its use in less developed tropical areas. For laboratories with limited equipment, the barium sulfate turbidimetric method of Chesnin and Yien (1951) is the most practical. The use of stabilizers – Tween 80 (Quin and Woods 1976), poly-vinyl-alcohol (Rocks et al 1963) – has overcome the major problem of instability in the barium sulfate precipitate experienced in this method.

Table 2. A comparison of ashing methods for sulfur determinations in plant material (adapted from Sansum and Robinson 1974).

Method	Sulfur (%)
Dry ashing	0.150
$HNO_3/HClO_4$	0.207
$HNO_3/HClO_4$ + 1-hour digestion after clearing	0.335

The extraction of soil with sodium bicarbonate and digestion of plant material with magnesium nitrate plus perchloric acid allow the simultaneous determination of phosphorus and sulfur in soil and plant material. For this reason, these methods should further be evaluated in the tropics.

Researchers have listed the *critical values* proposed for soil sulfur by various extractants (Ensminger and Freney 1966, Reisenauer 1975), and their findings, along with other published data from tropical soils, have been tabulated by Blair (1979). The data cover a wide variety of crops and soil types. The great variability in critical levels among the studies contradicts the findings of Reisenauer (1975) that "the values agree surprisingly well and indicate a high level of dependability in these tests."

This variability does not render the soil test procedure useless; instead, it serves to emphasize the need for correlation studies in limited areas with specific crops, soil extracts, and methods.

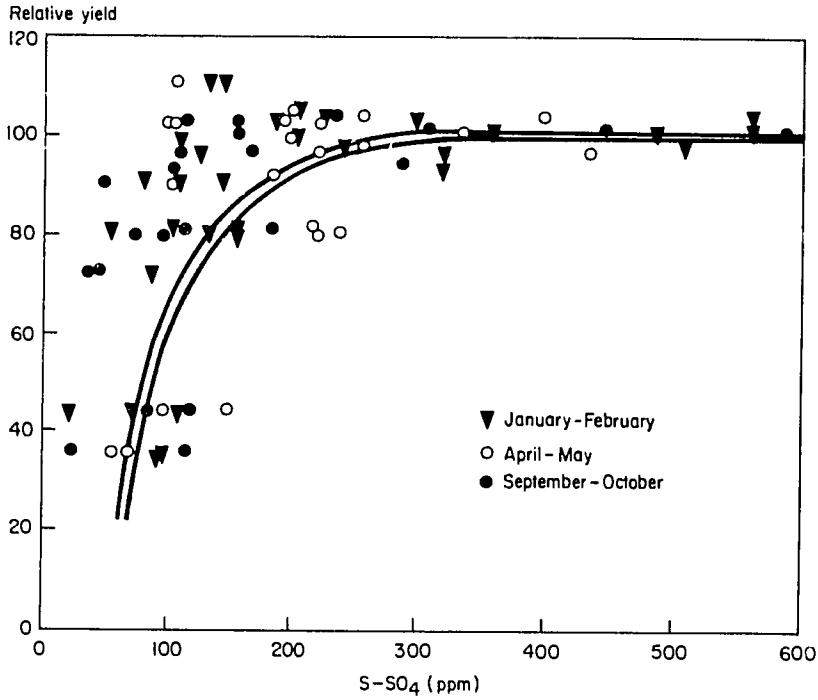
Tissue testing for sulfur status

A tabulation of data showing critical levels but without a specification of the method of digestion and determination, such as that made by Eaton (1966), is of little value for setting levels of adequacy.

Of the methods available to oxidize organic sulfur to sulfate, wet ashing using nitric/perchloric acid plus dichromate and metavanadate and a 1-hour digestion beyond color change appears the most acceptable (Sansum and Robinson 1974, Table 2). A second method worthy of investigation is the magnesium nitrate/perchloric acid method proposed by Quin and Woods (1976). Both methods require a minimum of equipment and, with trained personnel, are rapid and reproducible.

Often critical levels are established on shaky evidence. The example in Figure 5 is taken from De Freitas et al (1972) who conclude from these data that "about 200 ppm SO_4^{2-}-S in coffee leaves indicates adequate S nutrition." However, on examination of the correlation data, it was found that 10 samples had a relative yield of >90% with an S content below 200 ppm, and 27 samples a relative yield >90% with an S content above 200 ppm. The wide spread of data indicates this criterion to be too insensitive for use as a diagnostic tool.

Many researchers have suggested that the nitrogen-sulfur ratio can be used as a diagnostic tool (Dijkshoorn and Van Wijk 1967). Lott et al (1969) concluded that sulfate-sulfur was more sensitive than total sulfur as an index of deficiency



5. Relative yields (%) of coffee as related to the concentration of sulfate-sulfur in leaf samples at various seasons of the year (De Freitas et al 1972).

for coffee. This criterion is not satisfactory on its own – sulfates may accumulate under conditions of molybdenum deficiency even in circumstances where sulfur is deficient (Anderson and Spencer 1950).

Fox et al (1977) have shown that the critical level of sulfur in cowpea (*Vigna unguiculata* [L.] Walp) varies between cultivars. In their solution culture experiment, the critical value varied between 0.032% total sulfur in cultivar Sitao Pole and 0.064% in TVU76-2E. This cultivar-specific variation makes the setting of critical levels even more difficult.

The use of multiple criteria of nitrogen-sulfur ratio, sulfate S, and total sulfur in cereals has been suggested by Blair and Crofts (1970) for overcoming the deficiencies inherent in the single-factor classification system. This approach has been extended to published rice data (Blair et al 1978). The criteria used are given in Table 3. Any attempt at setting critical levels should consider the use of multiple criteria.

Ensminger and Freney (1966) list the effect of age on sulfur contents in several species. Because it is necessary to select a plant part that has a relatively constant sulfur content, the effect of maturity on the sulfur content of the plant part(s) should be examined to determine sensitivity to sampling time.

Table 3. Preliminary classification of nitrogen (N) and sulfur (S) status of whole rice tops sampled from tillering to flowering stages (Blair et al 1978).

Category	Nitrogen (%)	Sulfur (%)	N:S	Status	
				N	S
I	>1.6	<0.10	>15	Adequate	Deficient
II	>1.6	0.10–0.15	>10	Adequate	Marginal
III	>1.6	>0.15	<10	Adequate	Adequate
IV	<1.6	>0.15	<10	Deficient	Adequate
V	<1.6	<0.10	Variable	Deficient	Deficient

SULFUR USAGE TRENDS AND SULFATIC FERTILIZERS OF THE FUTURE

To date, the major fertilizer sources of sulfur have been single superphosphate and sulfate of ammonia (Fig. 4). They have generally been used as primary nitrogen and phosphorus sources with sulfur applied incidentally.

Where sulfur deficiency has been recognized and fertilizers have been used to correct the deficiency, elemental sulfur and gypsum ($CaSO_4 \cdot 2H_2O$) are two of the major sources used.

According to data on new fertilizer production facilities (Table 4) (FAO 1975), the trend away from sulfur-containing phosphorus forms of fertilizer is likely to continue at least until 1980. The data show that phosphorus production will increase by 1.19 million, while sulfur usage in these forms will increase by only 36,216 t. The changes in consumption are a major contributing factor to the increased incidence of sulfur deficiency.

Future sulfatic fertilizers for the tropics

In tropical areas of the world, capacity has been established to produce large quantities of urea, triple superphosphate, monoammonium phosphate, and diammonium phosphate, which are devoid of or low in sulfur. It seems that future

Table 4. New fertilizer production facilities to start or planned to start production before 1978 in tropical areas of the world (FAO 1975).

Region	Planned production capacity (t P)			
	Phosphoric acid	TSP[a]	Single superphosphate	MAP + DAP[b]
Africa	144,084	0	26,820	0
Central and South America	518,704	52,200	0	0
Asia	433,560	0	0	19,800
Total	1,096,348	52,200	26,820	19,800

[a]Triple superphosphate. [b]MAP = monoammonium phosphate, DAP = diammonium phosphate.

additions of sulfur in tropical agriculture will be primarily as admixtures of sulfur to these four products. Many such products developed to date must be evaluated as multiple nutrient sources under tropical conditions.

Elemental sulfur added to the soil as a fertilizer undergoes oxidation to form plant-available sulfate. Because the process results in increased acidity, there is a need to study this aspect of sulfur fertilization in modified fertilizers to avoid or minimize long-term detrimental changes in soil pH.

The addition of elemental sulfur to triple superphosphate and rock phosphate offers an attractive, low-cost way of adding sulfur to existing fertilizer materials. Rock-phosphate reactions in the field are slow, and it has been demonstrated (Swaby 1975) that mixtures of rock phosphate and elemental sulfur are successful in increasing the phosphorus release rate from rock phosphate under tropical conditions. Formulations of this material with different rock sources should be made and evaluated as phosphorus and sulfur sources under tropical conditions.

The reactions of triple superphosphate with soil constituents are rapid, and often the applied phosphorus is fixed into less available or unavailable plant forms before an active plant root system has been developed. Coating triple superphosphate granules with elemental sulfur would slow the release rate of phosphorus from the granules. In addition, it will supply sulfur to the plants. Sulfur-coated fertilizer material should be developed and tested under tropical conditions.

Experiments in Indonesia (Blair et al 1979b) have shown that elemental sulfur is a satisfactory source of sulfur for flooded rice. Not enough is known of sulfur transformations in rice paddies in the presence of plants. Basic studies should be conducted to evaluate elemental sulfur for rice and to evaluate the nutritional value of sulfur in sulfur-coated urea.

Because of the wide and varied range of available sulfur-containing fertilizers and the problems inherent in the use of triple superphosphate and rock phosphate in tropical soils, modifications to existing sulfatic fertilizers rather than radical new developments may be expected. The materials developed must be evaluated in the tropical environment, in tropical soils, and with tropical plants.

Research priorities

There is a paucity of information concerning sulfur in the tropics and this review suggests five areas of sulfur research that should be undertaken:

1. Coordinated investigations of the effect of sulfur fertilization on the yield and quality of tropical crops and pastures;
2. Reactions to fertilizer sulfur in upland and wetland soils to determine the agronomic effectiveness, residual value, and long-term effects on soil pH;
3. Chemical methodology of sulfur analysis in soils and plant tissues;
4. Differences in tolerance for sulfur deficiency within and between species, to reduce the need for sulfatic fertilizer; and
5. Ways of incorporating sulfur into fertilizers that tropical countries are committed to, e.g. urea, triple superphosphate, rock phosphate, and ammonium phosphate.

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Potassium deficiency in soils of the tropics as a constraint to food production

G. KEMMLER

With the change to intensive cropping with high yielding cultivars, the potassium requirement of plants increases and application of potassium fertilizers becomes necessary in areas where potassium deficiency was not a problem.

Generally speaking, available potassium is lower in soils in the humid tropics than in those in the semiarid tropics because of more intensive weathering and continuous leaching in the humid tropics. Sandy soils and soils with predominantly kaolinitic clay may show a fair level of exchangeable and soil solution potassium, but potassium buffering is poor; thus, high yields can be maintained only with repeated potassium application. Heavy soils with illite and montmorillonite types of clay usually have a high content of exchangeable potassium and a low but well-buffered potassium concentration in the soil solution. They provide the plants with large amounts of potassium, even from nonexchangeable sources. When the soils are exhausted, they need heavy rates of fertilizer potassium to overcome fixation. Effective availability of potassium is reduced by low soil moisture, high pH, and, in submerged paddies, by strongly reducing soil conditions.

As potassium deficiency of soils growing food crops is aggravated under intensive cultivation, response to potassium application is observed notably in long-term fertilizer experiments. Responses to potassium have likewise been obtained in numerous field trials with irrigated and rainfed crops. To identify soils and crops that need potassium fertilization for increased food production, modifications of soil tests (or soil test interpretation) and soil test-crop response studies are suggested.

Bünteweg 8, 3000 Hannover 71, Federal Republic of Germany.

WITH THE CHANGE TO more intensive farming and the introduction of modern varieties in the tropics, the potassium requirements of crops have increased. In many cases, potassium needs can no longer adequately be met by the supply from the soil.

In the soil four fractions of potassium are usually distinguished (Wiklander 1954).

1. potassium as a structural element of soil minerals,
2. fixed (or nonexchangeable) potassium,
3. exchangeable potassium, and
4. potassium in the soil solution.

Fractions 3 and 4 are often called *available* potassium.

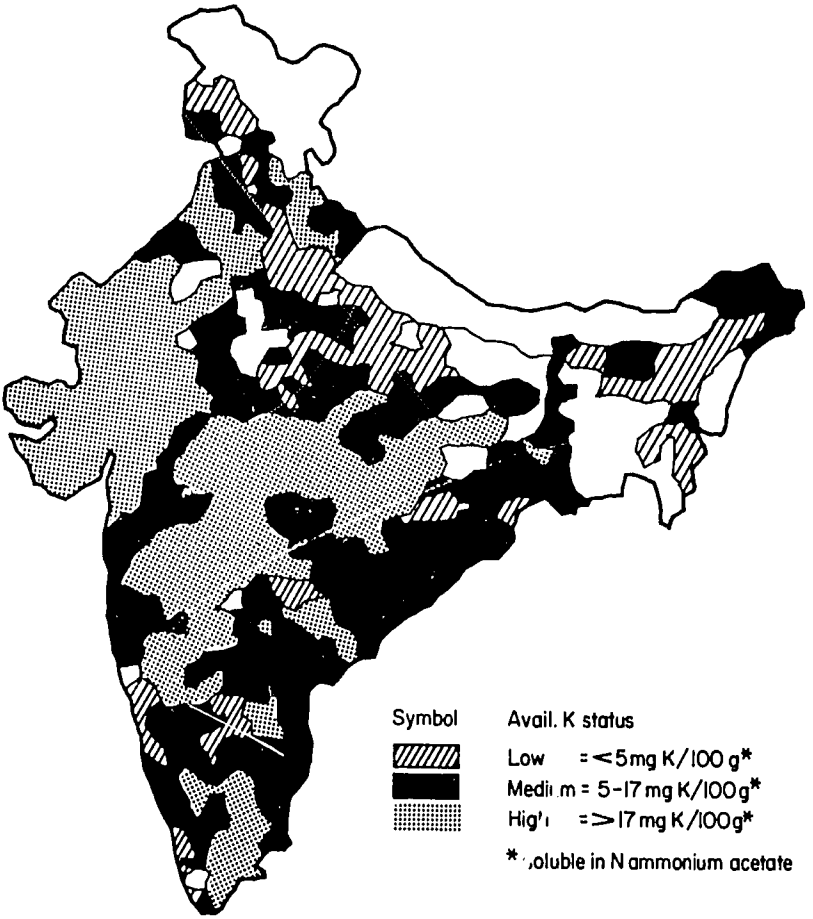
POTASSIUM STATUS OF TROPICAL SOILS

Detailed information on soil potassium in tropical Asia is available for India (Ghosh and Hasan 1975), Southeast Asia (Kawaguchi and Kyuma 1977), and China. In most cases the available, or exchangeable, potassium is extracted by ammonium acetate. The value obtained is not sufficient to describe the status of potassium availability in soils that differ in texture and clay composition, but the graphs and tables contained in the publications cited give an idea of the geographical extent of potassium deficiency. Table 1 shows the soil test rating in the three areas. Figure 1 is a reproduction of the map by Ghosh and Hasan

Table 1. Potassium status of tropical soils based on soil tests in India, Southeast Asia, and China.

Status of available K	India (N ammonium-acetate) (kg K/ha = mg K/100 g soil)		Southeast Asia[a] (N ammonium-acetate) (meq/100 g = mg K/100 g soil)	
Very low				
Low	<110	<5	<0.15	<5.9
Medium-low			0.15–0.30	5.9–11.7
Medium	110–280	5–17	0.30–0.45	11.7–17.6
Medium-high				
High	>280	>17	0.45–0.60	17.6–23.4
Very high			>0.60	>23.4
Status of available K	**China[b] (N ammonium-acetate) (mg K_2O/100 g = mg K/100 g soil)**		**China[c] (boiling N HNO_3) (mg K_2O/100 g = mg K/100 g soil)**	
Very low	<4	<3.3	<8	<6.6
Low	4–8.3	3.3–6.9	8–20	6.6–16.6
Medium-low			20–40	16.6–33
Medium	8.3–15	6.9–12.5	40–60	33–50
Medium-high			60–90	50–75
High	15–20	12.5–16.6	90–140	75–116
Very high	>20	>16.6	>140	>116

[a]Kawaguchi and Kyuma 1977. [b]Nanking Institute of Soil Science 1978. [c]Nanking Institute of Soil Science, unpublished.



1. Available potassium status of Indian soils (Ghosh and Hasan 1975).

(1975) on the available potassium status of Indian soils. Of the 310 districts for which soil test information was available, 20% were classified as low in available soil potassium, 53% as medium, and 27% as high.

Table 2 gives a summary of exchangeable potassium in paddy soils of Southeast Asia (Kawaguchi and Kyuma 1977). Although the number of samples analyzed was too small to allow definite conclusions, the table indicates that Bangladesh, Cambodia, Sri Lanka, and Thailand have areas of rice-growing soils with very low contents of exchangeable potassium.

The map of China (Fig. 2) on the status of slowly available potassium (Nanking Institute of Soil Science, unpubl.) shows clearly that soils in the tropical

Table 2. Exchangeable potassium in paddy soils of some Asian countries.[a]

Country	Samples (no.)	Mean exchangeable K (mg/100 g soil)	Standard deviation	Exchangeable K (mg/100 g soil)	
				Min	Max
Bangladesh	53	11.7	7.8	tr	31.2
Burma	16	15.6	7.8	3.9	27.3
Cambodia	16	7.8	7.8	tr	31.2
Indonesia	44	15.6	11.7	3.9	46.8
W. Malaysia	41	15.6	15.6	3.9	70.2
Philippines	54	19.5	11.7	3.9	66.3
Sri Lanka	33	7.8	7.8	tr	27.3
Thailand	80	11.7	15.6	tr	101.4
Total or mean	337	13.26	10.92	3.9	50.31

[a]Source: Kawaguchi and Kyuma 1977.

areas with high rainfall and intensive farming (3 or more crops/year) have very low to low potassium contents.

Potassium availability as related to climate and soil

Generally speaking, soils in the humid tropics will have less of available potassium than soils in semiarid or arid areas. That is a result of more intensive weathering, leaching of nutrients into lower layers, or their complete loss (Pagel 1972).

In a climatically uniform region, the soil potassium status varies according to the composition of the parent material. Soils derived from sandstone consisting mainly of quartz are very deficient in potassium, while sandy soils of young volcanic origin may have a high content of available potassium.

Oxisols of the humid tropics (ferrallitic soils) are usually deficient in available potassium (Boyer 1972). In China, soils classified as Latosols and Lateritic Red Soils (Nanking Institute of Soil Science 1978) have low to very low contents of slowly available potassium (soluble in N HNO_3) as indicated in Figure 2.

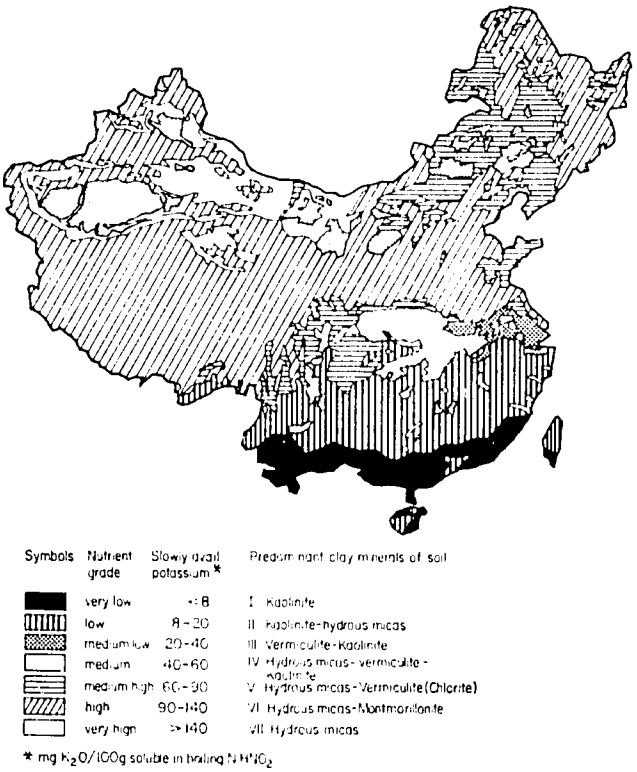
Fifty-eight samples of ferrallitic soils (Oxisols) from Ghana and Tanzania (Pagel 1972) showed average values of exchangeable potassium around 8.2 mg/100 g soil. They did not differ too much from other soils, but their poor potassium supplying power is demonstrated by a comparison of their values for slowly available potassium with those of soils from other climatic areas (Table 3).

Apart from the Oxisols, the soils of the semihumid to semiarid tropical regions, particularly those continuously cropped, may also develop potassium deficiency (Kanwar 1972, 1974).

In the case of hydromorphic soils additional factors, which influence the availability of potassium, come into play.

Potassium availability as related to soil texture and clay mineral composition

Soil test values, such as of exchangeable potassium, often do not correlate well with crop responses in field experiments, notably when soils differ in clay con-



2. Status of potassium nutrient in the soils of China.

Table 3. Average contents of exchangeable[a] and slowly available[b] potassium in some soils of the humid and arid tropics.[c]

Soils (no.)	Kind of soil (country of origin)	pH	Clay (%)	CEC (meq/ 100 g)	Exchangeable K mg/ 100 g	Exchangeable K CEC (%)	HNO_3– soluble K (mg/100 g)
73	Arid and subarid soils (Yemen, Sudan)	7.4	12.9	19.4	25.7	3.4	126.5
29	Vertisols, Paravertisols (Sudan, Cuba, Ghana)	7.0	40.2	39.0	11.3	0.7	33.7
33	Ferrallitic and similar soils (Sri Lanka, Cuba, Ghana, Zanzibar)	6.0	27.0	12.2	10.2	2.1	20.8
58	Ferrallitic soils – Oxisols (Ghana, Tanzania)	4.5	32.3	10.2	8.2	2.1	8.8
15	Rendzina-type soils – Rendolls (Zanzibar, coral-limestone)	6.8	14.9	27.1	8.6	0.8	25.2

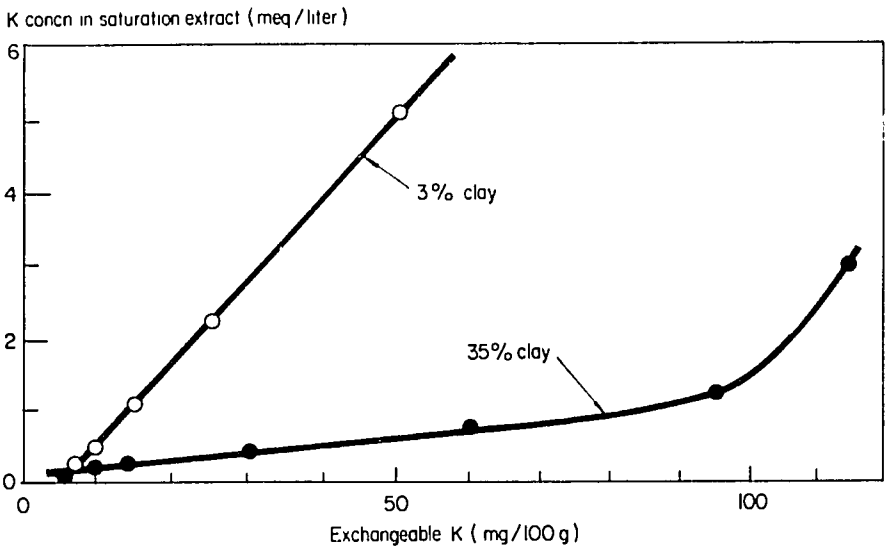
[a]N ammonium acetate-soluble. [b]Soluble in boiling N HNO_3. [c]Source: Pagel 1972.

tent and clay composition (Jankoviç and Németh 1974, Kemmler 1974a, Goswami et al 1975, Grimme 1975). This is not surprising. Plant roots take up nutrients from the soil solution. As the potassium concentration in the solution increases, more potassium ions can reach the plant roots within a given time and the amount of potassium ions that can be taken up by the plant increases (Grimme et al 1971, Jankoviç and Németh 1974, Németh 1975).

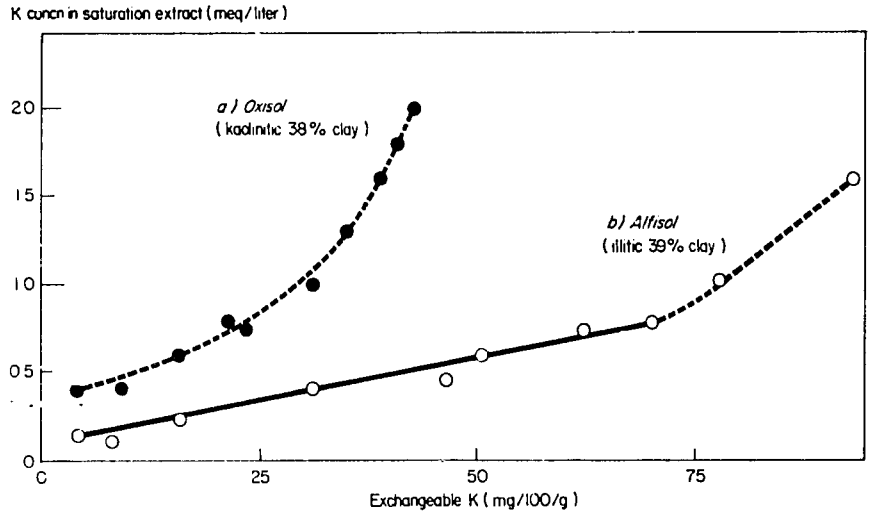
But the soil solution concentration is not simply a function of exchangeable potassium. Figure 3 shows exchangeable potassium versus potassium concentration for two soils that differ in clay content but not in clay composition (Grimme et al 1971). At equal content of exchangeable potassium, e.g. 20 mg K/100 g soil, the clay soil has a much lower potassium concentration in the soil solution than the sandy soil.

The relationship illustrated in Figure 3 refers to soils with mica-derived clay minerals (illite type) which adsorb potassium selectively (Schouwenburg and Schuffelen 1963). Soil montmorillonitic clays – as opposed to pure montmorillonite – have a selectivity similar to that of illitic clays (Schwerdtmann 1962). This is especially true of the montmorillonites in Vertisols.

Kaolinitic clay minerals, on the other hand, have no specific binding sites for potassium and show a low cation exchange capacity. Thus, they are similar to sand and soil organic matter as far as their behavior toward potassium is concerned. They have, however, a higher water-holding capacity and, therefore, do not obtain as high potassium concentrations as sandy soils. Figure 4 shows the change of potassium concentration in the soil solution with increasing exchangeable potassium in two soils of similar clay content but with different clay minerals (Németh 1971).



3. Change of potassium concentration in the soil solution with increasing exchangeable potassium in two soils differing in clay content.



4. Change of potassium concentration in the soil solution with increasing exchangeable potassium in two soils differing in clay mineralogy (source: Németh 1971).

Most soils contain a mixture of clay minerals. Even in lateritic soils in India illites have been found, in addition to kaolinite, as dominant clay minerals (Mohanti et al 1974).

In most cases, therefore, the soil test ratings mentioned in Table 1 should be modified to consider the clay content (or the inorganic cation exchange capacity) and possibly other parameters, as outlined in the following sections.

BUFFERING, RELEASE OF NONEXCHANGEABLE POTASSIUM, AND POTASSIUM FIXATION

Buffering

The concentration of the soil solution is an important characteristic of the effective nutrient availability. But it is only an indicator of momentary availability. For optimal crop production the important factor is whether the concentration of the soil solution decreases rapidly during the growing period or is maintained at a fair level, i.e. well buffered (Németh 1972). Sandy soils show poor potassium buffering even though their initial potassium concentration may be high. Clay soils possess a better potassium buffering capacity; they can maintain the potassium concentration of the soil solution at a similar level for a long time. Thus, the optimum concentration of potassium in the soil solution can be lower in a clay soil (containing illite or montmorillonite) than in a sandy soil.

Release of nonexchangeable potassium

The soil solution potassium may be replenished from exchangeable and nonexchangeable potassium sources. In the immediate vicinity of plant roots, the

potassium concentration of the soil solution can become extremely low. If the transport rate of potassium from the adjacent soil is not sufficient to meet the uptake requirements of the plants at the time of fast vegetative growth, non-exchangeable potassium will be the source of potassium (Mengel 1978).

These phenomena may explain the apparent contradiction between:

- the observation that the uptake of originally nonexchangeable potassium can be a major factor in crop production (Scheffer et al 1960, Grimme 1974, Singh and Brar 1977), and
- the finding that plants take up their nutrients from the soil solution and that the uptake rate depends on the nutrient concentration of the solution (Mengel et al 1969, Nye 1972).

The rate of potassium release from the nonexchangeable fraction is rather low – diffusion coefficients for release of potassium from minerals are in the order of 10^{-15} to 10^{-23} cm^2/second against 10^{-6} to 8^{-8} cm^2/second in the moist or dry soil (Nye 1972). Thus the supply from this source is not sufficient to sustain high crop yields.

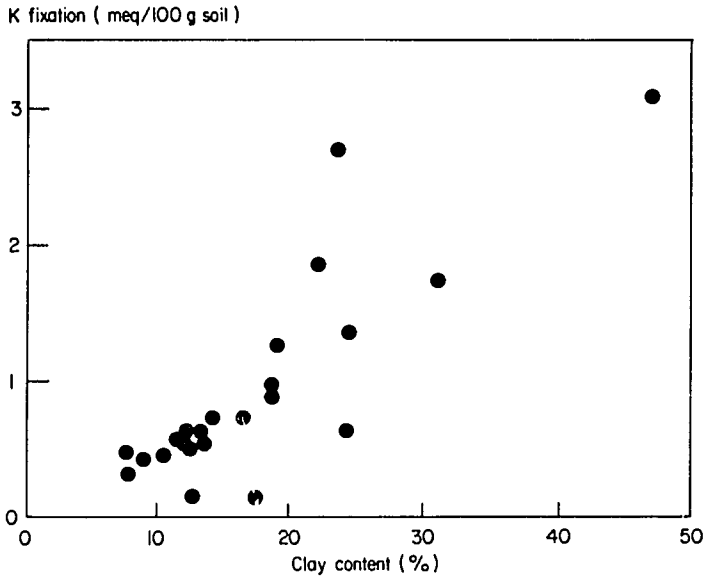
Reliance on the release of nonexchangeable potassium leads to gradual decline in soil fertility (von Boguslawski and Lach 1971, Singh and Brar 1977). Potassium-depleted minerals represent a strong sink for soluble potassium, and as soon as the competition of the plant roots for soluble potassium is stopped, the potassium-depleted minerals will remove potassium from the soil solution (Mengel 1978). This can lead to strong fixation of applied potassium.

Potassium fixation

Considerable research on potassium fixation in India is summarized by Grewal and Kanwar (1973). Generally, soils containing clay minerals of high selectivity for potassium, such as illite, fix potassium more strongly than sandy soil or soils with kaolinite as the dominant clay mineral. According to Mitra et al (1958) pure clay minerals fixed potassium as follows:

- Bentonite – 9.98 meq/100 g
- Illite – 10.93 meq/100 g
- Kaolinite – 0.33 meq/100 g

The relationship between clay content and potassium fixation in 23 soils of Punjab, Haryana, and Himachal Pradesh, India, with illites as dominant clay minerals, is shown in Figure 5. Drying favors potassium fixation. Various Indian authors found highest values for potassium fixation after alternate wetting and drying of soils (Grewal and Kanwar 1973). As NH_4^+ and H^+ (H_3O^+) are very similar to K^+ in ionic radius, both ions can compete with potassium for fixing sites in the clay minerals (Bartlett and Simpson 1967, Rich and Black 1964). Accordingly, several Indian researchers who determined potassium fixation by various soils after saturation with different cations found lower values for K fixation in H- and NH_4-soils and higher values in Ca-, Mg-, and Na-soils (Grewal and Kanwar 1973). These results explain why K fixation is usually less important in acid soils than in neutral or alkaline soils.



5. Relation between clay content and potassium fixation in 23 soils of Punjab, Haryana, and Himachal Pradesh, India (Grewal and Kanwar 1967).

Fixation of potassium can be of considerable importance in agricultural practice. A fixation capacity of 1 meq K/100 g in a soil containing 20% clay (Fig. 5) means that the soil has the capacity to fix more than 1,000 kg K_2O/ha. Poor responses to potash application on potassium-deficient soils may be due to the high potassium fixation capacities of those soils (Grewal and Kanwar 1973). To obtain satisfactory yields on such soils, high fertilizer rates are required to overcome the fixation of potassium by the clay minerals.

INFLUENCE OF SOIL MOISTURE, pH, AND OTHER NUTRIENTS ON EFFECTIVE POTASSIUM AVAILABILITY

Soil moisture

According to Nye (1972), diffusion is the main factor for the transport of potassium toward the roots. That it is strongly influenced by soil moisture was confirmed in laboratory experiments where potassium diffusion took place from the soil into an ion exchanger (Grimme et al 1971). In moist soils, diffusion rate was higher, potassium depletion greater, and the distance of potassium movement longer than in drier soils. At an equal level of exchangeable potassium, therefore, the effective availability of potassium is higher at optimum soil moisture.

To find the influence of different soil moisture levels on potassium availability to corn plants, a split root technique was used to measure variations in potassium availability caused by variations in soil water content but without subjecting the plants to moisture stress (von Braunschweig and Grimme 1973). At each of the potassium levels tested, potassium uptake (and corn yield) increased with increasing soil moisture. Because all growth factors except potassium availability were kept constant, the differences were attributed solely to the effect of soil moisture on potassium availability. The reduction of potassium availability caused by low water content could be compensated by increasing the potassium concentration in the soil solution. The soil water contents applied, between 20 and 40% (by volume), and corresponding to water tensions of 0.1 to 0.5 bar, would be well within the limits of good water supply. Thus, the nutrient transport in the soil is already reduced at moisture levels at which plants do not suffer from water shortage (Mengel and von Braunschweig 1972).

pH

Soil pH has a definite influence on potassium availability. At equal levels of exchangeable potassium (or potassium saturation of the inorganic cation exchange capacity [CEC]), the potassium concentration of the soil solution decreases with an increase in the pH in soils with illitic clay minerals (Németh and Grimme 1972, 1974a). Thus, liming to correct soil acidity (up to about pH 6) reduces the effective availability of potassium in these soils. This is due to an increase not only of the effective CEC but also of the number of K-selective sorption sites, occupied by Al-hydroxo-polymers at lower pH.

Other nutrients

Application of mineral fertilizers increases concentration of all cations in the soil solution, including some not added with fertilizer. The concentration of magnesium in the soil solution is increased by potassium fertilizer application (Németh and Grimme 1975). This does not contradict the observation of potassium-magnesium antagonism, which occurs in soils deficient in available magnesium (Kansal and Sekhon 1974, Randhawa and Pasricha 1975), notably when such soils have a low effective CEC as, e.g., many Oxisols and Ultisols in Latin America (Villachia 1978). In any case, the magnesium and calcium content in the plant decreases with increased potassium availability in the soil. Plants are able, however, to take up sufficient magnesium and calcium, even in the presence of a high potassium level, provided that the magnesium and calcium supply meets plant requirements (Grimme et al 1974, Johansson and Hahlin 1977).

POTASSIUM AVAILABILITY IN SUBMERGED RICE SOILS

It is well-known that potassium availability increases after soil flooding (Ponnamperuma 1964) because the conditions for nutrient mobility are more favorable than in a dryland soil. Gorantiwar et al (1973) found the following amounts

of available potassium (Olson) after the cultivation of rice: 17 mg/100 g in a submerged soil, 23 mg in a soil of 0 bar water tension, 33 mg in a soil of 0.7 bar water tension (where plant growth had been very poor).

The increase in potassium availability in a flooded soil results in higher potassium uptake by the rice plants, compared with uptake in dryland soils. Consequently potassium exhaustion in submerged soils will be faster.

Some potassium is supplied with the irrigation water, but it cannot replace a fertilizer treatment, considering the potassium requirement of high-yielding rice varieties. Irrigation water potassium has the effect of saving potassium because it helps compensate for losses due to leaching or runoff.

In submerged soils the uptake of potassium can be impaired by reduction processes in the rhizosphere if such processes lead to the accumulation of hydrogen sulfate, butyric acid, and other products of anaerobic fermentation. These substances impede the respiration of the roots and, consequently, hinder the absorption of nutrients. Physiological disorders, such as Akiochi or Akagare, are closely related to potassium deficiency (Baba 1963, Takahashi 1970, Park et al 1970).

Because of their oxidizing power, healthy rice roots have the ability to raise the redox potential in the rhizosphere, causing precipitation of Fe^{3+} at the root surface. Under strongly reducing conditions and high concentrations of Fe^{2+} in the soil solution, the roots may lose their iron excluding power so that the rice plants suffer from iron toxicity (bronzing). According to Tanaka and Tadano (1972), potassium deficiency reduces the iron excluding power of rice roots. This can be explained by the findings of Trolldenier (1973, 1977) that the oxidizing power of the rice root largely depends on the potassium supply of the crop.

CROP, YIELD LEVEL, AND CROPPING INTENSITY AS FACTORS OF POTASSIUM DEFICIENCY OR SUFFICIENCY

Many crops take up similar or higher quantities of potassium than of nitrogen (Table 4). For some crops the potassium requirements are especially high, e.g. root and tuber crops, vegetables, and fruits such as banana and pineapple. As long as yield levels are generally low, potassium will be a limiting factor only on soils inherently deficient in potassium. On other soils, yields of 1 t wheat/ha or 2 t rice/ha can be obtained continuously without applying any potash fertilizer. This is one reason a high percentage of early fertilizer experiments in the tropics did not show a significant response to potash application.

However, with a gradual increase in farming intensity, and the introduction of high yielding varieties, plus the increase of nitrogen fertilizer application and other yield improving inputs, potassium deficiency becomes noticeable in areas and on soils previously considered as well supplied with potassium (Kanwar 1974; von Uexküll 1976, 1978).

The amounts of plant nutrients contained in grain and straw at harvest time are usually lower than at the time of maximum dry matter production. This is

Table 4. Uptake of plant nutrients by some cereal crops based on kilogram nutrients per hectare contained at harvest in grain plus straw.

Crop and country	Grain yield (t/ha)	Nutrient uptake (kg/ha)				Source
		N	P_2O_5	K_2O	MgO	
Wheat						
India						
Local	3.0	80	39	90		Roy and Seetharaman 1977
Kalyan Sona (5 places)	5.0	109	42	182		"
Sonalika (4 places)	5.0	117	48	173		"
Germany	6.0	165	72	155	29	Sturm and Jung 1973
Maize						
India	2.7	114	47	105		FAI 1978
Nigeria	4.4	142	30	106		Bromfield 1969
India	5.0	134	51	107		Khera and Tyagi 1972
France	8.0	175	75	150	35	Loué 1963
USA	9.5	187	85	230	40	Barber and Olson 1968
Rice (paddy)						
India						
Tall	2.8	82	23	123		FAI 1978
Padma, kharif	5.0	87	22	140		" "
Jaya, "	6.1	84	25	147		" "
IR8, "	6.3	95	25	149		" "
Korea	5.0	103	23	117		Kim and Park, 1969, pers. comm., Institute of Plant Environment, Office of Rural Development
Sorghum						
India	1.1	52	18	86		FAI 1978
Niger	1.8	89	19	132	30	Bertrand et al 1972
USA	9.0	207	90	289	24	Vanderlip 1974

particularly true for potassium. Because of leaching and leaf fall, a wheat crop in England lost, by harvest time, half or more of the potassium contained in the plants at flowering (Cooke 1972). Most crucial for cereals is the time just before flowering, when the daily uptake by high yielding rice, corn, or wheat may amount to 2–6 kg K_2O/ha (Mengel and Kirkby 1978, Kemmler 1974b). If the soil cannot maintain that rate of supply, there will be poor grain filling. After flowering an interruption of potassium supply has no detrimental effect on grain yield (Forster 1973).

Another aspect of the potassium supply for cereal plants is that most of the potassium contained in the crop at harvest time is present in the straw. In countries like China where the straw is used for the preparation of compost, its potassium content plays a major role in the nutrient supply to the following crop. In countries like Bangladesh, India, or Pakistan where the straw is used mostly as cattle feed and the cow dung later used as fuel, the supply of potassium becomes a constraint to higher yields unless potassium is added in the form of mineral fertilizer.

POTASSIUM RESPONSE IN FIELD EXPERIMENTS

To pinpoint the areas where potassium deficiency is a problem, and the crops that may respond to the application of potassium fertilizer, many countries use soil testing and fertilizer trials. In many cases, annual trials show a fair response to the application of nitrogen, but the response to phosphorus and potassium becomes visible only in the second or third year of experimentation when the amounts easily available in the soil have been exhausted by increased plant growth, accelerated by the repeated application of nitrogen.

Long-term trials

Fertilizer experiments carried out over 5 to 10 years are needed to find out the gradual changes in soil fertility that make the application of potassium necessary, even on soils where it is initially well supplied. The following examples with irrigated wheat from India and paddy rice from the Philippines illustrate the change. The four sites (Table 5) comprise soils of low to very high potassium availability status.

In the wheat experiment at Ludhiana, India, on alluvial sand of low potassium status, response to 37.5 kg K_2O/ha was immediate with 150 kg N/ha and 75 kg P_2O_5/ha. The 5-year average amounted to 15 kg grain/kg K_2O applied (NPK minus NP).

On the New Delhi soil a positive response to fertilizer potassium was obtained from the third year on. The soil was initially classified as medium in available potassium. After 5 years of intensive cropping without potassium application, the ammonium acetate-soluble soil potassium had dropped to 5.9 mg K/100 g or a potassium saturation of 1.4%. In the NPK-treated plots, the potassium status gradually improved (Table 6).

On the Vertisol of the Rice Research and Training Center, Maligaya, Philippines, rice would not be expected to respond to potassium application because of an initial soil analysis of 17.8 mg available K/100 g soil. However, on this

Table 5. Soil potassium status and response to potassium application at four long-term experiments in India and the Philippines.[a]

	Ludhiana (India)	New Delhi (India)	Maligaya (Philippines)	IRRI (Philippines)
Clay content (%)	7	14	46	48
CEC[b] (meq/100 g)	5.1	10.6	36	45
Initial available K (N ammonium acetate, mg/100 g)	4.0	7.1	17.8	60.2
K saturation (%) of CEC	2.2	1.7	1.3	3.4
Crop	Wheat	Wheat	Rice	Rice
K response in 1st year	yes	no	no	no
K response later	yes	yes	yes	no

[a]Source: Kemmler 1978. [b]Cation exchange capacity.

Table 6. Changes of soil potassium status at four long-term experiments in India and the Philippines.[a]

	Ludhiana (India)	New Delhi (India)	Maligaya (Philippines)	IRRI (Philippines)
Initial available K (N ammonium acetate, mg/100 g)	4.0	7.1	17.8	60.2
Available K determined again after	5 yr	5 yr	7 yr	10 yr
Available K at NP plot (mg/100 g)	3.4	5.9	4.3	46.3
Available K at NPK plot (mg/100 g)	5.3	8.2	6.5	47.4
Average fertilizer rate (kg K_2O/ha per crop)	44	40	60	30
Kg N/ha	107	87	105	100
Kg P_2O_5/ha	63	53	60	30
No. of crops/year	3	3	2	2

[a]Source: Kemmler 1978.

heavy clay soil with a CEC of 36 meq/100 g, the potassium saturation amounted to not more than 1.3% of the CEC, indicating a very low potassium concentration in the soil solution. Thus, potassium became a major yield-limiting factor within a few years. In the dry season the response to potassium increased from zero in the first 2 years to 15 kg paddy rice/kg K_2O in the fifth year (De Datta and Gomez 1975). In the treatments without potassium there was a severe deterioration of the potassium status during 7 years of experimentation. In 1974–75 (av of 2 samplings) the available potassium level under continuous NP treatment was as low as 4.3 mg K/100 g soil. Even the application of 60 kg K_2O/ha per crop (2 crops/year) was not sufficient to maintain the original level of 17.8 mg K/100 g (Table 6, personal communication, S.K. De Datta, IRRI).

At IRRI the soil is so high in available potassium and so well buffered with regard to potassium that no response to potassium application has been observed since the initiation of a long-term fertility experiment in 1964–65. However, some decrease in the soil potassium status in the plots with intensive nitrogen treatment has taken place (Table 6).

In view of the importance of long-term fertilizer experiments in determining suitable fertilizer recommendations and in monitoring changes in the soil fertility status, IRRI has started international long-term fertility trials within the International Network on Fertilizer Efficiency in Rice (INFER).

Trials in farmers' fields

In developing countries long-term fertilizer experiments with intensive crop rotations are few. Yet numerous simple trials in farmers' fields for just one season show that, in general, balanced fertilizer application is significantly superior to NP only. In this case potassium deficiency is a constraint to higher yield. The summary of results of trials on irrigated rice in six Asian countries

(Table 7) reveals that potash fertilizers – applied in addition to nitrogen and phosphorus – increased average paddy yields by 4 to 14 kg/kg K_2O. The effects of potassium differ with season (in India, higher in rabi [winter season] than in kharif [summer season]) and with locality (in the Philippines, high on calcareous soils in Mindoro, negative on Vertisols in Iloilo).

The responses of rice to potassium on different soils in India, obtained in such simple trials, are shown in Table 8 (Goswami et al 1975). Responses to potassium were highest on red and yellow soils (Ultisols), and lowest – surprisingly – on lateritic soils (Oxisols).

Under dryland conditions the average response to 30 kg K_2O/ha in 465 wheat trials was 235 kg/ha or 7.8 kg grain/kg K_2O (Goswami et al 1975). The magnitude of response to potassium in nonirrigated agriculture is not surprising, considering the reduced availability of potassium at suboptimum soil moisture conditions.

Similar results as those obtained with rice and wheat have been reported for other food crops (UNDP/FAO 1971, Kanwar 1974, Goswami et al 1975). The importance of potassium as a major yield-limiting factor in root and tuber crops has been known for a long time (Jacob and von Uexküll 1958). Potassium application is indispensable for high yields. The same is true for estate crops such as sugarcane, banana, pineapple, oil, and coconut palm or cocoa cultivated under intensive management (de Geus 1973, Ng 1972, von Uexküll 1972, Mainstone and Thong 1978).

Nitrogen-potassium interaction

In many of the simple trials in farmers' fields, fertilizer nutrients were tested at only one level. In experiments with increasing rates of nitrogen, higher removal figures for potassium are observed (Singh et al 1977). Consequently, strong nitrogen-potassium interactions are expected and have been found in numerous cases (Munson 1970, Loué 1978). Recent results from a long-term experiment at Varanasi, India, were summarized by Singh and Singh (1978). Potassium application increased rice yields at all levels of nitrogen application. However, the responses to potassium were largest at the highest nitrogen rate. At 200 kg N/ha the application of 100 kg K_2O/ha increased the yield by 1 t/ha. But this potassium rate was not sufficient to prevent a gradual decline in the soil status of *available* potassium.

Soil test-crop response studies

Although the results of thousands of field trials suggest that potassium deficiency is widespread in arable soils of the tropics, blanket recommendations of fertilizer potassium application are not useful. Even recommendations based on soil tests may be misleading. The average response to 90 kg K_2O/ha applied to rice in 59 trials – kharif 1971–72 in five Indian districts – on heavy soils was much larger (728 kg vs 398 kg/ha) on soils testing high in available potassium than on soils with a medium potassium status (Kemmler 1974a). The opposite result would

Table 7. Response of irrigated rice to potassium in farmers' fields in some Asian countries.

Country	Trials (no.)	Treatment (kg/ha)			Response to K over NP		Source
		N	P_2C_5	K_2O	Kg grain/ha	Kg grain/ kg K_2O	
Pakistan	540	60–150	60– 80	60– 80		4.6	UNDP-FAO (1971)
India	1573	120	60	60			Kanwar et al (1973)
kharif					279	4.6	" " " "
rabi					493	8.2	" " " "
Bangladesh	1908	40–120	40– 80	30– 80		5.9	UNDP-FAO (1971)
Sri Lanka	20	100–150	100–150	50–150	520	5.2	FAO-FFHC (1969)
Indonesia	87	120	45	30	428	14.3	Personal communication BIMAS/INMAS 1979
Philippines	541	69	30	30		3.6	Personal communication FAO 1977
Oriental Mindoro	92					16.2	Personal communication FAO 1977
Iloilo	85					–6.6	Personal communication FAO 1977

Table 8. Response of rice to potassium in India, by soil class, kharif season 1968–69 to 1973–74.[a]

Soil class	Trials (no.)	Av yield (t/ha)		Response to potassium	
		No fertilizer	NP[b]	Kg grain/ha[c]	Kg grain/ kg K_2O
Alluvial	675	2.37	4.17	234	3.9
Red and black	419	3.59	5.49	218	3.6
Medium black	301	2.92	3.89	280	4.7
Red	349	3.12	5.16	311	5.2
Red and yellow	282	3.14	4.77	400	6.7
Coastal alluvial	412	3.05	4.59	266	4.4
Lateritic	556	3.58	5.13	174	2.9

[a]Source: Goswami et al 1975. [b]N = 120 kg/ha, P_2O_5 = 60 to 120 kg/ha. [c]K_2O = 60 kg/ha.

have been expected. Careful examination of crop response in relation to soil test data is necessary and already done in the on-going projects of long-term fertilizer experiments.

SUGGESTED APPROACHES TO SOLVE POTASSIUM DEFICIENCY PROBLEMS

Modifications of soil interpretation

As discussed earlier the usual soil analysis does not satisfactorily describe the actual availability of potassium. Information on the exchangeable potassium status (quantity) does not reveal anything about the potassium concentration in the soil solution (intensity). To improve soil test interpretation, the soil analysis report should at least contain details on soil texture, better clay content (or clay plus silt), inorganic CEC (as an indicator of clay mineral composition), and pH. As an example, the potassium soil test rating chart for southwest Germany (Staatl. Landw. Untersuchungs- und Forschungsanstalt Augustenberg 1977) is shown in Table 9. The classification of the values for sandy soils (<10% clay) corresponds more or less to the rating by Kawaguchi and Kyuma (Table 1). A clay loam (>25% clay) with a soil potassium level of 12 mg K/100 g would be rated as *low*; a sandy soil with the same level would be *high* in available potassium. Determination of the nonexchangeable potassium would provide information on the potassium reserves (Table 3).

The only method, to my knowledge, which provides a thorough insight into the potassium dynamics (and that of other nutrients) of soils is the method of electro-ultrafiltration (Németh 1972, 1978, 1979). It measures the desorption rate and its change with time by applying an electric field to an aqueous soil suspension. From the results one can infer the potassium concentration in the soil solution, the quantity of exchangeable potassium, potassium fixation, buffering, and potassium reserves. With this method some data concerning tropical soils are already available (Németh and Grimme 1974b, Thiagalingam and Grimme 1976).

Table 9. Potassium soil test rating for arable soils in southwest Germany in relation to soil texture.

Rating	Potassium content (mg K/100 g soil)[a] in soils with clay content[b] of		
	<10%	10–25%	>25%
Low	0– 6	0– 9	0–12
Medium	7–10	10–21	13–25
High	11–21	22–33	26–41
Very high	>22	>34	>42

[a]Extracted with calcium acetate lactate solution. [b]Potassium selective clay minerals predominant.

To obtain a fair picture of the potassium status of important agricultural regions, projects of systematic soil mapping are suggested, using the modified soil test criteria.

Soil test data must be calibrated by field experiment before they can be utilized for fertilizer recommendations. This should be done in replicated long-term trials conducted on permanent sites, with the same treatments applied to the same plots throughout the rotation for several years. Determination of the soil potassium status in each of the treatment plots before the experiment and in consecutive years permits the monitoring of changes in soil potassium availability caused by continuous application or nonapplication of potassium.

A further step in soil test-crop response correlation studies would be the establishment of a potassium fertility gradient and subsequent determination of crop response to additional potassium application.

Adjusting potassium applications to crop requirement

Because potassium is the cheapest of the three major plant nutrients, its application is profitable wherever a yield response is observed. On those soils and for those crops where the beneficial effect of potassium fertilization on the yield has been established, experiments on levels and timing of the potassium application should be carried out. On light soils and under heavy rainfall, splitting of the potassium doses is advisable to avoid leaching losses and to secure best utilization of the fertilizer potassium. On potassium-fixing clay soils, placement of potassium and splitting of higher potassium rates should be tried as a possible solution.

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Micronutrients in soils of the tropics as constraints to food production

A. S. LOPES

Although micronutrients have been the subject of many studies, their role in food crops production in the tropics has not been evaluated in a systematic and definitive way. In most of the studies, lack of precise soil characterization prevents extrapolation of the results within and between soil groups. In many cases, only local names are given to the soil, or sometimes only the test site, pH, organic matter, and texture are presented as background characterization. Broad generalizations can be made only on the geographic distribution of micronutrient-related constraints to crop production and only limited ones on their extent in broad soil orders.

Zinc deficiency is definitely a serious limitation to food crops production on *campo cerrado* soils in Brazil and soils from the *llanos orientales* in Colombia. Relatively low rates of zinc fertilizers are necessary to overcome this limitation.

Alkaline soils from Colombia (Mollisols) have shown severe deficiencies of boron and zinc. Acid Ultisols from the Amazon jungle in Peru can present limitations in boron, copper, and molybdenum, but 3 kg copper and 1 kg molybdenum/ha + lime, nitrogen, phosphorus, potassium, sulfur, and magnesium have been adequate for the change from shifting cultivation to improved agriculture, with reasonable yields of rice, soybean, and corn. In volcanic ash soils (Andosols) in Latin America micronutrient deficiencies, mainly molybdenum, increase on the older soil.

Calcareous soils in Africa are very responsive to iron fertilizers; however, studies on sources and rates are lacking. Molybdenum deficiency is a serious limitation identified in Africa, mainly in acid sandy

Departamento de Ciencias do Solo, Escola Superior de Agricultura de Lavras, Caixa Postal 37, 37.200 Lavras, M.G., Brazil.

soils and organic soils in northern Senegal, Ghana, northern Nigeria, and Egypt.

Micronutrient evaluation for wetland rice in Asia is more advanced than for other food crops. Knowledge of the kinetics of micronutrients in wetland soils has led to considerable improvement of micronutrient deficiency and toxicity problems. Zinc deficiency is probably the most widespread micronutrient disorder for wetland rice in the tropics. It is primarily associated with the calcareous soils in India, Pakistan, Japan, and the Philippines. Zinc deficiency is also common in Mollisols for other food crops in India. Iron deficiency is widespread in calcareous and alkali soils and flooded soils where organic matter is too low to produce soil reduction. Iron toxicity occurs in wetland rice when certain highly weathered acid Oxisols, Ultisols, or Sulfaquepts are flooded. Under practical field conditions, only liming, drainage of Oxisols and Ultisols to reoxidize the ferrous iron, or use of tolerant varieties seems satisfactory. Manganese deficiency and toxicity are not considered a problem for rice production in Asia, but information concerning other food crops is meager. Even though flooding increases molybdenum levels in the soil solution, molybdenum application has been shown to be helpful to the nitrogen metabolism in lowland rice.

MOST OF THE AREAS in the tropics have been under traditional agriculture, with shifting cultivation as a major system (Table 1). Under that system the long fallow period in the forested and savanna areas generally regenerate macro and micronutrients sufficient for subsistence crops through the return of plant material.

Once the traditional agricultural system gives way to modern agricultural technology, with high yielding varieties and high rates of macronutrients applied, the need for one or more micronutrients often arises. Evidence of these needs has been obtained for large areas in South America in the *campo cerrado* in Brazil, *llanos orientales* in Colombia, and in the Amazon jungle. In other areas of the tropics a similar trend has recently been observed. The tendency for the use of higher analysis macronutrient fertilizers will accelerate micronutrient needs in the tropics (Sauchelli 1969).

Micronutrient problems in tropical soils in general were reviewed by Drosdoff (1972), and those in tropical Latin America by Cox (1972). The broader aspects of micronutrients in agriculture were extensively covered by Mortvedt et al (1973). Micronutrient limitations in acid tropical rice soils were extensively discussed by Ponnamperuma (1974).

Table 1. Agricultural management systems in the tropics.[a]

System	Area (%)
Nomadic herding	14
Livestock ranching	11
Shifting cultivation	45
Subsistence tillage	12
Subsistence tillage (rice)	5
Plantation agriculture	4
Nonagricultural area	9

[a]Source: Sanchez 1976.

This paper summarizes current information on micronutrients for food crop production in the tropics to:

- identify the occurrence of micronutrient constraints in terms of geographic distribution and soil taxa;
- evaluate the possibility of extrapolation of data between different soil taxa; and
- describe management methods used to correct micronutrient constraints.

GEOGRAPHIC DISTRIBUTION OF MICRONUTRIENT CONSTRAINTS

One of the main points clarified in recent years is that tropical soils are not uniform and, consequently, the macro and micronutrient problems would not be the same all over the tropics. Sanchez (1976) presented a summary of the approximate extent of major soil suborders in the tropics (Table 2).

Despite the considerable variation of soils at the order and suborder levels, it appears that no systematic studies have evaluated the role of micronutrients in food crop production in the tropics as a whole, except for rice production on tropical acid soils (Ponnamperuma 1974) or evaluation of molybdenum and copper in soils of the arid and humid tropics (Prasad and Pagel 1976, Pagel and Prasad 1975).

Considerable responses to micronutrient applications have, however, been obtained in the last decade for various food crops cultivated in different soils and in diverse climates in tropical regions. I present a summary of those results.

TROPICS IN GENERAL

Few studies on a worldwide basis have been conducted to evaluate the general micronutrient status in tropical soils. Most works are restricted to regions within a country or are on a country basis. Estimation of available micronutrients in relation to soil properties that affect their content, with detailed soil description and climatic conditions, can be an adequate approach to extrapolation of scientific knowledge. A series of papers by Prasad and Pagel (1970, 1976) and Pagel and Prasad (1975) gave analytical results for 196 soil samples comprising both

Table 2. Approximate extent of major soil suborders in the tropics.[a]

Order	Suborder	Area (million ha)			Area (%)
		Africa	America	Asia	
Oxisols	Orthox	370	380	0	15.0
	Ustox	180	170	0	7.5
Aridisols	All	840	50	10	18.4
Alfisols	Ustalfs	525	135	100	15.4
	Udalfs	25	15	0	0.8
Ultisols	Aquults	0	40	0	1.0
	Ustults	15	35	50	2.2
	Udults	85	125	200	8.2
Inceptisols	Aquepts	70	145	70	6.0
	Tropepts	0	75	40	2.3
Entisols	Psamments	300	90	0	8.0
	Aquents	0	10	0	0.2
Vertisols	Usterts	40	0	60	2.0
Mollisols	All	0	50	0	1.0
Mountain areas		0	350	250	12.2

[a]Source: Sanchez 1976, from calculations by Drosdoff based on the maps of Aubert and Tavernier (1972).

surface and profiles from different geographical locations (Yemen, Sudan, Tanzania, Ghana, Cuba, and Sri Lanka) and climatic regions (from arid to humid tropics). Besides a complete characterization of the soils involved, they give available zinc by CH_3COONH_4 at pH 4.0, available copper by 0.43 N HNO_3, and available molybdenum by ammonium acetate pH 4.0. The main conclusions of these studies were:

- Available zinc was higher in soils of the humid regions (1.66 ppm) than of the arid regions (0.364 ppm) and tended to decrease in the order of Fersiallitic soils (Alfisols and Ultisols), Ferrallitic soils (Ultisols and Oxisols), Vertisols, and Rendzinas (A-C soils and Aridisols).
- Available zinc showed significant positive correlations with clay (and silt) and humus and negative correlation with pH, exchangeable calcium, sulfur, and T values.
- The average content of available copper decreases in this order: Fersiallitic (9.0 ppm) >Vertisols (6.4 ppm) >Ferrallitic (4.8 ppm) >arid and subarid soils (4.6 ppm) >Rendzina type soils (2.6 ppm).
- Considering sandy soils with <2.0 ppm copper as deficient and loam and clay soils with <1.5 ppm copper as deficient, the percentage of samples with sufficient content would be 84 in Vertisols, 70 in Fersiallitic soils, 65 in arid and subarid soils, 47 in Ferrallitic soils, and 36 in Rendzina-type soils.
- The highest amount of available molybdenum was in arid and subarid soils (0.216 ppm) and in Rendzina-type soils (0.226 ppm). The lowest content (0.045 ppm) was found in Ferrallitic soils of the humid tropics.

- Available molybdenum was significantly positively correlated with soil pH, base saturation percentage, CEC, and exchangeable calcium, and negatively correlated with clay content.
- With 0.14 ppm molybdenum as the critical limit with pH below 6.3, and 0.05 ppm molybdenum with pH above 6.3, the proportion of samples with low molybdenum content was 40% in Vertisols, 64% in Fersiallitic soils, and 89% in Ferrallitic soils. Deficiency of molybdenum was less in arid and subarid soils (24% of the samples).

Manganese forms and their equilibrium in soils from Central America were studied by Fassbender and Roldan (1973) who worked with 62 samples (10 from Guatemala, 10 from El Salvador, 12 from Honduras, 11 from Nicaragua, and 19 from Costa Rica) mainly Fluvisols (21) and Andosols (17). The soils showed little variation with respect to manganese forms. The Fluvisols contained an average of 2.64 ppm water-soluble, 13.18 ppm exchangeable, and 333.0 ppm reducible manganese. Andosols showed corresponding values of 2.64, 13.18, and 333.0 ppm. In general the soil groups showed great variation in manganese content.

Comparison of sources of micronutrients is important for some areas of the tropics where different sources have different commercial values and different agronomic effectiveness. One such case is that of zinc sulfate and zinc oxide, where the zinc sulfate is considerably more expensive in most cases. The effectiveness of zinc sulfate applied and mixed thoroughly with soil was compared with zinc oxide also applied and mixed thoroughly with soil, banded with fertilizer, coated with fertilizer, and coating the seed. Corn was the test crop. There were no significant differences for the first three treatments in relation to yield (greenhouse conditions) and zinc concentration (ppm) in the plant. The soil was a paraferrallitic sand, with pH 4.1, and was limed (1.000 ppm dolomitic lime) to pH 5.6 (Nalovic and Pinta 1972).

LATIN AMERICA

Central Plateau

Zinc. Among the several micronutrients, zinc has one of the most widespread deficiencies in the Central Plateau (*campo cerrado*) area in Brazil (Oxisols, Ultisols, and some Entisols). Responses to zinc fertilizers have been observed in several greenhouse and field studies with various crops (Igue and Gallo 1960, Freitas et al 1960, Britto et al 1971, NCSU 1974, Souza and Hiroce 1970, Santos 1971).

A comprehensive study conducted by Lopes (1975) with 518 tropical soil samples of the *campo cerrado* area (Table 3) indicated a range from 0.2 to 2.2 ppm and a median of 0.6 ppm zinc using 0.05N HCl + 0.025N H_2SO_4 extraction. A critical level of 1 ppm Zn has been suggested (NCSU 1974) for a sensitive crop like corn. By that criterion 95% of the 518 samples were below the critical zinc level, suggesting a high probability of response to zinc fertilizers in the highly weathered, acid, low CEC soils of Central Brazil.

In recent years evidence of dramatic responses to zinc as zinc sulfate in the *campo cerrado* has been accumulated. In an area limed to pH 6.4 in the first year of cultivation, rates of 3 kg Zn/ha increased maize yields from 1 to 6 t/ha in a clayey dystrophic Dark-Red Latosol (Acrustox) at Brasilia (NCSU 1974). The same experiment has been maintained to study the residual effects of zinc. Nine kg zinc/ha applied in 1972–73 maintained yields of maize, sorghum, and soybean above 90% of relative yield for as long as 5 years (Lopes and Galrão 1979). By the missing-element technique in greenhouse and field studies only the treatment without zinc showed significant reduction in dry matter of maize and dry matter and grain yields of upland rice (CPAC 1978, 1979; Galrão et al 1978).

Copper. Data from Table 3 (Lopes 1975) show a range from 0.0 to 9.7 ppm extractable copper. Specific studies to evaluate the effects of copper fertilization in these soils are lacking but considering 1 ppm Cu as a critical level, 70% of the samples would be deficient in copper. Most greenhouse and field experiments with copper include other micronutrients. In the few cases where the individual effects of micronutrients have been studied, no beneficial effect from copper fertilization was observed for upland rice and maize (CPAC 1978, 1979; Gairão et al 1978).

Iron and manganese. Availability of iron and manganese seems to be adequate for most food crops in the *campo cerrado.* The range for extractable iron varies from 3.7 to 74.0 ppm with a median at 32.5 ppm (Table 3). No attempt has been made to evaluate the critical level of extractable iron in the *campo cerrado* soils. Virtually no iron fertilizer has been used in the region, and no response to iron sulfate was obtained for corn and upland rice (CPAC 1978 1979; Galrão et al 1978). Iron toxicity on the well-drained, leached Oxisols and Ultisols has been observed only in very small localized areas of poor drainage.

The median for extractable manganese in *campo cerrado* soils was 7.6 ppm, with a range from 0.6 to 92.2 ppm (Table 3). According to Cox (1972) there are ordinarily two stages for developing manganese deficiency in acid soils: first, reducing conditions to produce Mn^{++} and its subsequent leaching, and second, deficiency induced by overliming. Neither condition is common in *campo cerrado*

Table 3. Summary of the range of some micronutrients observed in 518 topsoil samples under *cerrado* vegetation in Brazil (includes 16 samples under forest vegetation).[a]

Micronutrient[b]	Accepted critical level[c] (ppm)	Samples (%) below critical level	Range (ppm)	Median (ppm)
Zinc	1.0	95	0.2–2.2	0.6
Copper	1.0	70	0.0–9.7	0.6
Iron	?	–	3.7–74.0	32.5
Manganese	5.0	37	0.6–92.2	7.6

[a]Source: Lopes 1975. [b]Extracted by 0.05 NHCl + 0.025 NH_2SO_4. [c]According to soil testing services in Minas Gerais state, Brazil.

soils. A value of 5.0 ppm extractable manganese (0.05N HCL + 0.025 N H_2SO_4 extraction) has been suggested as a critical level for a sensitive crop like soybean (Cox and Kamprath 1973). Because most *campo cerrado* soils have pH between 4.8 and 5.2, the critical level for manganese would be less. No attempt has been made to evaluate the critical level of manganese in these soils. By using 5.0 ppm as a critical level, only 37.3% of the samples were considered low. The data suggest that Oxisols and Ultisols in the Central Plateau of Brazil are well supplied with available manganese (CPAC 1978, 1979; Galrão et al 1978).

Boron, cobalt, and molybdenum. The availability of boron, cobalt, and molybdenum in the *campo cerrado* soils has not been evaluated in any survey. Maize and upland rice have shown no response to the three micronutrients (CPAC 1978, 1979; Galrão et al 1978), but dry beans have shown considerable yield response to molybdenum and cobalt (Netto et al 1977).

Most of the experiments with micronutrients for leguminous crops in the *campo cerrado* area use mixtures of micronutrients, leading to uncertainty as to which elements are limiting for those soils. In a study with dry beans on a podzolic soil (Ultisol) in Minas Gerais state, applications of 12.9 g molybdenum ha and 0.25 g cobalt/ha to moist seeds increased grain yields by 100 and 130%. Together, molybdenum and cobalt were as efficient as ordinary superphosphate. Similar studies are highly recommended for the *cerrado* area.

No on-going study is evaluating the ability of the *campo cerrado* soil to support advanced food crop production without the addition of micronutrients other than zinc. With intensive crop production, other micronutrient problems, beside zinc deficiency, may soon occur.

Lower Amazon

Considerable responses to micronutrients have been observed in other areas of Latin America. In the lower Amazon jungle at Yurimaguas, Peru, with annual rainfall of 2,000 mm and no definite dry season (red yellow podzolic soils, dystrophic Paleudults, pH 4.4, low CEC, and low in bases), deficiencies of boron, copper, and molybdenum may be limiting to crop production (Sanchez 1977). With the use of the missing-element technique, copper deficiency was demonstrated in greenhouse tests for maize dry matter production (NCSU 1974). Later, in a field experiment with soybean and corn, soybean yield increased from 0.59 to 2.4 t/ha with two sprays of a mixture of micronutrients (zinc, manganese, iron, copper, boron, and molybdenum). The experimental area had 4.4, 4.8, and 0.1 ppm Olsen-extractable manganese, zinc, and boron, respectively (NCSU 1975). A micronutrient response was clear, but because the micronutrients were applied together, it was not possible to identify which was responsible for the increase.

With 4 t lime, 160 kg P_2O_5, 180 kg N, 150 kg K_2O, 50 kg MgO, 24 kg S, 3 kg Cu, and 1 kg Mo/ha at Yurimaguas, it was possible to obtain 3 crops a year (rice, soybean without nitrogen, and maize), with yields of 3 t rice, 2 t soybean, and 4 t maize/ha, continuously (Sanchez 1977).

Colombia

Zinc. Zinc deficiency is frequently seen in Colombia in areas under cassava cultivation, both in acid and alkaline soils. However, the ideal management system for overcoming the problem in the two soils is different. In an acid (pH 4.5) Oxisol (Typic Haplustox, clayey, kaolinitic, isohyperthermic) at Carimagua, 5 kg Zn/ha as zinc sulfate increased cassava yield from 8.3 to 12.7 t/ha for variety M Mex 59, and 1.7 to 8.4 t/ha with variety M Mex 23. The zinc content of the leaves increased from 25 to 35 and 21 to 34 ppm. There was no significant difference between using zinc sulfate in band or zinc oxide as broadcast, but foliar application or stem cutting treatments were less effective. But in a Mollisol (pH 6.7 to 8.0) at CIAT, the best treatment was to submerge the stem cuttings for 15 minutes in a suspension of 4% ZnO or in a solution of 4% $ZnSO_4$ (CIAT 1978a).

Zinc deficiency for cassava is common on acid, highly weathered Oxisols in Colombia when high rates of lime are used. An application of 20 kg Zn/ha was effective in overcoming zinc deficiency induced by the use of 6 t lime/ha for a cassava crop. The treatment NPK + 20 kg Zn/ha gave the same yield (16 t/ha) as NPK + Zn + Cu + Mo + Mn, showing that the limiting micronutrient was zinc (Howeler et al 1977).

Boron. On a high-pH Mollisol in the Cauca Valley of Colombia, bean (*Phaseolus vulgaris*) yields were seriously limited by boron deficiency. Boron applied directly before seeding at the rate of 2 and 4 kg/ha gave optimum yields for 2 and 3 successive crops. Critical levels were 20–24 ppm boron in leaves and 0.65 ppm as hot-water-soluble boron in soil. Toxicity occurred above 40 to 45 ppm in leaves and 1.3 to 1.5 ppm in the soil. In the same area mung bean (*Vigna radiata*) was highly tolerant and responded negatively to boron application (Howeler et al 1978). This shows the need for different plant species when evaluating critical levels of micronutrients in soils and plants.

Other Latin American countries

Responses of food crops to micronutrient applications under diverse soil types and climatic conditions have been observed in other countries in Latin America. Working in a typic Quartzipsamment in Guyana, Saxena and Locascio (1975) obtained increases in dry bean yields (216–1,800 kg/ha) from application of 45 kg FTE 503/ha at reasonable levels of nitrogen, phosphorus, and potassium fertilization. In a greenhouse, maize on an Inceptisol from the subtropical zone in Peru (pH = 4.9, low CEC, extractable Mn in $NaHCO_3$ 0.5M – pH 8.5 plus EDTA 0.01M = 61 ppm) showed a negative yield response to manganese (Villachica and Cabrejos 1974). These data show that the limits for deficiency and toxicity of micronutrients must be carefully evaluated to develop criteria for their adequate management as a crop production constraint.

Micronutrients in volcanic ash soils. Volcanic ash soils (Andosols) from Latin America seem to differ in available micronutrients according to geographic distribution and age of ash material. Working with three acid volcanic ash soils

(pH 5.0–5.4) from the *Meseta Central* in Costa Rica, Marinho and Igue (1972) found that zinc absorbed by maize plants was better correlated with 0.01 M EDTA-extractable zinc than with zinc extractable with 0.1N HCl. The levels for extractable zinc in the three soils were 1.8, 1.3, and 0.7 ppm by 0.01 M EDTA, and 8.1, 4.3, and 2.2 ppm by 0.1N HCl. The levels were considered low.

A similar result was obtained (Martini 1970) in 17 soils and subsoils (recently formed, volcanic ash) from Costa Rica that did not show crop responses to a mixture of copper, zinc, manganese, iron, molybdenum, and boron. Volcanic ash soils from Chile have shown considerable effect on the proportion of leguminous plants in pasture from molybdenum application (200 g/ha) mainly in older ash soils (Weinberger and Wenzel 1973). Availability of copper, zinc, and iron seemed adequate, but there was a potential manganese deficiency in nine volcanic ash soils from southern Chile (Schalscha et al 1968). Boron deficiency is reported for several crops on volcanic ash soils from Ecuador (Tollenar 1966).

AFRICA

In his review of soil micronutrients in Africa Drosdoff (1972) observed that more and more micronutrient deficiencies are being recognized in a wide range of crops and of soils. He stated that apparently deficiencies of molybdenum, zinc, and boron are the most prevalent, but those of copper, manganese, and iron have occasionally been identified.

Little has been added to the knowledge of micronutrients specific for food crop production during the last decade in tropical Africa. Studies about the effectiveness of micronutrient extractors, calibration for various soils and crops, and methods to eliminate micronutrient constraints are almost lacking. Heathcote (1972) indicated that Nigerian fertilizer practices with reference to potassium and trace elements will have to be drastically amended to maintain high yields of maize, sorghum, and groundnuts in intensive systems of agriculture. A similar trend would be expected in other African countries now changing their agricultural system.

Manganese and zinc

Although bean, soybean, and groundnut are on acid soils that are high in manganese, manganese toxicity in those crops in a ferrallitic soil (Oxic Quartzipsamments) in Madagascar (Ngo Chan Bang et al 1971) has been reported. The interaction of liming and manganese and zinc availability in highly weathered soils from Africa seems quite similar to that observed in highly weathered Oxisols and Ultisols from South America. In two Ultisols from southern Nigeria (Ustoxic Paleustult and Oxic Paleudult), considerable reduction in yield and manganese and zinc uptake by maize was observed when the soils were limed to pH above 6.2 and 5.6, respectively (Juo and Uzu 1977). Overliming of highly weathered, low CEC soils seems to have more deleterious than beneficial effects.

Boron

Boron deficiency is common on hydromorphic soils in Africa. Le Mare (1970) stated that boron deficiency probably occurs widely in Tanzania, especially on light-textured soils and wetter areas. Recently, Oliver et al (1974) conducted a pot trial in Malagasy to study the effect of boron on wheat in three hydromorphic soils. The soils had pH 4.8–5.8, 4.7–28.1% organic matter, 10.3–15.4 ppm total boron, and 0.120–0.389 ppm hot-water-soluble boron. Considerable response to boron was observed, and 3 mg B/kg soil was sufficient to correct boron deficiency.

Iron

Calcareous soils from Africa have shown dramatic responses to iron fertilizers but few studies have compared sources and rates of iron or ways of controlling iron deficiency. In calcareous soils from Egypt, Abd Elnaim and others (1974) worked with different iron compounds ($FeSO_4$, Fe-EDTA, Fe-EDDHA) with maize in a greenhouse, either treating the soil or spraying plants at a rate equivalent to 2.5 kg/ha. They concluded that a spray was best for applying iron sulfate, and soil application was the best method for applying Fe-EDTA. For peanuts in Israel pelleted Sequestrene/38 (Fe-EDDHA) broadcast and slightly worked in to correct iron-induced chlorosis, was equally effective as powder or flowable product dissolved and injected into the soil (Lanchover and Ebercon 1972). This indicates that different physical forms of a single iron chelate have different effects in solving iron problems in calcareous soils. Another way of overcoming the effects of iron-induced chlorosis in calcareous soils is through genetic variability of plants. Groundnut cultivars tested in calcareous soils in Israel showed different efficiencies for iron utilization (Hartzook et al 1974).

Molybdenum

Molybdenum deficiency is a severe constraint to several food crops in tropical Africa, mainly in acid sandy and organic soils. A mixture of micronutrients (iron, manganese, copper, zinc, boron, and molybdenum as Nutramin) applied at the rate of 3 kg/ha markedly increased groundnut yield in northern Senegal. Further studies showed that the active micronutrient in the mixture was molybdenum because the response to ammonium molybdate at 29 g/ha was as good as that to 3 kg Nutramin/ha (Martin and Fourrier 1965). Similarly, micronutrient studies in 10 agricultural stations in Ghana showed only slight response to application of molybdenum in groundnut (Drosdoff 1972).

Frequently, the increased solubilization of indigenous molybdenum can explain the beneficial effect of liming acid soils in food crop production. Field trials in northern Nigeria on a well-drained, acid, ferruginous soil formed over crystalline rock showed considerable increase in cotton and maize yields due to lime and a significant increase of molybdenum in the cotton and maize leaves (Heathcote 1970).

Recently, further evidence of the response of maize and leguminous crops to molybdenum has accumulated in Africa. In a field experiment in South Africa, seed treatment of 125 g Na_2MoO_4/100 kg maize seed increased grain yield by 11% and almost doubled the molybdenum concentration in the grain (0.043 to 0.072 ppm). Similarly, Ashour and Hassan Moawad (1975) observed in sandy, calcareous soils (pH 7.9) in Egypt a positive effect from soaking groundnut, broad beans, and lupine seeds in a 2.10 M $Na_2MoO_4 2H_2O$ solution before sowing. However, a similar seed treatment with 2.10^{-3} M $ZnSO_4 \cdot 7H_2O$ and 2.10^{-2} $CoSO_4 \cdot 7H_2O$ gave positive effect from zinc only for groundnut and horsebean, and from cobalt for lupine only. The highest yields were obtained by a seed treatment that combined trace elements and nodule bacteria. These data indicate that although molybdenum deficiency can be a serious problem in sandy soils and organic soils in Africa, liming as well as seed treatment has been effective in reducing the constraint for production of some food crops.

ASIA

Most of the research on micronutrients for food crops production in the tropics during the last decade has been in Asia, and primarily in India and the Philippines with wetland rice. Two surveys covering rice-growing soils were conducted during 1976: one involving landform, hydrology, genesis, taxonomy, and suitability; the other emphasizing chemical problems of current and potential rice-growing soils (IRRI 1977). A summary of the latter survey indicated about 100 million ha of land in South and Southeast Asia physiographically and climatically suitable for rice production but uncultivated largely because of soil problems such as salinity, alkalinity, strong acidity, or excess of organic matter (Table 4). The different kinds of soils indicate possible differences in micronutrient constraints – iron toxicity on strongly acid soils (acid sulfate soils) and zinc deficiency on alkaline soils, organic soils, and wet soils.

Zinc

Zinc deficiency is probably the most widespread micronutrient constraint to wetland rice production in the tropics. It occurs in parts of India, Pakistan, and the Philippines and is generally associated with calcareous soils (Tanaka and Yoshida 1970; Yoshida and Forno 1971; IRRI 1972, 1973, 1977). In Asia, zinc deficiency is regarded as a major limiting factor for wetland rice on about 2 million ha (Ponnamperuma 1974). The problem is aggravated for wetland rice because flooding depresses zinc availability (IRRI 1967, 1969; Sanchez 1976) and high levels of organic matter in the soil accelerate zinc deficiency (Yoshida and Tanaka 1969, IRRI 1969).

Zinc deficiency in submerged soils has been explained by studies of the kinetics of micronutrients. After studying the kinetics of water-soluble copper, zinc, boron, and molybdenum in submerged Louisiana clay, Ponnamperuma

Table 4. Problem rice soils (current and potential) of South and Southeast Asia.[a]

Kind of soil	Extent (million ha)
Saline	62.5
Alkali	2.2
Acid sulfate	9.8
Organic	29.0

[a]Source: IRRI 1977.

(1974) observed that the concentrations of zinc and copper decreased, the concentration of manganese markedly increased, while the concentration of boron remained more or less constant (Table 5). More recently, studies of 12 organic soils in the Philippines showed that zinc concentration ranged from 0.02 to 0.07 ppm 6 weeks after submergence despite a pH change of less than 0.3 (IRRI 1977).

Dramatic responses to zinc fertilizers have been obtained on saline-alkaline soils in India (Abrol et al 1972, Singh and Dhar 1973, Forno et al 1975a) and on calcareous soils in India (Varma et al 1977), Pakistan (Kausar et al 1976, Chaudry et al 1973), Japan (Yoshida and Tanaka 1969), and the Philippines (Yoshida and Forno 1971). Not all calcareous or saline rice soils are deficient in zinc. Lockhard et al (1972) observed that addition of zinc did not increase rice yields in three Luzon soils with pH 6.4–7.4, 1.5–2.0% organic matter, and 0.80–1.65 ppm 0.1N HCl extractable zinc. It has been observed that coastal saline soils in West Bengal, India, had total and available zinc, copper, and manganese adequate for normal growth of rice (Bandyopadhya and Adhikari 1972).

Considerable research in Asia has evaluated zinc extractants, rates of zinc fertilizers and methods of overcoming zinc deficiency for several crops and soils. Most of the research did not have enough information about soil characteristics to allow decisive and precise extrapolations.

Results of conventional soil tests are well correlated with rice plant zinc content and yield responses. The critical level of zinc is 1.5 ppm by the method of Trierweiler and Lindsay (1969) according to Ponnamperuma (1974). How-

Table 5. Kinetics of water-soluble copper, zinc, boron, and molybdenum in submerged Luisiana clay.[a]

Micronutrient	Concn (ppm) in soil solution				
	0 wk	1 wk	2 wk	3 wk	4 wk
Zinc	0.29	0.20	0.25	0.10	0.05
Copper	0.14	0.12	0.09	0.04	0.03
Boron	0.24	0.22	0.24	0.27	0.25
Molybdenum	0.01	0.02	0.18	0.39	0.47

[a]Source: Ponnamperuma 1974.

ever, several extractors have shown considerable variation in predicting responses. Working with peaty, red and alluvial soils from India (pH 3.3–8.5, 0.39–7.42% organic matter, 0.05–1.25% $CaCO_3$, CEC 4.77–23.42 meq/100 g), Tiwari and Mohan Khumar (1974) concluded that dithizone-ammonium acetate extracting solution was suitable for estimating available zinc for rice plants. Similar results were obtained by Mithyantha et al (1971) in some soils of Mysore state in India, and by Rai et al (1971) also in India. Dithizone zinc extraction was highly correlated with wheat yields and uptake of zinc, while zinc extracted by 1N NH_4OAc (pH 4.6), 0.2% EDTA, and 2N $MgCl_2$ were significantly correlated and uncorrelated with 0.1N HCl. A critical level of 0.55 ppm dithizone extractable zinc was suggested (Grewal et al 1968).

After testing 11 zinc extractants on alluvial, red, and lateritic soils (pH 8.3–8.4, 5.3–7.0, 5.4–6.2; and organic carbon 0.15–0.14%, 0.89–2.61%, 0.82–2.28%, respectively), Iyengar and Deb (1976) concluded that NH_4OAc (pH 4.6), EDTA-NH_4OAc, DTPA, and EDTA $(NH_4)_2CO_3$ showed a very high degree of correlation with zinc uptake by maize and mung bean in India.

Several methods have shown efficiency in overcoming zinc deficiency for rice in various soils in India. Varma et al (1977) observed that soaking of rice roots in 4% ZnO suspension resulted in an increase of dry matter, compared to direct application of 2.5 ppm $ZnSO_4$ in calcareous soils. In saline-alkaline soil (pH 10.6), 45 kg $ZnSO_4$/ha before sowing the rice increased rice yields about 30% (1,000 kg/ha) (Abrol et al 1972). Foliar spraying (10, 25, and 50 days after transplanting) of a zinc sulfate solution (15 ppm Zn) significantly increased the rice yield on a saline soil (pH 9.1) according to Singh and Dhar (1973). However, 100 and 200 kg $ZnSO_4$/ha applied to the soil produced significantly higher rice yields than 10, 15, or 25 kg $ZnSO_4$/ha, which was foliar sprayed (Singh and Pandey 1972). Ponnamperuma (1974) stated that zinc deficiency in transplanted rice is easily corrected by dipping the roots of the seedlings in a 2% suspension of zinc oxide in water before planting. In direct-seeded rice, the application of 50 kg $ZnSO_4 \cdot 7H_2O$/ha has been effective in preventing zinc deficiency.

Breeding varieties with improved resistance to adverse soil conditions (including zinc deficiency) is another alternative. However, little has been done on this subject concerning micronutrients in tropical Asia and also in other areas of the tropics. The possibility of this alternative has been discussed by Ponnamperuma and Castro (1972) and Forno et al (1975b) in the Philippines for rice, and by Safaya and Singh (1977) for cowpea in India.

Considerable responses to zinc fertilizers have been obtained for other food crops in tropical Asia. Kapur and Gangwar (1975) obtained significant increase in the dry weight of the soybean shoots with application of 5 ppm zinc in a typic Haplaquoll (pH 7.1, 2.2% organic matter, and 0.5 ppm dithizone extractable zinc) in India. A similar rate of zinc (5 ppm) combined with 100 kg P_2O_5/ha increased the yield of maize dry matter in a loamy coarse sand soil (pH 7.1, 0.49% organic matter, 0.52 ppm dithizone-NH_4OAc extractable zinc) in India (Rajagopal and Mehta 1971). In other studies, lower rates (20 kg

$ZnSO_4$/ha) resulted in maize grain yield of 5 t/ha, compared to 4.5 t/ha with 10 kg $ZnSO_4$/ha and 3.8 t/ha in the control (Rathore et al 1972).

Iron

Iron deficiency was one of the first nutritional disorders to be recognized in rice. It is widespread in calcareous and alkali soils under both dryland and wetland conditions and is also found in some flooded soils where organic matter is too low to produce soil reduction (Sanchez 1976). It is widespread in Central and Northern India, the Philippines, and part of Japan (Tanaka and Yoshida 1970, Okajima et al 1970).

Although iron deficiency is common in calcareous soils, rice on such soils does not always experience iron deficiency. Sanchez (1976) observed no iron deficiency symptoms but noted prominent iron coatings in calcareous soils of pH 8.3 throughout the coastal area of Peru.

With the possible exception of bleached sands, acid soils in the tropics are well supplied with iron; consequently, iron deficiency is rare in upland crops with their reducing rhizospheres. However, iron deficiency has been observed in acid soils with pH around 5.0 in the Philippines and in Brazil, when dryland rice was under periods of water stress (De Datta et al 1975, Costa and Souza 1972). A possible explanation for this behavior in acid soils was given by Sanchez (1976) who reported that although the solubility of iron was high, the crystallinity of the forms, or sheer water stress, could induce iron deficiency.

Iron deficiency for rice can be corrected by applying ferric sulfate, ferrous sulfate, or iron oxides to the floodwater or by incorporating them with the soil (Sanchez 1976). But the simplest way is to lower the redox potential to less than 0.2 V at pH 7.0 through submergence, saturation, or even partial saturation of the soil (Ponnamperuma 1974). But because little water control is possible on upland soils where rice is grown, the use of varieties tolerant of iron deficiency may be the only other practical solution besides iron fertilizers incorporated into the soil (Ponnamperuma 1974). Varietal differences in relation to iron deficiencies have been identified (Ponnamperuma and Castro 1972; IRRI 1972, 1973).

Acid tropical soils are normally well supplied with iron. Iron toxicity occurs when certain highly weathered Oxisols, Ultisols, or Sulfaquepts are flooded. Within a few hours after flooding the redox potential of most soils fall below 0.2 V at pH 7 and iron comes into solution as Fe^{2+}. The rate of formation of water-soluble Fe^{2+}, the peak height, and the subsequent rate of decline depend on pH, the organic matter content of the soil, the nature and content of Fe (III) oxide hydrates, and the temperature (Ponnamperuma 1974). Fe^{2+} concentrations that exceed 300 ppm can be observed on strongly acid Ultisols and Oxisols, and Sulfaquepts can have concentrations as high as 5,000 ppm, a few weeks after submergence.

Ponnamperuma (1974) summarized the treatments that have alleviated iron toxicity for rice growing in pots as follows: liming, drainage, presubmergence,

late submergence, midseason soil drying, application of manganese dioxide, and avoidance of organic matter. Under practical field conditions, however, only liming, soil drainage to reoxidize the ferrous iron, or use of varieties tolerant of iron toxicity seems to be satisfactory (Ponnamperuma 1974, Sanchez 1976).

Little work has been done on iron deficiency in soils for other food crops in Asia in the last decade. Lodha and Baser (1971) studied available copper, boron, and iron in seven representative soil groups in Rajasthan, India, and observed maximum available iron in desert and mixed red and black soils and minimum amounts in grey brown soils. Deep black soils of Madhya Pradesh, India, were only slightly deficient in soluble iron (Rai et al 1970), but iron-carrying fertilizers helped wheat yields on black soil in the same area (Subba Rao and Datta Biswis 1971).

For other food crops grown in iron-deficient soils, application of iron-carrying fertilizers or foliar sprays are reasonable alternatives. However, little research has been done on the management of these alternatives in tropical Asia.

Manganese

Studies concerning evaluation of the status of other micronutrients in Asia are fewer than those for zinc and iron. Manganese deficiency seems not to be a severe problem for rice production in Asia.

Tanaka and Yoshida's survey (1970) of nutritional disorders of rice in Asia observed no symptoms of manganese deficiency. Samples of black soils, alluvial soils, and saline soils in India revealed that available manganese was adequate for crop growth (Rai et al 1970; Bandyopadhya and Adhikari 1968, 1972). However, manganese deficiency would be expected in slightly acid or alkaline soils, poorly drained areas, and soils with high levels of soluble iron, copper, and zinc. Vamadevan and Mariakulandai (1972) observed significant yield responses from 10 kg $MnSO_4 \cdot 4H_2O$/ha on rice in India.

Acid tropical soils have much less manganese than iron, but do not commonly show manganese deficiency. Ponnamperuma (1974) explained that the concentration of manganese in the soil solution of normal oxidized acid soils is always higher than that of iron, its closest competitor, and that manganese uptake is favored by nitrate. Manganese toxicity was not found to be a nutritional disorder of wetland rice in Asia (Ponnamperuma 1974).

Copper and molybdenum

The available information about copper and molybdenum for food crops production in Asia is meager. Ponnamperuma (1974) observed that the kinetics of the two micronutrients under wetland rice conditions are opposite. Copper concentration in the soil solution decreased but molybdenum increased considerably upon flooding. Kausar et al (1976) stated that flooded soils appeared responsible for copper and zinc deficiency for rice in calcareous soils of Pakistan.

Although flooding increases molybdenum levels in the soil solution, molybdenum application can be helpful to nitrogen metabolism in wetland rice

plants. Das Gupta and Basuchaudhuri (1974) observed that IR8 significantly increased total and soluble nitrogen in the leaves, stem, and grains and also increased free and protein-combined amino acids after application of ammonium molybdate (40 g/ha) as foliar spray alone or in combination with 400 kg N/ha in an alluvial soil (pH 5.9) in India. The data suggest that in wetland crops like rice, where use of ammonium fertilizers is common, molybdenum could bring about improvements in the nitrate reducing process. Further studies of the molybdenum and nitrogen interaction are indicated for food crops production in the tropics.

The peat soils of Asia show a need for copper fertilizers to achieve high yields. Kanapathy (1972, 1976) observed that most of the food crops studied responded significantly to copper fertilizers. Dressings of 17, 34, and 68 kg $CuSO_4$/ha increased maize yields in the 9th consecutive crop to 4.3, 4.0, and 4.1 t/ha, whereas the control yielded only 1.3 t/ha. The long residual effect of copper applications suggests that basic dressings of 12–36 kg $CuSO_4$/ha applied at 5-year intervals are adequate to maintain copper at appropriate levels.

Boron

Little information is available concerning boron availability and responses of food crops to boron application in Asia. However, boron deficiency should be expected in coarse-textured soils that are low in organic matter, especially in high rainfall areas, and also in nearly neutral or alkaline soils. Singh and Sinha (1976) working with 200 soil samples from northeastern Bihar, India (pH 4.8–9.8, 2–16% clay, 0.2–1.7% organic carbon) obtained a range of hot-water extractable boron – from traces to 1.05 ppm, with an average of 0.42 ppm. If 0.5 ppm is the critical limit, 65% of the samples could be deficient. Available boron and that in wheat plants showed a high correlation ($r = 0.708^{**}$).

The limits between boron deficiency and boron toxicity seem to be much closer than those for other micronutrients. In the Philippines application of 5 or 10 ppm boron increased potted rice grain yield from 70 to 90 g/plant in one soil at the 5-ppm level only. For three other soils boron toxicity symptoms and sharp reduction in the yield were observed (Lockhard et al 1970). Similar results were obtained by Lockhard et al (1972).

Most of the studies in relation to tropical Australia have been with pasture soils of Queensland (Teitzel and Bruce 1971a, 1971b, 1972a, 1972b) and compared soils derived from metamorphic, granitic, and basaltic rocks. The main micronutrient deficiency was that of molybdenum. The Australian studies demonstrate the effectiveness of conducting soil fertility evaluation studies in the greenhouse before going to expensive field experiments.

RESEARCH NEEDS

Some future research needs are:

- In areas with a lack of information on limitations to food crops production imposed by micronutrients, greenhouse studies of extractant solutions and

missing-element techniques should be stimulated. Soil samples should be completely characterized with soil profile descriptions on a level of generalization to allow adequate future extrapolations. Such preliminary studies are highly recommended before going to expensive and detailed field experiments. In areas that have already passed through this preliminary phase studies of rates, sources, efficiencies (organic and inorganic), methods of application, interactions among macro and micronutrients and other factors or soil characteristics should be emphasized.

- New areas in cultivation where responses are not prominent should be evaluated to determine for how long the indigenous availability will be enough to support high crop yields. Because relatively little information is available about the residual effect of micronutrients applied and because the limits between deficiency and toxicity are narrow for some micronutrients, some long-term experiments are probably needed.
- Breeding and testing of varieties tolerant of micronutrient deficiencies or toxicities should be considered for areas where macronutrient problems have already been solved or for special areas where efficiency in micronutrient utilization from traditional methods of application is restricted.
- A worldwide sampling in the tropics of typical soils of diverse physiographical, climatic, and landscape characteristics, and evaluation of micronutrients (total and available) in the laboratory and the greenhouse would probably be desirable. Absorption curves studies for most food crops in the tropics are lacking, and the knowledge of adequate balance of nutrients at various growth stages is definitely important to achieve adequate management of the crops.
- Finally, because modern methods of soils analysis for micronutrients are not as difficult as in the past, there should not be much of a problem in analyzing micronutrients by standard methods when doing soil surveys in areas where there are laboratory facilities.

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Nitrogen as a constraint to nonlegume food crop production

D. R. BOULDIN, R. S. REID, AND P. J. STANGEL

The present state of knowledge of nitrogen as a factor limiting yields of nonlegume food crops is reviewed. We conclude that the concepts for improving the yields of crops through improved nitrogen supply are reasonably well known and substantial increases in food production can be obtained by translating these concepts into information useful to farmers. The basic experimental data for this application require a well-supported, -designed, and -executed field program. Emphasis in this field program should be on recycling of nitrogen, correct timing and application of the proper amount of nitrogen fertilizer, and improving use of organic sources of nitrogen.

THIS REVIEW OF THE STATE of knowledge of nitrogen as a factor that limits yields of nonlegume crops has several limitations.

- Only nonlegume food crops are considered.
- Mainly biological limitations are considered; socioeconomic constraints are largely ignored.
- Biological nitrogen fixation is not considered because it is covered in another paper.
- Organic matter is considered only as a source of nitrogen; we recognize that this is poor agronomy.
- Major emphasis is on the next 5–25 years, although there are implications for the longer-term problems.
- Major emphasis is on nitrogen management required to give yields of corn in excess of 2,000 kg/ha, wheat in excess of 1,500 kg/ha, rice in excess of 3,000 kg/ha, etc.

The following are our opinions and judgments on the most important problems.

Department of Agronomy, Cornell University, Ithaca, N.Y. 14853, USA; Department of Agronomy, Cornell University, Ithaca, N.Y. 14853, USA; International Fertilizer Development Center, P.O. Box 2040, Muscle Shoals, Alabama 35660, USA.

THE PROBLEM AND THE PRESENT KNOWLEDGE

How prevalent is nitrogen as a factor limiting crop yields? Perhaps this question can best be answered by considering the following three categories:

1. land areas where nitrogen is in excess for the crop production potentials and hence increased yield would result from improving present management (water, varieties, crop protection, relay cropping, etc.) but with no substantial change in nitrogen management,

2. land areas where crop yield potentials exceed the nitrogen supply and hence increased yields would result from enhanced nitrogen supply, and

3. land areas where crop management and nitrogen supply are well matched and increases in yields could be obtained only if *both* management and nitrogen supply were improved.

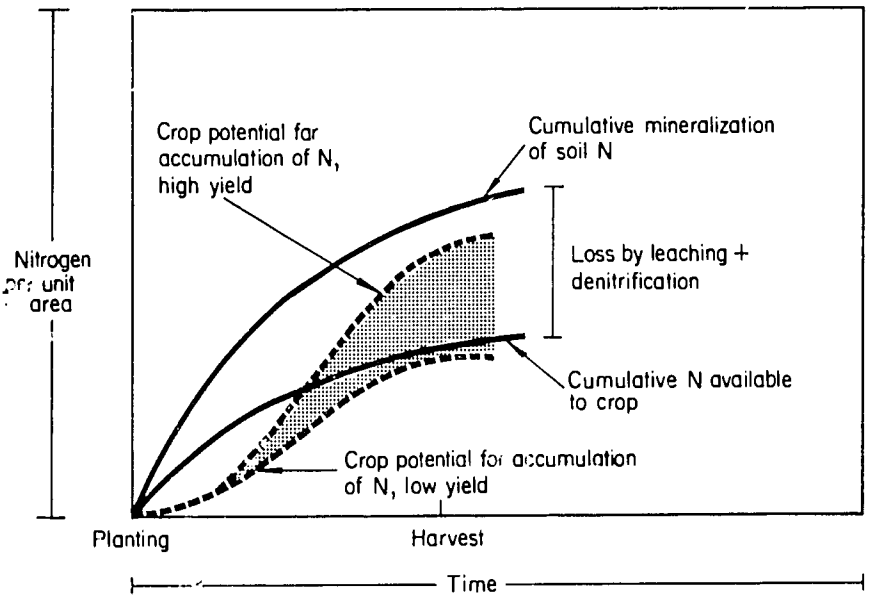
Information on the land area in each of these categories is not easily found. Experiment station data are not useful because of the different conditions under which the crops are grown. Data from farmers' fields are usually limited in scope, and many times nitrogen as a factor is not isolated (i.e. several other variables are changed simultaneously). In any event, the following are some judgments based on the data we have.

Nitrogen in excess of crop yield potential

Probably the largest area where nitrogen is in excess of crop yield potential is under shifting cultivation in forest regions. In Africa during the first 2 years of cultivation following at least 10 years of fallow, total mineralization of nitrogen exceeds crop uptake by a substantial margin (Nye and Greenland 1960, Bartholomew 1977).

Under shorter fallows, some response to nitrogen can be expected under reasonable crop managements (Nye and Greenland 1960). Similarly, under intensive relay cropping where there is always a crop using the nitrogen as rapidly as it is mineralized, response to nitrogen can be expected when crops are well managed. An example is afforded by data from the tropical forest region of Peru, where corn yields of about 1,000 kg/ha were obtained in intensive relay cropping and yields were more than doubled by adding fertilizer nitrogen even during the initial phases of cropping (NCSU 1975, 1976).

The evidence reviewed by Nye and Greenland (1960) and Bartholomew (1977) indicates monthly mineralization rates in the order of 10–30 kg N/ha after bush fallow. Rates of loss by leaching and denitrification will vary considerably with site and year so that the effectiveness of mineralized nitrogen varies accordingly (Bartholomew 1977, Greenland 1958). The conceptual diagram in Figure 1 may help to clarify the many possibilities and to delineate areas of concern. In the example, leaching and denitrification have removed enough of the mineralized nitrogen to limit crop yields. Without leaching and denitrification, the mineralized nitrogen would have been sufficient for high yields. About midway between planting and harvest, the potential *rate* of uptake by both crops is considerably



1. The conceptual relationships among various nitrogen components in the crop-soil system during the cropping season. The solid lines represent the supply functions and the broken lines represent the potential of the crop to accumulate nitrogen under conditions of adequate supply.

in excess of the rate of mineralization. The significance of this latter observation is discussed later. A reasonable hypothesis is that if a crop (or a succession of crops) with potential for rapid initial nitrogen uptake had been grown, it would have taken up most of the nitrogen as it was mineralized and this would have prevented a substantial portion of the leaching and denitrification losses. Under shifting cultivation following clearing, the mineralization of nitrogen might be in the order of 100 kg N/3 months or even more. Whether this is sufficient for a high yield will be determined largely by the leaching and denitrification losses and whether crop uptake is well matched to mineralization rates. When expected grain yields are 1,000–2,000 kg/ha, little response to additional nitrogen can be expected. If yield expectations are larger, responses to additional nitrogen might be expected, particularly in those areas where leaching and denitrification are appreciable and where intensive relay cropping is used.

Areas with inadequate nitrogen

Considerable areas may exist where adequate water and varieties with high yield potential are now used with inadequate nitrogen. IRRI (1978) summarized several years of results in farmers' fields and concluded that often an additional ton of rice could be obtained with more fertilizer (usually nitrogen). Stangel (1978) summarizes data for rice on a worldwide basis and makes a similar conclusion.

In contrast to rice, neither corn nor wheat is fertilized to produce anywhere near their potential yield. For example, there are large areas in Zaire (Diamond et al 1975), Mexico (Hill 1978), and Brazil (Shields et al 1974) where the addition of some 50 to 100 kg N/ha can increase corn grain yields as much as 2 t/ha. These data are fairly representative of those from the corn-growing areas of Central America (Shields et al 1975), South America, and Africa.

Wheat is another major food crop that is not fertilized to produce near its yield potential. Research with wheat in such major production areas as Turkey, Pakistan, and the Punjab of India has shown that yields can easily be increased 0.3–0.5 t/ha with an additional 10–20 kg N/ha. Considerable effort is needed to get farmers to more closely match nitrogen levels to yield potential, especially in areas where the technology is in place.

Areas with yield and nitrogen matched

By far, the predominant condition in terms of area is the land where yields and nitrogen are matched. Evidence for this is the implied assumption – prevalent in most research designed to increase yields – that only small or no response to improved supplies of nitrogen will be obtained unless the yield potential of the crop is also improved. This general idea probably arises from the meager responses to complete fertilizer in numerous trials in farmers' fields 15–20 years ago. In those trials the only management variable was fertilizer addition.

Another piece of evidence is that generally yields are not improved appreciably when varieties with high yield potential are substituted for varieties with low yield potential. To realize even some of the yield potential of improved varieties, it is necessary (but not always sufficient) to increase nitrogen supplies.

INORGANIC NITROGEN

The instability of inorganic nitrogen in soils is perhaps one of its best known qualities. Some of the things that can happen to inorganic nitrogen follow:

- taken up by plants;
- incorporated into microbial tissue;
- leached from the root zone (usually as NO_3);
- denitrified, or
- volatilized as NH_3 gas.

The objective of agronomists is to maximize that taken up by plants and minimize the others. The best way of accomplishing the objective is to get the inorganic nitrogen into the plant as quickly as possible; once it is in the plant it ceases to be subject to the loss mechanisms listed. We focus on this simple idea. Our emphasis is on the increases in economic yields obtained and increases in nitrogen content of the aboveground dry matter rather than on what was not recovered or what happened to the unrecovered nitrogen.

Dryland crops are good scavengers for inorganic soil nitrogen. We found 15 sets of data in the literature where the residual inorganic nitrogen in the rooting zone

at the end of the cropping season was determined, and where the nitrogen additions were not in excess of the ability of the crop to utilize the nitrogen available. In most cases, the concentrations of inorganic nitrogen were considerably less than 5 ppm with dryland crops. Wetland rice was in only one set of data, which indicated somewhat higher concentrations.

Loss adds uncertainty to predicted needs for nitrogen amendments. A characteristic of inorganic nitrogen losses in the field is that they vary greatly among years and sites. Losses are essentially a function of soil characteristics, climate, and, in the case of denitrification, energy available for microbial activity. Climatic events add considerable uncertainty to predictions of losses, whether the source of inorganic nitrogen is through mineralization of organic sources or from fertilizer nitrogen. Thus, crop recovery of nitrogen from any given nitrogen management scheme will vary from year to year.

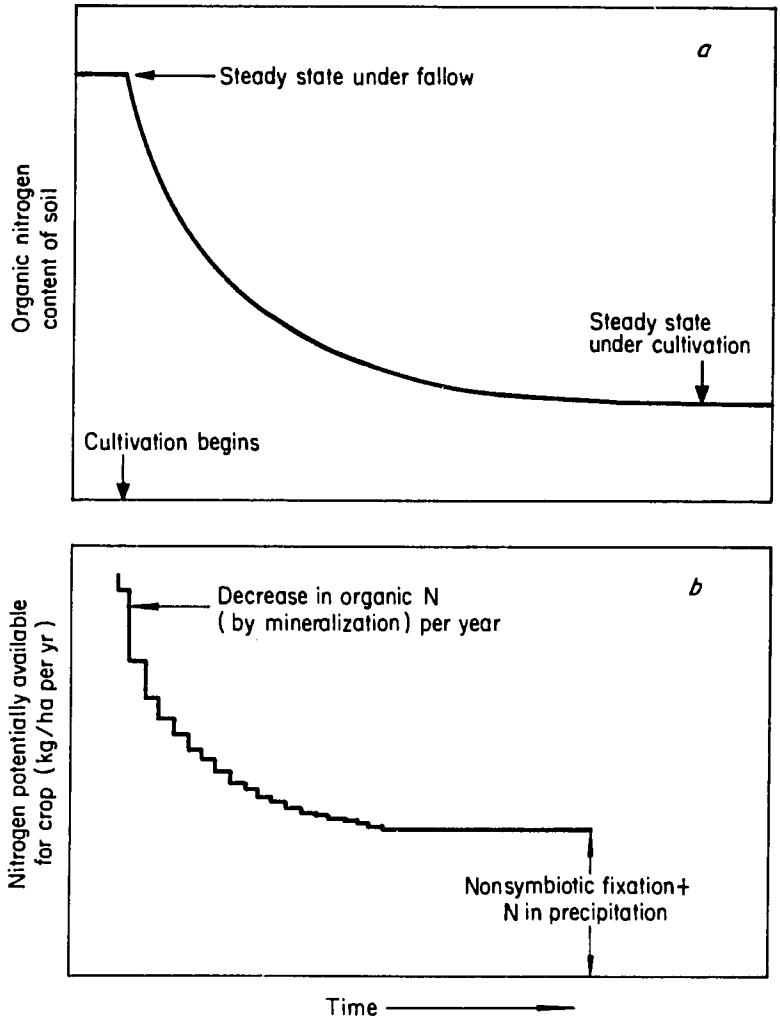
The variable nature of losses of inorganic nitrogen adds uncertainty to predictions of nitrogen needs. Nitrogen additions aimed at the average year will be too much in those years with below average losses and too little in those years with above average losses. Thus amending for an average year becomes expensive in any event and ensures that applied nitrogen will not achieve maximum effect.

The probability of loss increases as residence time of the inorganic nitrogen in the soil increases. Therefore, the more nearly the timing of inorganic nitrogen additions to the soil coincides with plant uptake, the less likely losses become and the more likely recommendations made for an average year will be correct.

ORGANIC NITROGEN

The concepts of soil organic nitrogen behavior under various cropping systems in temperate and tropical regions have been admirably discussed in a number of publications (Nye and Greenland 1960, Jenny 1961, Jones and Wild 1975, Bartholomew 1977 among others). Basically, the general concept that has evolved is that the organic nitrogen content of soils under a given management system tends toward a steady state level, at which time inputs of nitrogen equal losses by crop removal, denitrification, leaching, etc.; that is, the organic nitrogen content does not change with time once a steady state is reached. When the management system is changed, the old steady state is disturbed and the soil organic nitrogen content begins to change toward a new steady state characteristic of the new management system. The implication of this concept for crop production are illustrated in Figure 2 for a system that has been undisturbed for a long time and then is placed under intensive cultivation for nonlegume food crops.

Initially, large amounts of nitrogen are available for crop production but as the organic matter is depleted, the supply of nitrogen available through mineralization is reduced considerably, and finally the only nitrogen available for crop *removal* is that put into the system through nonsymbiotic fixation and nitrogen in the precipitation. The time required for the changes illustrated in the diagram



2. Illustration of a) the changes in organic nitrogen content of a soil initially under fallow and then placed under continuous cultivation to nonlegume crops without fertilizer nitrogen, and b) the nitrogen potentially available for crop production under the situation described in *a*. In *b* the nitrogen potentially available to a crop during one season is the decrease in organic nitrogen depicted in *a* plus nonsymbiotic fixation plus inputs from precipitation. Seldom does a crop accumulate the maximum potential available nitrogen, for reasons illustrated in Figure 1.

varies considerably and depends primarily on conditions favorable for microbial activity because the mineralization is essentially determined by the amount of carbon the microorganisms *burn up* to support their metabolic activities; the amount of nitrogen mineralized is equal to that in the substrate decomposed

minus that incorporated into microbial tissue. The usual way to express the rate of change is the so-called half-time, which is equal to the time in years required for 1/2 of the *change* in organic nitrogen content to occur. Half-time values vary from 2 years to 25 to 50 years: the former under high temperature and continuous rainfall near the equator and the latter under conditions where microbial activity is limited by temperature or water, or both, for considerable periods of the year.

An additional concept elaborated recently (Jenkinson and Raynor 1977, Jenkinson and Ayanaba 1977) is that there are fractions of organic matter which vary in susceptibility to decomposition. Recently added residues continue to be more subject to decomposition than the native soil carbon for a period of 3 to 5 years. Turning attention to the implications of these concepts for nitrogen supply for crops, the following generalizations seem most important to the task at hand:

1. Once a soil is placed under cultivation with nonlegume food crops after a fallow period, the organic nitrogen content usually decreases and the *potential* nitrogen available for crop production is equal to the decrease in organic nitrogen plus inputs from nonsymbiotic fixation and precipitation. As the organic nitrogen content decreases with time, the rate of mineralization of organic nitrogen also decreases and hence the potential amount of nitrogen available to the crop decreases. Thus, crop production is often sustained at fairly high levels for a short period of time at the expense of the organic nitrogen built up during a previous fallow period.

We found no comprehensive review of practical guidelines for estimating, by tests on soil samples, the ability of soil organic matter to supply nitrogen to plants when the soil organic nitrogen is in transition between two steady states. The conceptual framework described has not been translated into a precise and universal procedure for extension personnel to use in advising farmers about how much nitrogen the soil can supply. In general, nitrogen recommendations are based on yields obtained in field experiments, on soil organic matter content, on field history, and on residual inorganic nitrogen, with judgments based to some extent on the preceding conceptual framework and local experience.

2. After the soil organic matter has approached a new steady state, the nitrogen available for crop *removal* is essentially equal to nonsymbiotic fixation plus that in the precipitation. Available evidence suggests that these inputs will support dryland crop yields of 1,000–2,000 kg/ha and wetland rice yields of 2,000–3,000 kg/ha.

3. Once the new steady state level is reached, alternatives for increasing the nitrogen supply include:

- amendment of the soil with organic residues and fertilizer nitrogen;
- restoration of organic nitrogen through a change in cultivation regime, such as natural fallow or forage legume crop; and
- enhancement of nonsymbiotic fixation.

Managing fertilizer applications

The first and most important factor in any fertilizer management program is to match the quantity of fertilizer applied to the ability of the crop to utilize the inorganic nitrogen. A procedure for accomplishing this is described in a later section.

The second important principle for managing fertilizer applications is to time the applications so that the fertilizer is applied just before the period of maximum uptake by the plant. Innumerable reports in the literature illustrate the utility of this principle and we emphasize this as an integral part of *any* program in fertilizer use.

If the preceding two principles are properly applied, losses of inorganic nitrogen by leaching and denitrification are generally minimized.

The third and most important principle is to avoid or minimize loss by ammonia volatilization. This is almost exclusively confined to surface applications and is probably most important when the soil pH values *at the point of application* exceed 7. Volatilization from surface-applied urea and ammonia sources can occur on soils with a pH below 7 because of high pH conditions produced locally by the fertilizer itself.

Loss of fertilizer ammonia by volatilization can be minimized in dryland soils by incorporation of fertilizer in the soil. If incorporation is not feasible avoid use of urea and aqua ammonia, if possible. Use ammonium sulfate (when the resulting acidification can be managed) or ammonium nitrate on acid soils and nitrate sources on alkaline or acid soils.

In a rice paddy, the pH of the water may approach 10 during the day because of the removal of carbon dioxide for photosynthesis of various organisms in the water and on the soil surface. In these cases, surface application of any ammonium source may be undesirable.

It is not entirely clear how ammonia volatilization losses from a flooded soil where incorporation is not feasible can be minimized. Such losses can probably be minimized by minimizing photosynthetic activity in the paddy water, that is, applying most of the nitrogen after a complete plant canopy has developed. Another practice would be to avoid a simultaneous application of nitrogen and phosphatic fertilizer when they are likely to cause a proliferation of algae.

Managing organic nitrogen sources

In the developing countries the amount of nitrogen contained in manures and residues far exceeds the amount of fertilizer nitrogen available (FAO 1975). The strategies for maximizing plant recovery of inorganic nitrogen mineralized from organic sources fall under two categories:

1. timing of the organic source application to coincide with crop needs, and
2. timing of crop production to coincide with the mineralization of the organic nitrogen.

In either case, the management involves more uncertainties than for fertilizer nitrogen – such as total quantity of nitrogen involved, rate of its mineralization,

requirement for incorporation, losses before crop uptake, positional availability, and timing of release relative to crop needs. Even with the incorporation of compost and manure, an evaluation of losses during composting or storage must be weighed against direct application and resulting losses before crop utilization. Additional complicating factors are the unfavorable effects of freshly incorporated organic matter on soil conditions (generation of toxic substances, etc.) and depletion of soil water by green manure crops.

The residual effects of organic nitrogen are usually appreciable; probably only about 50% is mineralized the year of application.

Timing of crop production to utilize the flush of inorganic nitrogen usually produced at the beginning of the rainy season is another example of management. However, one must proceed with caution because early rains may be followed by a prolonged dry period, which is fatal to seedling plants (Nye and Greenland 1960, Jones and Wild 1975, Greenland 1958).

As shown in Figure 1, the mineralization of organic nitrogen is a continuous process (except under adverse conditions); however, the potential nitrogen uptake rate of vigorously growing crops may exceed the mineralization rate. Under these conditions three situations are therefore possible:

1. yield potential of the crop is not realized unless very large additions of organic nitrogen are made (in which case relay cropping may be required to effectively utilize the nitrogen);

2. planting of the crop is delayed until the nitrogen accumulated in the soil plus current mineralization will allow the crop to achieve its yield potential; in this case a sizable fraction of the inorganic nitrogen may be lost; or

3. the nitrogen derived from the organic nitrogen by mineralization is supplemented with timely application of fertilizer nitrogen.

The concepts for most efficient use of organic nitrogen within these situations follow:

- use large amounts of organic amendments and utilize the more or less continuous supply of mineralized inorganic nitrogen by intensive relay cropping (i.e. have an actively growing crop present at all times);
- use moderate amounts of organic nitrogen and supplement it with any necessary fertilizer at critical periods of crop development (i.e. when plant uptake has depleted accumulated inorganic nitrogen and the current rate of mineralization of organic nitrogen is too slow to supply plant needs).

FUTURE RESEARCH NEEDS

In offering our opinions on future research needs, we limited ourselves to emphasis of use of organic matter, organic residues, and fertilizer nitrogen. An important role for biological fixation will be covered in another paper.

The literature indicates that the concepts of nitrogen behavior are reasonably well developed. The major deficiency is linkage of these concepts to food production systems in farmers' fields. We believe that there are many oppor-

tunities for improving the nitrogen economy of food production through applications of the concepts already at hand. We describe an experimental framework that focuses attention on applications of these concepts.

A unified framework for future research

The relationship between yield and nitrogen content of the aboveground dry matter of a mature crop furnishes a reasonable estimate of the amount of nitrogen that must be accumulated by the crop (Stanford 1973, 1978). This nitrogen must come from mineralization of soil organic nitrogen, mineralization of added organic sources, and fertilizer nitrogen. Thus, for a given yield goal, we know what the summation of the contributions from the various sources must be, as stated by the following equation:

$$N_P = N_S + N_M + N_L + K_F N_F$$

where:

N_P = nitrogen in aboveground dry matter for the selected yield goal,

N_S = nitrogen supplied by soil organic matter,

N_M = nitrogen supplied by manure, compost, or other organic amendments,

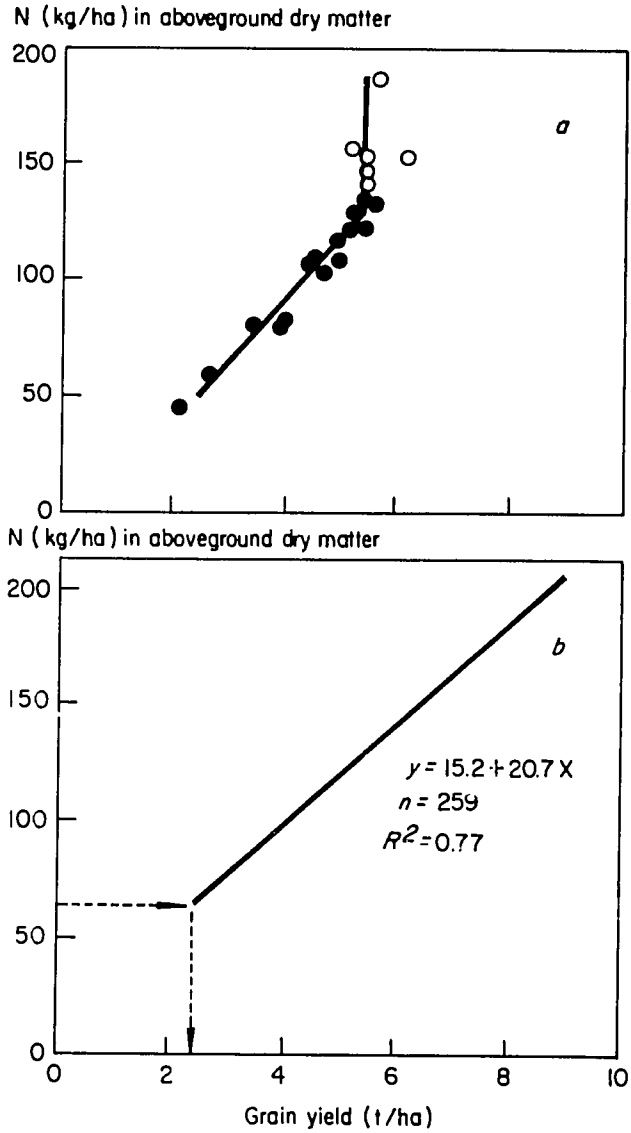
N_L = nitrogen supplied by legume residues or a previous fallow,

K_F = increase in nitrogen content of the aboveground dry matter per unit of applied fertilizer nitrogen, and

N_F = amount of fertilizer nitrogen added.

Each component of the above equation must be determined. We illustrate the procedure with examples from New York where farmers produce corn using soil nitrogen, manure, legume residues, and fertilizer simultaneously – often on the same field:

- The relationship between yield of corn grain and the nitrogen content of the aboveground dry matter is illustrated in Figure 3. From the kind of data illustrated in Figure 3, we estimate N_P for a given field based on average economic yields for the soil series and management level.
- The amount of nitrogen supplied by the soil (N_S) is estimated from the preceding relationship and yields (Y_S) are measured in fields that have not received recent additions of manure, legumes, residues, or fertilizer nitrogen. This is illustrated by the broken lines in Figure 3.
- The nitrogen available to the crop from manure is the result of any inorganic nitrogen in the manure and the mineralization of some organic nitrogen in the manure during the first year after application, plus the mineralization of any residual organic nitrogen from previous applications. The decay series for manure nitrogen follows:



3. Relationship between nitrogen content and aboveground dry matter and grain yield. Part *a* illustrates data from Thorsby, Alabama, USA, over several years for several quantities of applied nitrogen; the data indicated by open circles were eliminated because they represent results obtained when nitrogen was applied in excess of crop needs. Part *b* shows the relationship for data from New York (USA), southeastern USA, Puerto Rico, Mexico, and Brazil. Although several sets of data are pooled here for purposes of summarization, the precision of estimates can be increased by restricting the land area over which data are pooled (adapted from Grove 19 .).

$$N_M = Q_1 M_1 + Q_1 M_1 + Q_2 M_2 \cdots Q_X M_X$$

where:

$Q_1 \cdots$ = quantity of manure added in a given year from the current (1) up to x (usually 4) years ago,

M_i = increase in nitrogen content of aboveground dry matter per unit of manure applied in the current year from the *inorganic* nitrogen fraction, and

$M_1 \cdots M_x$ = increase in the nitrogen content of the aboveground dry matter from mineralization of the organic nitrogen fraction per unit weight of manure added.

Under New York conditions, most of the inorganic nitrogen in the manure is volatilized from the soil surface if not plowed down within a week. Much of the remaining inorganic nitrogen is lost by denitrification or leaching prior to plant uptake. Unless care is used to conserve the inorganic nitrogen, its contribution ($Q_i M_i$) is nearly zero.

Only about 50% of the organic nitrogen in the manure is mineralized the year of application. The residual 50% is mineralized in the following years. The quantities of nitrogen from dairy manure in New York are 1.5, 0.5, 0.2, and 0.1 kg N/t for years 1 to 4 after application, respectively.

- The nitrogen from legume residues or fallow is estimated as:

$$N_L = N_{L1} + N_{L2} \cdots NL_x$$

where

$N_{L1} \cdots L_x$ = increase in nitrogen content of aboveground dry matter for years 1 to x after a sod or fallow is placed under cultivation.

The contribution of the organic nitrogen from the plowed sod is similar to that obtained from the manure. It has been estimated that the half-life of this organic nitrogen is one growing season (or year). A good legume sod will contain about 300 kg N/ha; a grass-legume sod, about 200 kg/ha; and a grass sod, about 150 kg/ha. Thus the contribution from a good alfalfa-grass sod in New York would be about 150, 75, 37, 18, and 10 kg/ha for years 1 to 5 after plowing. Usually only one residue is involved so that N_L is one of the above.

- The value of K_F is based on the kind of data illustrated in Figure 4 where the increase in nitrogen content of the aboveground dry matter of corn is plotted against fertilizer nitrogen additions at several locations.
- Finally the amount of fertilizer nitrogen needed is calculated:

$$N_F = \frac{N_P - N_S - N_M - N_L}{K}$$

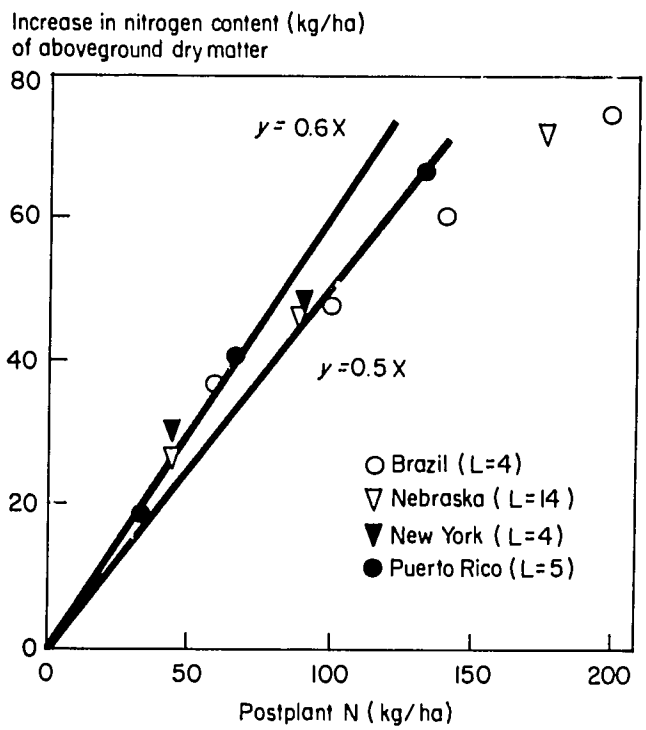
The several approximations used in the preceding were necessary because space limitations preclude elaborate discussions and because the state of knowledge does not justify anything better in some cases. The important question at this point is not the approximations *per se* but: *Should the framework be adopted as a reasonable starting point that needs improvement, or should it be discarded for another framework?*

The major experimental programs within the framework are field experiments that require neither elaborate or expensive equipment nor an infrastructure that is unavailable in remote locations. However, they are expensive in terms of time and labor. A major requirement is the dedication of funding agencies to accomplishing such a program and their willingness to provide the necessary support. Furthermore, field experiments require well-trained and experienced scientists

who are properly rewarded for planning and supervising excellent field programs.

The following is an outline of the kind of experiments needed. All require several years at a given site and enough sites to represent the soils and cropping programs of interest.

- Manure, compost or other organic nitrogen sources should be added at several rates with provisions for measuring residual effects in subsequent years and discontinuing additions on selected plots. The organic nitrogen effects should be measured against fertilizer nitrogen. Yields and total nitrogen content of plants should be measured each year and the organic sources of nitrogen should be carefully characterized as to total nitrogen content and carbon-nitrogen ratio at least.
- Fertilizer rate studies (if fertilizer is a feasible alternative) should be continued for several years with the same treatments applied to the same plots in succeeding years. From the data N_S and K_F can be calculated.



4. The increase in nitrogen content of aboveground dry matter of maize plotted against the amount of fertilizer nitrogen added. "L" in the legend refers to the number of location-years of data averaged. The nitrogen was applied when the maize was 12- to 30-cm tall and it was placed 5 to 10 cm deep in the soil to limit ammonia volatilization. As a starter fertilizer, 10 to 15 kg N/ha was applied by banding 5 cm to the side and 5 cm below the seed at planting.

This framework furnishes a convenient way of incorporating various types of organic sources and methods of fertilizer application. For example, the value of K_F is likely to be about 0.6 for nitrogen that is properly timed and applied so that ammonia volatilization losses do not occur (illustrated in Figure 4). For situations where urea is broadcast on the surface, K_F may be only 0.4 or 0.5; when all of the nitrogen is applied preplant to dryland crops, K_F may be only 0.3 to 0.4. In fact, the data reviewed suggest that if K_F is not in the range of 0.6, then the method or timing of application of fertilizer should be examined carefully.

The residual effects of manure and compost need to be emphasized. In the first year about one-half of the organic nitrogen is mineralized. Therefore, the effective plant uptake may be no more than 20 to 30% of the applied organic nitrogen. Fairly large amounts of manure or compost may be needed to achieve high yields. However, the residual effects will be considerable and, if added yearly, less and less of the organic source will be needed to achieve high yields.

Laboratory studies are needed on the following two subjects.

1. Chemical or incubation procedures, or both, for soil samples need to be developed as a means of interpolating the results of field experiments. The basic objective would be prediction of the ability of soil organic matter and residues to supply nitrogen to crops. A routine procedure suitable for a large number of farmer samples would be one possibility, but probably more elaborate procedures that could be applied on a regional basis and for specific cropping systems would be about equally as valuable.

2. Similar procedures are needed to characterize residues and manures so as to develop a means of predicting their mineralization-immobilization behavior in soil. For example, despite the incredible number of experiments that have been performed with animal manures, there is no good basis for comparison of results among experiments, primarily because the manures were not characterized.

Because of the simple nature of the experiments and the fact that they may be in or close to farmers' fields, one of the most valuable aspects of the framework is that it affords an opportunity to involve and to train extension workers as an integral part of the research. This ensures that they will understand and use the results. It also ensures a well-trained body of workers who have confidence in the data and methods and know how to perform and evaluate demonstrations in farmers' fields. The experiments themselves can be used as demonstrations for farmers and extension personnel not actively engaged in the research.

Nitrogen nutrition of crops

Several aspects of the nitrogen nutrition of crops are not well known. The relationship between age of plants and their nitrogen content is fairly well documented, but that does not necessarily establish the nitrogen requirement. The nitrogen requirement may change rapidly during certain periods of plant devel-

opment, such as during the early growth stages, at tillering, or at grain primordia initiation. For example, the rate of tillering of wetland rice is highly correlated with the percentage of nitrogen in the young plant (IRRI 1968). With wheat or transplanted rice with low populations, a high tillering rate is essential to the development of a high yield potential. A reduced yield potential is set by low, early season nitrogen, and high nitrogen at later dates will not overcome an early season deficit. Thus more information is needed on the nitrogen requirements of plants by age, not just on nitrogen contents.

There is need for knowledge about how much nitrogen must be accumulated by the crop to achieve set yield goals. We have presented a model for estimating nitrogen needs of crops that rests on data relating yield goals to the amount of nitrogen that must be accumulated by the crop. The model assumes the nitrogen is available when the critical needs of the crop occur. Such data are fairly easy to collect and should be accumulated for a range of crops.

Some examples of the influence of timing of nitrogen application on yield potential follow. Maize yields for different timing of fertilizer nitrogen when leaching, denitrification, and ammonia volatilization were unimportant are shown in Table 1. Delaying application reduced the potential yields (i.e. yields at the higher nitrogen rates applied 7 weeks after planting). Hamid and Sarwar (1976) compared ammonium nitrate and urea applied all at planting or split into two or six applications for winter wheat in Pakistan. The results in Table 2 show that the six splits reduced yield potential even though the total nitrogen in the plant was not reduced. Thus, the plants took up the nitrogen, but the grain yields were not increased by a corresponding amount.

To obtain the yield potential of grains, crops must produce an optimum number of seed heads per given area. At normal planting rates, wetland rice must produce 4 to 10 panicles; wheat, 1 to 4 ears; and maize, 1 to 2 ears/plant. The number of seed heads per area is a function of both planting density and tillering. The response to nitrogen of spring wheat in North Dakota, USA, was primarily through survival and grain production by the tillers (Power and Alessi 1978). With a wheat population of 200 plants/m^2, increasing the nitrogen from 0 to 210 kg/ha increased the number of ears from 330 to 560/m^2 for 2 varieties. Thus, the number of ears per plant ranged from less than 2 to more than 3. If

Table 1. Influence of timing of nitrogen (N) applications on yields of maize at Samaru, Nigeria.[a]

N applied (kg/ha)	Yield of maize grain (t/ha)	
	All N 7 wk after planting	All N at planting
0	1.8	1.8
56	3.9	4.1
112	4.4	4.8
224	4.4	5.5

[a]Source: Jones 1973.

Table 2. Influence of timing of nitrogen (N) applications on yield of winter wheat in Pakistan.[a]

Method of application of 120 kg N/ha	Yield of grain (t/ha)	N in grain + straw (kg/ha)
All at planting	4.2	72
2 splits	4.6	84
6 splits	3.6	84

[a]Source: Hamid and Sarwar 1976.

the fertilizer timing had been incorrect, the increased number of tillers would not have survived and the yield potential would have been reduced regardless of the availability of nitrogen later in the growing season.

Similar data for wetland rice were recently reported by Yamada et al (1978). Rice was transplanted at 2 plants/hill in a 20 x 25 cm pattern. At harvest, the number of panicles ranged from 4 to 9/plant among sites as the fertilizer application rates ranged from 9 to 90 kg N/ha.

Enhancement of recycling of nitrogen

The growing realization that the days of cheap energy and low-cost nitrogen are a thing of the past has caused leaders of governments in a number of nations, particularly in the developing world, to mount major programs to recycle organic wastes. Particular emphasis is on better utilization of organic nitrogen from these sources. India (FAO 1975) and China (FAO 1977), in particular, have taken major steps toward reaching this goal. To sustain crop yields, Chinese agriculture currently derives fully two-thirds of its additional nitrogen from organic sources. Inorganic nitrogen, which in 1977 was used at the average rate of 33 kg N/ha, is treated as a secondary source of nitrogen.

Five conditions appear (Stangel 1978) responsible for the Chinese success. These are:

1. high density and close proximity of urban and rural populations,
2. a highly integrated and complementary system of crop production,
3. fish culture and animal husbandry designed to utilize wastes,
4. proper cultural attitudes, and
5. a national policy aimed at maximum use of indigenous resources including manpower.

Some argue that the China example is unique and applicable only at a particular stage in its economic development and therefore the importance of recycling organic waste is likely to decline as industrialization proceeds. Recent increases in the cost of energy and capital investments of fertilizer plants raise doubts about the validity of that assumption. In view of this uncertainty, a major effort should be made to evaluate the Chinese experience to see whether it might serve not only as a model for the densely populated developing countries but also as a prototype of what the industrialized nations might also have to achieve.

One of the major deficiencies in this subject matter is the lack of good data on how the application of nitrogen in residues, manures, and human waste changes the nitrogen content and yield of crops. Despite many estimates of the nitrogen content of residues, manures, etc., there are few data on the amount of this nitrogen actually applied in the field, the time course of its mineralization, its effectiveness in increasing yield of crops, or the management of the additions so that the yield responses are maximized (FAO 1975).

A wide range of interesting topics that require future research is thus opened.

- Crop residues are often burned because they are troublesome to incorporate without heavy machinery, they may be carriers of diseases, they may immobilize inorganic nitrogen, or they may produce toxic substances during decay. Some or all of these difficulties may be overcome through some form of composting or method and timing of incorporation. These subjects need extensive research.
- Animal manures and human wastes are another source of nitrogen. However, available evidence illustrates that under a wide range of conditions at least 50% of the total nitrogen is lost before the manure is returned to the soil. Simple ways of reducing this loss are not evident.
- Use of human wastes, animal manures, and other organic materials for methane generation will leave a residue (under proper management) containing most of the original nitrogen. Management of this residual nitrogen for efficient use in crop production needs serious study (Laura and Idnani 1972, FAO 1975).
- One obvious interface between forage legumes and nonlegume food crop production is the production of animals on forage raised on marginal land or good cropland with legumes, or both, and then use of the manure from these animals for food crop production.

Fertilizer nitrogen research

The research needs with respect to fertilizer nitrogen basically revolve around timing application such that the essential needs of the plant are met yet excessive losses do not occur. The basic concepts are well known; the major problem is *fine tuning* to fit the local conditions and characteristics of the various soils, crops, and cultivars. Information gained relative to nitrogen nutrition of crops (described earlier) is an important part of this fine tuning.

With respect to sources, the fertilizer industry must be encouraged to continue to provide alternatives to urea. Urea is not suitable for surface applications because of volatilization losses. When band placed near the seed or seedling, toxic conditions may be produced because high pH and ammonia concentrations result from urea hydrolysis. In many situations, ammonium nitrate, ammonium sulfate, and calcium nitrate are better sources of nitrogen than urea. Recognizing the sizable urea capacity now in place, an attractive alternative is to develop modifications of urea that will circumvent problems where they occur. Such things as urease inhibitors, coating, etc. need more research.

Addition of compounds that inhibit nitrification of ammonium may reduce losses long enough under some conditions so that the timing of application

becomes less critical. There seems to be no reason to expect these additives to be anything but a substitute for proper timing. It should also be recognized that use of these compounds with banded urea may prolong the period during which toxic conditions occur in the band. Coatings to delay dissolution of fertilizer are also possible substitutes for proper timing and placement of fertilizer nitrogen. These aspects of fertilizer technology are summarized by Hauck and Koshino (1971) and Horn (1978).

Consideration of the future role of fertilizer nitrogen relative to legumes and fallows must consider the source and availability of energy to make fertilizer nitrogen, and how best to manage crop production systems to use residues, legumes, and fallows. Presently, the highest production of energy for the human diet per unit area and time is obtained with well managed root crops and nonlegume grain crops well supplied with nitrogen. The nonlegume grain crops also supply substantial amounts of protein.

Several strategies might be followed to maximize human food production. The following three alternatives need to be *very carefully considered* from the standpoint of human nutrition, acceptability to the target population, land resources, cost and availability of fertilizer nitrogen, and compatibility with the local social and economic structure.

1. Continue to use fertilizer nitrogen on nonlegume grain crops to produce a major share of energy and protein in the human diet. By careful use of fertilizer nitrogen, return of all crop residues, and supply of one-third of dietary protein through legume grains and animals produced on legume forage and grain, the total energy required per capita for fertilizer nitrogen production should be about 0.015 t coal equivalents/year. This is about 4% of the average per capita energy use in Africa and less than 3% of the average per capita energy use in Asia (UN 1977).

2. Use essentially the same strategy as above but reduce the need for fertilizer nitrogen even more by using nonlegumes with very low protein content and hence low nitrogen needs per unit of dietary energy. The bulk of the protein in the human diet must then be supplied by legume grains and from animals fed with forage legume nitrogen.

3. Utilize fallows and legume green manures to supply almost all of the nitrogen needs for nonlegume grains. This strategy has the disadvantage of requiring more land area (initially). The increase in land area may be partially compensated by increased yields from better nitrogen nutrition and decrease in total energy requirement.

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Constraints to biological nitrogen fixation in soils of the tropics

A. APP, D. R. BOULDIN, P. J. DART, AND I. WATANABE

Biological nitrogen fixation is vital to subsistence farming. In other types of farming, the importance of biological fixation is often overshadowed by fertilizer nitrogen. The apparent potential for biological fixation exceeds its present utilization.

Reasons for underutilization of biological fixation include a) fertilizer nitrogen has been less expensive and is easier to manage than biological fixation, b) yields of grain legumes are generally low and grain legumes have usually not responded to high levels of management, c) technology for legume-based forage systems for animal production on marginal soils was not available, d) there was (and is) a general lack of knowledge about the potential for nonsymbiotic fixation.

There are no major biological or soil-related constraints of symbiotic nitrogen fixation that cannot be alleviated with appropriate technology and amendments. The biological limitations on nonsymbiotic fixation are less clear, but there appear to be many ways of augmenting the contribution from nonsymbiotic fixation.

Major research areas that need emphasis in the near future include a) selection and distribution of proper strains of *Rhizobium* suited to local soils and matched to local cultivars, b) utilization of soil amendments such as phosphorus and molybdenum, c) development of superior yielding varieties of grain legumes, d) development of legume-based forage production systems for soils marginal for food grain production, e) development of mycorrhizal inoculants for legumes, f) development of improved methodology for estimating

Boyce Thompson Institute at Cornell University, Ithaca, N.Y., USA; Department of Agronomy, Cornell University, Ithaca, N.Y., USA; International Crops Research Institute for the Semi-arid Tropics, Hyderabad, India; and International Rice Research Institute, Los Baños, Philippines.

nonsymbiotic nitrogen fixation, g) selection of variant forms of azolla and blue-green algae that are suited to local soils, and h) development of screening methods for associative nitrogen fixation and screening of appropriate germplasm.

IN PAST CENTURIES, farmers depended on biological nitrogen fixation, manures, composts, etc., as sources of nitrogen for crop production. The use of commercial nitrogen fertilizer in agriculture is a recent innovation and is an important factor supporting high crop yields in some parts of the world.

Cereal crop yields on what are now subsistence farms cannot be expected to increase without an increased input of nitrogen. Farmers in the developed nations use fertilizer nitrogen, and average national yields are correlated with fertilizer use. Should this be the model for development or should biological nitrogen fixation be considered as an alternative? We are convinced research on biological nitrogen fixation is essential for the following reasons.

- Biological nitrogen fixation is the only alternative to factory manufactured fertilizer nitrogen, which requires fossil fuels and a large capital investment in manufacturing facilities. The uncertainty in fossil fuel supply makes fertilizer nitrogen supply also uncertain and jeopardizes the present precarious balance between cereal grain production and population.
- The infrastructure and socioeconomic development necessary to make commercial nitrogen fertilizer available to many farmers in the developing regions of the world will not be present in the immediate future. To improve the lot of the subsistence farmer, researchers should concentrate on methods or systems whereby he may produce more food without fertilizer nitrogen.
- Increasing biological nitrogen fixation requires some inputs -- perhaps a change in the farming system, and the use of inoculants, new seeds, and soil amendments. Even the minimum inputs also require some infrastructure development and extension, but the costs are likely to be less than those currently associated with fertilizer nitrogen. In many situations, changes in energy costs would make biological nitrogen fixation a viable alternative to or complement of fertilizer nitrogen.
- One should interpret with caution the historical record of fertilizer nitrogen vs biological fixation. Is the current widespread use of fertilizer nitrogen a good example of a fulfilled prophecy? The predictions over the last 25 years that fertilizer nitrogen would substitute for biological fixation are consistent with past and present trends. Perhaps biological fixation is less important now because the necessary technology has not been developed. If half the money invested in the last 25 years in nitrogen fertilizer research and extension had been diverted to work on biological nitrogen fixation, we suspect today's situation would be much different.

This paper summarizes the current knowledge of the constraints on biological nitrogen fixation in tropical soils. It is primarily conceptual in nature and focused on identifying research strategies and priorities.

NONSYMBIOTIC NITROGEN FIXATION IN THE TROPICS

Until recently, it was generally believed that only symbiotic nitrogen fixation (i.e. nitrogen fixation by nodulated plants) had much agricultural importance. Despite the considerable research on nonsymbiotic nitrogen fixation organisms in temperate region soils, the consensus was that they contributed little to the nitrogen economy of agricultural crops (Allison 1955, 1965). Some of the most convincing evidence that nonsymbiotic nitrogen fixation may be important in fields in the temperate region has come from the Broadbalk plots at Rothamsted. Depending on the magnitude of denitrification, nonsymbiotic nitrogen fixation may amount to 18 to 28 kg N/ha annually in plots continuously cropped to wheat since 1843 and receiving no nitrogen fertilizer, and more than 39 kg N/ha in plots left to develop natural vegetation (Jenkinson 1976, Witty et al 1977). Nonsymbiotic nitrogen fixation may be of greater importance in the tropics than is generally known (Nye and Greenland 1960, Moore 1966, Jones and Wild 1975, Dart and Day 1975, De 1936, Neyra and Dobereiner 1977, Granhall 1976), but little data are available to indicate how much is fixed under different cropping systems.

One major constraint to research progress is the lack of a suitable methodology for measuring low levels of biological nitrogen fixation. Estimates can be made by determining an increase in total nitrogen by Kjeldahl analysis, by the fixation of $^{15}N_2$, and by the acetylene reduction assay (Hardy and Holsten 1977). Net changes in total nitrogen over a cropping period determined by Kjeldahl analysis provide the most convincing measure of biological nitrogen fixation. This net change reflects input and losses (about which we know little for tropical conditions), and thus does not represent total nitrogen fixation.

The uptake of $^{15}N_2$ gives the most direct measure of nitrogen fixation, but it is technically difficult (and expensive) to measure, particularly in the field. The relatively low activity of nonsymbiotic systems necessitates long assay times and increases the difficulties of maintaining natural conditions of temperature, humidity, and carbon dioxide concentration during the assay. It is possible that variations in the natural abundance of $^{15}N_2$ in plants and soil can be used in estimating nonsymbiotic nitrogen fixation, but further research is necessary to validate this approach (Hauck and Bremner 1976, Amarger et al 1977, Rennie et al 1978).

Acetylene reduction assays are specific tests for nitrogenase activity at any given point in time, but the extrapolation of data from them to an entire cropping duration can be misleading. Many recent data on nonsymbiotic nitrogen fixation are based on acetylene reduction assays, and have stimulated interest in nonsymbiotic nitrogen fixation in the tropics.

Cultivars of tropical cereals and grasses show genotypic differences in their ability to stimulate acetylene reduction. For example, 10% of over 300 sorghum and 140 millet lines tested at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) had high activity in the field. The activity varies from field to field throughout the season, is reduced by addition of nitrogen fertilizer, and is correlated with soil moisture. The heritability of the ability

to stimulate nitrogenase activity needs clarification before one can select for increased nitrogen fixation by crops.

The flooded conditions associated with rice production provides an environment conducive to nonsymbiotic nitrogen fixation. Recent work at the International Rice Research Institute, Los Baños, has indicated that 35 to 50 kg N/ha may be fixed during a crop of flooded rice. The figures were derived from Kjeldahl nitrogen analysis of the soils from long-term fertility plots that have received no nitrogen fertilizer (De Datta and Gomez 1975, Koyama and App 1979). Biological nitrogen fixation is the most important source of nitrogen, while losses result from volatilization, denitrification, leaching, and runoff. The individual contributions of the cyanobacteria, photosynthetic bacteria, or heterotrophic bacteria cannot be determined from the data.

Kjeldahl nitrogen analysis data from a greenhouse pot experiment on nitrogen balance offer some insight into the basic principles governing nonsymbiotic nitrogen fixation associated with flooded rice. The data in experiment A indicate that rice grown in flooded soil (Maligaya clay loam, pH 6.8) had a positive nitrogen balance (Table 1). The addition of either azolla or phosphorus and iron to the pots significantly increased the positive balance. Inoculation with blue-green algae was not effective because the nitrogen balance of pots receiving iron and phosphorus alone was not significantly different from that of the inoculated pots. This suggests that the indigenous population of blue-green algae was adequate. The data in experiment B indicated that heterotrophic nitrogen fixing microorganisms were active in flooded rice. Their activity depends on the presence of the rice plant – the fallow pots have a negative nitrogen balance. It is not possible to attribute the entire difference in nitrogen balance between the planted and fallow pots to heterotrophic fixation because the rice plant may assist in reducing nitrogen losses. The effect of rice plants on losses of nitrogen from the soil may depend on the nitrogen source (Broadbent and Tusneem

Table 1. Nitrogen balance of flooded soils in pots planted to rice.[a]

Planted to rice	Exposed to light	Supplemental treatment	N balance[b] (mg N)
		4 crops IR28	
+	+	None	387 a
+	+	P, Fe	723 b
+	+	P, Fe, algae	914 bc
+	+	P, Fe, azolla	1153 c
		6 crops IR28	
+	–	None	181 a
–	–	None	–243 b

[a]+ = yes, – = no. Black cloth covered the surface of the pot to prevent soil exposure to light.
[b]All balances significantly different at 1% level. Means followed by the same letter not significantly different at the 5% level (App, Watanabe, Alexander, Ventura, Daez, Santiago, and De Datta, unpublished data).

Table 2. Percentage of nitrogenase-positive isolates (aerobic heterotrophs) in the rhizosphere and stem of IR26 rice.

Portion	Isolates tested (no.)	Nitrogenase-positive isolates	
		No.	%
Rhizosphere soil	41	1	2.4
Stem	24	9	38
Rhizoplane	25	19	76
Histosphere[a]	117	95	81

[a]Within the root and stem tissue after prolonged washing to remove organisms on the surface.

1971, Manguiat and Broadbent 1977).

It appears that most microorganisms found in the histosphere and rhizosplane of rice roots are capable of nitrogen fixation (Table 2). However, they require a supply of nitrogen in the media for growth, and the nitrogenase is only expressed in the presence of organic nitrogen (Watanabe and Barraquio 1979).

Other reports have documented the potential of phototrophic agents for nitrogen fixation in flooded rice fields. Inoculation of paddies with blue-green algae may contribute the equivalent of 25 to 30 kg N/ha in a cropping season (Venkataraman 1975). With appropriate management, one crop of azolla may provide the equivalent of 20 to 40 kg N/ha (Watanabe et al 1977, Rains and Talley 1979).

Soil constraints on nonsymbiotic nitrogen fixation

There are three principal agents recognized as important for nitrogen fixation in rice: blue-green algae, azolla, and heterotrophic bacteria. In the field, algae and heterotrophs are often present, but azolla must be introduced. Growth of and nitrogen fixation by all three agents are vulnerable to water stress, but the economic consequences of water stress on the rice plant are usually more important.

Phosphorus fertilization is required for optimum growth and nitrogen fixing activity by azolla and blue-green algae (De and Mandel 1956, Mitsui 1954, Watanabe et al 1977, Okuda and Yamaguchi 1952). Maintaining an adequate supply of soluble phosphorus in the floodwater of rice is difficult; frequent application may be required if the usual forms of commercial phosphorus fertilizers are employed. Excess acidity is detrimental to the growth of azolla and blue-green algae (Watanabe et al 1977, Fogg et al 1973, Okuda and Yamaguchi 1956, Roger and Reynaud 1977).

Except for some acetylene reduction data, little research has been done on the effect of pH on heterotrophs in flooded rice soils (Matsuguchi 1979). It is possible that heterotrophs will remain active at lower pH values, however, and may be the principal nitrogen-fixing organisms in acid flooded soils. Incidentally, it has been observed that the addition of lime and phosphorus fertilizer appears to assist in maintaining natural nitrogen fertility in flooded rice soils in Japan (Yamaguchi 1979).

Heterotrophic nitrogen-fixing bacteria require a supply of organic matter for optimum activity in soil. This may be derived from root exudates, sloughed off tissue, dead roots, or from plant material that has been incorporated into the flooded soil. Low organic matter supply in soils as a substrate for nitrogen fixation could, therefore, be considered a constraint on nitrogen fixation. The effects of addition of organic matter on soil structure, nitrogen availability, and production of toxic organic substances may have greater economic importance than the benefits from nitrogen fixation (Oh 1979).

High levels of soil nitrogen inhibit nitrogen fixation by bacteria and blue-green algae associated with rice (Balandreau et al 1975, Watanabe et al 1978). The effect of nitrogen fertilizers on nitrogen fixation may be reduced by localized application of the fertilizer as a large pellet and by the timing of the application. The algal symbiont in azolla is apparently insulated by the host fern from combined nitrogen in the environment (Walmsley et al 1973, Peters and Mayne 1974).

Little is known of the effect of trace element deficiencies on nitrogen fixation in flooded rice. Lack of iron in the floodwater limits azolla growth, and molybdenum fertilization has been recommended to stimulate blue-green algal fixation in India (Subrahmanyan et al 1965).

Matsuguchi (1979) has recently reviewed the effect of soil properties on nitrogenase activity in rice soils.

Research priorities

The following research areas are suggested for alleviating soil constraints on nonsymbiotic biological nitrogen fixation:

Methodology. Develop improved methods to estimate and monitor nonsymbiotic nitrogen fixation in the field and greenhouse, particularly with the use of ^{15}N.

Nitrogen balance. Obtain basic information on nitrogen economy of specific crops.

1. Monitor changes in total soil nitrogen.

2. Obtain quantitative data on the importance of both phototrophic and heterotrophic nitrogen fixation.

3. Determine the effects of soil types and properties (acidity, phosphorus availability, etc.), cropping patterns, agronomic practices, and water management on the nitrogen balance.

Azolla.

1. Develop procedures to induce, store, transport, and germinate sporocarps. The establishment of an azolla germplasm bank is an essential prelude to selection and genetic improvement for increased nitrogen fixation. Since azolla cannot at present be crossed, attempts to induce mutations are warranted. Vegetative propagation of azolla is time-consuming, and is an unreliable method of maintaining a germplasm collection.

2. Identify species or variants that require less phosphorus, tolerate lower soil pH and high temperature, resist insects and pathogens, and regenerate

rapidly after drought.

3. Consider crop management.

a. Develop management practices for use of azolla in rice production (inoculum production and use, water management, phosphorus fertilization, insects and pathogen control).

b. Determine the effect on rice yields of azolla as a companion crop in different environments.

c. Evaluate potential of azolla to produce organic fertilizer at another site, or as a green manure crop grown prior to the rice crop.

d. Determine the effect of water management, plant spacing, soil type, and time and method of incorporating azolla residues on the nitrogen availability to the rice plant.

Blue-green algae.

1. Establish a culture collection of nitrogen fixing blue-green algae for distribution of cultures for research.

2. Select for low phosphorus requirement, tolerance for combined nitrogen and for acid pH, competitive ability with non-nitrogen fixing algae and predators in the field.

3. Determine factors during inoculum production and use which influence the number of propagules in the inoculum.

4. Determine factors influencing the density of nitrogen fixing blue-green algae in paddy water, i.e. epiphytes on rice plants and weeds, or surface crust in upland rice.

5. Define the effect of management factors – straw addition and method of incorporation, plant spacing, water management, fertilization with nitrogen and phosphorus, herbicide use, rice genotype, predator control – on blue-green algae in the field.

Associative bacteria.

1. Design screening methods for associative nitrogen fixation and screen appropriate germplasm for varieties that support high rates of nitrogen fixation. Heterotrophic nitrogen fixation is associated with the rice plant and may therefore be manipulated through plant breeding. It may be possible to introduce better rates of associative nitrogen fixation into modern rice varieties developed for tolerance for specific soil constraints.

2. Characterize the primary nitrogen fixing bacteria in the rhizosphere of promising varieties and determine if this population may be altered to better tolerate specific soil constraints.

SYMBIOTIC NITROGEN FIXATION

Grain and forage legumes have the potential to make substantial contributions to the nitrogen economy of crop production systems in the tropics. However, the average yields of grain legumes in the tropics are low and hence the potential of the symbiotic association is not realized. Even where livestock are important in the tropics, pasture legumes are little used. Thus there is potential for increased symbiotic fixation of nitrogen.

Effects of nitrogen fixation on the nitrogen economy of cropping systems

Grain legumes modify the nitrogen economy of cropping systems in three ways: 1) some of the nitrogen in the harvested portion is derived from fixation; 2) when the grain legumes are grown in association with nonlegumes, more nitrogen becomes available to the nonlegume; and 3) some of the nitrogen fixed by the legume remains as a residue, which enhances the nitrogen supply for any subsequent nonlegume and, possibly, a companion crop.

Forage legumes used as livestock feed fix an appreciable fraction of their nitrogen, and part of this is converted to human food when the animal products are consumed. An appreciable amount of organic nitrogen usually accumulates in the soil. This nitrogen is released over several seasons to nonlegume crops if the soil is cultivated after a period under forage legumes, and the manure from animals fed on the legume forage may be a valuable soil amendment for nonlegume crop production.

Both forage and grain legumes may be used as green-manure crops; under proper conditions the supply of nitrogen to succeeding nonlegumes may be enhanced appreciably.

Legume-based symbiotic nitrogen fixation systems

The following principles apply to most legume-based symbiotic nitrogen fixation systems.

1. Legumes fix nitrogen if insufficient nitrogen is supplied by the soil. Inorganic nitrogen in the soil or nitrogen mineralized during the course of the growing season is utilized to the extent that such nitrogen remains in the root zone. The remainder of the crop nitrogen is derived from atmospheric nitrogen. Thus the legumes generally conserve available soil nitrogen and add to it in direct proportion to the size of the sink created by the yield potential of the crop.

2. The host plant and Rhizobium strain must be compatible and the soil and environmental conditions must be favorable for survival of the Rhizobium and for nitrogen fixation in the nodule. Inoculation is necessary where the native organisms are ineffective or where they are absent or sparse (Vincent 1974). A strain that has the ability to persist in the particular soil must be utilized. It seems possible to select also for ability of a strain to move in soil – an important factor for deep-rooted legumes and for competing with indigenous soil Rhizobium populations subsequent to the initial response to inoculation.

Currently, there is considerable work on isolation of strains of Rhizobium that are adapted to a range of soil conditions including acidity (Edwards 1977, University of Hawaii College of Agriculture 1977, Date and Halliday 1979), salinity and high soil temperature (ICRISAT 1977–78). This appears to be a relatively easy means of circumventing soil amendments aimed only at Rhizobium survival. However, it may ultimately mean that several inoculants containing mixtures of several strains must be available for a given country or region. Although this may seem inexpensive relative to soil amendments, the infra-

structure required for proper delivery of the inoculum is not inconsequential.

3. Fixation of nitrogen will be limited by the biological yield of the host plant, even if the proper Rhizobium strain is present and is suited to the host plant and the soil environment. The host plant is the source of energy for the Rhizobium and the sink for the fixed nitrogen. Thus the mode of action of the soil constraints will likely be on yield limitations imposed on the host plant rather than on the Rhizobium if the proper strain is selected, as outlined in the preceding paragraph.

The influence of specific soil conditions on crop growth or nitrogen fixation, or both, varies among legumes, and among the environmental conditions under which they are grown. The basic idea we wish to emphasize is that adding required nutrients or eliminating toxic effects will increase the yield potential of the legume (host) and thereby the need for nitrogen either from the soil or by fixation. Given an effective Rhizobium-legume symbiosis, most of the nitrogen for high yields can be obtained by fixation. Thus the soil amendments must be manipulated so that the yield of the host plant is high, and the proper Rhizobium strain must be provided so that the nitrogen for high yield is obtained by biological fixation.

4. There are soil mineral constraints on host plant yields. In a recent review Munns (1977) summarized experience with the relationships between legume behavior and soil acidity as follows:

> "One does not confidently deduce the behavior of any legume, tropical or temperate, from experience with another. Therefore, this review will include information from legumes of all persuasions, as being likely to have equal relevance or irrelevance to the understanding of any particular tropical species."

We see no particular reason why this same statement cannot be extended to cover other soil constraints. Perhaps it should be extended to include comparisons of legumes and nonlegumes and state that, with the possible exception of molybdenum and cobalt, there are no mineral nutritional requirements peculiar to the legume-Rhizobium symbiosis (Andrew 1977, Franco 1977, Edwards 1977). Molybdenum is required in somewhat greater amount for symbiotic nitrogen fixation than where combined nitrogen is supplied. Molybdenum is likely to be a problem at soil pH below 6 and hence more serious in acid soils. As a result, response to liming may be a response to increased availability of molybdenum associated with increased pH.

Recent reviews point out the importance of phosphorus to yields of legume and by implication, at least, to nitrogen fixation (Franco 1977, Andrew 1977, Edwards 1977). Perhaps the phosphorus requirements of legumes are generally higher than those of nonlegumes; the evidence, however, is not clear. Again, the variability among legume species or varieties is high and generalizations are not useful. Selection of lines with enhanced potential for mycorrhizal infection, and development of mycorrhizal inoculants may be one way of improving legume mineral nutrition.

Limiting factors in symbiotic nitrogen fixation

Any attempt to isolate the effect of the legume on the nitrogen economy of cropping systems is likely to result in ambiguous answers because a basis for comparison cannot be defined clearly. This ambiguity arises because stability of yield, human nutrition, and economic yield are all of overriding importance; the net result of these considerations makes biological nitrogen fixation appear to be of secondary concern. For this review we have formulated three questions.

1. Is nitrogen accretion in the soil-crop system limited by an inadequate legume-Rhizobium symbiosis? This question is answered experimentally by determining if the legume responds to fertilizer nitrogen.

2. Would some soil amendment enhance accretion of nitrogen in the soil-crop system and, hence, food yield or protein yield or economic yield? This question is answered by field experiments with elements other than nitrogen and in the presence of what is known to be an effective legume-Rhizobium symbiosis.

3. Is nitrogen accretion by the soil-crop system limited by some constraints other than the legume-Rhizobium symbiosis and soil amendments? This refers to host plant yield potential primarily and such constraints as diseases, insects, growth characteristics, etc.

Grain legumes. Proceedings of several recent symposia have pointed out that average yields of grain legumes obtained by farmers in the tropics are often less than a third of experimental yields (ICRISAT 1975, Vincent et al 1977, Rachie 1977). The reasons are numerous, but are usually attributed to water deficits, diseases, insects, and soil constraints of various kinds.

In 24 out of 50 experiments, mostly in Brazil, Franco (1977) found that *Phaseolus vulgaris* responded to fertilizer nitrogen. Bazan (1975) reported similar results for Central America. Where soybean in Brazil was properly inoculated, response to fertilizer nitrogen was small (Franco 1977). Pigeon pea responded to N fertilizer on an Alfisol in India (ICRISAT 1977–78).

Grain legumes are an integral part of many intercropping systems throughout the world (ICRISAT 1975, Andrews and Kassam 1976, Papendick 1976, Willey 1979). The exact contribution legumes make to the nitrogen economy of the system is difficult to measure (Henzell and Vallis 1977).

An analysis of the data from several field experiments (Dalal 1974, 1977; Agboola and Fayemi 1971; Centro Internacional de Mejoramiento de Maiz y Trigo 1974; Oelsligle et al 1976; Saxena and Yadav 1974; Enyi 1973; Indian Agricultural Research Institute 1976; Singh 1977) on monocultures and polycrops of legumes and nonlegumes indicates that:

- Polycropping of a grain legume with a nonlegume grain will sometimes result in protein yields larger than that in a monoculture of the nonlegume grain.
- Yields of total grain in a polycrop are often not increased much and may even be decreased relative to a cereal monoculture.
- The yield of both legume and nonlegume responded in some cases to fertilizer nitrogen, indicating the legume-Rhizobium symbiosis was not working properly.

• The yields of the polycrops were sometimes increased by nutrients other than nitrogen, indicating the limitations of nutrients other than nitrogen.

Legume-based forage production. Production of livestock in the vast areas of the world where soils are marginal for food crop production is an attractive possibility. A necessary condition for its realization is the development of a legume-based forage production system (Jones 1977, Wilson 1978). Thomas (1973) concluded that tropical pasture legumes in Africa under good management have yield potentials that fall within the range of the results obtained in Australia and in the temperate regions. The Centro Internacional de Agricultura Tropical (1977, Sanchez and Tergas 1979) has an extensive program on forage for beef production based on legume nitrogen for the highly weathered soils in the wet-dry tropics. The experimental results to date illustrate the tremendous potential of this system.

In India, legume-based forage production will be on soils where food crop production is marginal. However, these areas are extensive (about 20% of the total land area available for agriculture in semiarid tropical India) and at present unproductive because of the high and uncontrolled grazing pressure, and lack of inputs. Seed preparation, soil fertility, and soil water problems are the important constraints. In other areas such as the llanos high plateau in South America and the lowland humid tropics, soil acidity and low fertility are the major constraints.

The major consideration becomes one of getting acceptable production with only minimum soil amendments and other management inputs. Selection of appropriate plant species and Rhizobium strains, and finding ways of making a small amount of soil amendment have a large impact should be the research goal.

One additional development that would be of great value is rotation systems with several years of pasture production followed by several years of food grain cropping. Such a system has promise for parts of Africa where the tsetse fly is not endemic (Musa and Burhan 1974), and for parts of South America. It is not yet in operation in the tropics on any extended scale, and is yet to be tried in much of the semiarid tropics.

Residual effects of legumes

The net benefit of legume-derived organic residues to succeeding nonlegumes depends on the amount of residue and on its rate of mineralization. Unfortunately, neither factor is well understood.

Grain legumes. Two factors limit the residual effects of grain legumes:

1. The major portion of the total plant nitrogen is removed in the seed and hence the amount of nitrogen in the residues is small. Exceptions are plants with either extensive root systems or large leaf drop (or both) such as pigeon pea.

2. The mineralization of soil nitrogen under grain legumes is likely to be comparable to that under nonlegumes and hence the rate of decline of soil organic nitrogen may be high (Wetselaar et al 1973, Juo and Lal 1977). Therefore, the substitution of a grain legume for a nonlegume grain crop in a cropping system may have only a minor effect on succeeding crops (Burhan and Mansi

1967, Jones 1974, Saxena and Tilak 1974). Compared with cereals, the grain legumes *Lathylus sativus*, chickpea, groundnut, and cowpea in India, however, can have measurable residual effects on subsequent cereal crops equivalent to 20–50 kg N/ha of fertilizer (ICRISAT 1977–78, Giri and De 1979).

Forage legumes. Usually much organic nitrogen accumulates over several years under legume-based forages. Cultivation of a nonlegume following several years of forage legumes usually releases 40 to more than 100 kg N/ha during the first crop, and gradually diminishing amounts to succeeding crops (Moore 1962, Smith 1962, Henzell et al 1966, Jones et al 1967, Jones 1967, Watson 1969, Wetselaar et al 1973). With irrigation in subtropical zones, a single season of legume fodders such as Berseem clover and lucerne can considerably enhance the nitrogen uptake by subsequent cereal crops. The potential for use of siratro *(Macroptilium atropurpureum) crotolaria* spp., *Lab lab purpureus* and similar rapidly growing legumes as one- to two-season fodder crops preceding cereals has been little explored.

Legume green manures and legume fallows. A legume green manure is grown during only one season; a legume fallow is grown for more than one season. Neither is harvested. Experiments in the tropics (Schofield 1945, Clark 1962, Jaiyebo and Moore 1964, Watson and Goldworthy 1964, Kannegieter 1969, Agboola and Fayemi 1972, Shel, a and Humphreys 1975, Juo and Lal 1977) indicate that:

- Legume green manures accumulate 100 to 250 [illegible] N/h[illegible] during a favorable growing season; 20 to 60% of this is mineralized u[illegible]r a cultivated crop during a subsequent growing season.
- Under some circumstances, soil organic nitrogen accumulates faster under legume fallow than under natural fallow.
- Legume green manure and fallow are not used much because from the farmers' viewpoint (apparently), the benefits do not justify the management and costs of growing the legume, nor the loss of a grain or cash crop.

Leguminous shrubs and trees. Species such as *Leucaena latisiliqua* and *Desmanthus virgatus* can be more productive of good quality forage than herbaceous species, and fix large amounts of nitrogen. More woody species such as *Sesbania grandiflore* and *Alysicarpus rugosus* can grow to 20 feet in 2 years and produce firewood and timber as well as some fodder. The nodulated nonlegume *Casuarina* spp. grows just as rapidly and is used extensively in parts of tropical India. It enriches the soil with considerable amounts of fixed nitrogen and farmers take advantage of this by growing it in rotation with annual crops. More extensive use of such plants particularly on otherwise wasteland would reduce the removal from arable fields of organic matter for animal feed.

The foregoing literature review indicates:

1. There is much evidence with *Phaseolus vulgaris* of a response to fertilizer nitrogen under experimental conditions. There is a similar response for pigeon pea, but few such experiments have been conducted with other grain legumes in the tropics. Surveys reveal poor nodulation of grain legumes in many farmers'

fields. Thus, there is reason to believe that in some areas, yields of grain legumes could be improved by inoculation. The major constraint is the lack of Rhizobium strains adapted to the soil fertility status and, more importantly, competitive with indigenous soil Rhizobium populations.

2. Yields of grain legumes are often low, even when soil fertility is not an apparent constraint. This is probably because land races have been selected primarily for stability of yield (e.g. pigeon pea), or the cultivars grown are poorly adapted to the environmental conditions. For example, chick-pea yields on experimental stations in peninsular India are about 1,500 kg/ha, but in North India they may reach 5,000 kg/ha. Thus, factors other than the Rhizobium-legume symbiosis and soil amendments appear to limit yields.

3. Not much use is made of legume-based pasture and fodder production although such systems have enormous potential. The major limitation is lack of suitable technology for giving relatively large yield increases with limited inputs.

4. Much of the work on the nitrogen economy of cropping systems with legumes is based on dryland cropping systems. In work on relay cropping in flooded wetland systems and successive dryland crops, little attention was given to the nitrogen economy of the system (Gomez and Zandstra 1977). Hence, little is known of the soil constraints to nitrogen fixation in such systems.

5. Legume green manures and legume fallows provide a large amount of nitrogen for a subsequent nonlegume grain crop, but this system is not used much in the tropics, probably because the farmer does not want to devote a whole crop season to nitrogen accretion.

6. The availability of low-cost nitrogen fertilizer has reduced the role of biological nitrogen fixation in agriculture. Symbiotic fixation was not an attractive source of nitrogen for subsequent cereal crops in countries with any degree of land pressure because applying fertilizer was easier and cheaper. The advent of fertilizer-responsive, high yielding cereals increased the requirement for nitrogen beyond that which biological nitrogen fixation had been supplying. In countries like Australia where the pressure on land is less, symbiotic fixation still contributes most of the nitrogen for cereal production. Lack of high yielding varieties of grain legumes contributed to a change in land use from pulse to cereal production.

Research and development opportunities

In many places, grain legumes respond to fertilizer nitrogen and inoculation; this means that there is a deficiency in the symbiotic relationship, which presumably can be corrected by inoculation with the proper strain of Rhizobium. This could have an immediate impact on food production.

Grain legumes often respond to phosphorus fertilizer. Research on the sources of phosphorus and methods of use that minimize the cost of this input is likely to result in increased yields. The potential for mycorrhizal inoculants needs to be carefully explored.

The critical role of molybdenum in nitrogen fixation suggests that in acid

soils (below pH 5.5 or 6.0) attention should be given to field studies on crop responses to molybdenum.

Much more work needs to be done on selecting varieties for specific soil situations. This should lead to better yields, an extension of the area where legumes can be successfully cultivated, and a reduction in the need for soil amendments.

Water deficiency and excess are major limiting factors in many areas; research on ways to limit their impact on nitrogen fixation is needed.

The use of legume residues and green manures in nontraditional ways should be investigated. The possibilities include:

a. Legumes planted at the end or beginning of the traditional cropping season, or as live mulches under other crops, perhaps combined with the use of herbicides and limited tillage. This is particularly needed for flooded rice cropping systems.

b. Selection of grain legumes with large amounts of residues. This characteristic need not be inimical to higher grain yields.

Much effort is being devoted to selecting and breeding legume varieties with high yield and nitrogen fixation potential, to finding effective Rhizobium strains for specific adverse soil conditions, and to cropping systems utilizing legumes. Microbiologists must work with soil and plant scientists in the field as part of a team working on improvement of legume production. The experience of most soil microbiologists is largely confined to the laboratory and greenhouse and it takes time to become accustomed to the harsh realities and frustrations of field work. The time has come to ensure that proper microbiological input is available for field experimentation.

It is now necessary to narrow research objectives to fit specific situations (soils, climates, social and economic situations) and to include utilization in farmers' fields. For example, we know that the effectiveness of Rhizobium strains differs among cultivars and soil environments; the objective then should be to get proper strains into use in farmers' fields where the present soil populations are inadequate. Experience demonstrates that the path from clearly defined results in experiments to utilization in farmers' fields is strewn with problems.

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Water stress as a constraint to crop production in the tropics

T. C. HSIAO, J. C. O'TOOLE, AND V. S. TOMAR

Plant water stress results from the interaction of soil water status, evaporative demand, and physiological factors. This paper first reviews the fundamentals of water flow in the soil-plant-atmosphere continuum using a conceptual and simple hydraulic tank model. The model emphasizes the importance of soil water-holding capacity, rooting depth, water potential gradients, flow resistances, and a threshold water potential triggering stomatal closure in leaves. Attention is also directed at the unavoidable reduction in carbon dioxide assimilation and dry matter production accompanying stomatal closure and transpiration control. Some physical and physiological fundamentals underlying the model are given. The allowable lower limit of leaf water potential is discussed in the light of the known sensitivities of expansive growth and carbon dioxide assimilation to water stress.

Selected examples from the tropics where soil and rooting characteristics resulted in plant water stress and constrained production are then reviewed. Data from the International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, are notable for illustrating the crop-soil interactions and behavior described by the hydraulic tank model.

The third part briefly covers some methods of measuring plant and soil water status and the assessment of soil water usable by crops grown for high productivity. The need to know plant water status and associated physiological changes is emphasized. A new semi-empirical procedure is proposed for the estimation of the allowable

Agronomy Department, IRRI, and on sabbatical leave from the Department of Land, Air, and Water Resources, University of California, Davis, CA 95616, USA; Agronomy Department, IRRI; Agronomy Department, IRRI, and on study leave from the Department of Soil Science, G.B. Pant University of Agriculture and Technology, Pantnagar, Nainital, India.

lower limit of soil water potential in various depth layers of the root zone. The procedure explicitly accounts for the effect of total rooting depth on this limit.

Future research needs conclude the paper. Specific needs include: more data on water content as related to water potential for tropical soils and on the presence of root restricting layers; evaluation of crop species for potential rooting depth and rooting depth in low-input agriculture; evaluation of germplasm for root-related drought adaptability; and development of more accurate and theoretically based practical procedures for assessing amounts of soil water extractable by crops.

THIS CONFERENCE FOCUSES on constraints imposed by the soil on crop production. Soil serves as a storage reservoir for excess water when rainfall exceeds evapotranspiration (ET); the stored water can be used by crops during periods of rainfall deficit. The portion of water stored in the soil that is usable by the crop is dependent on the ET rate, rainfall excess, and the maximum water-holding capacity of the soil, as well as on two crop factors: the effective rooting volume and the maximum allowable tissue water stress. Thus, in discussing the soil's role in water stress and drought, the whole soil-plant-atmosphere system must be taken into account.

We start with a conceptual review of the soil-plant-atmosphere continuum, with emphasis on the soil as the water reservoir, on rooting as a means to tap the reservoir, and on allowable levels of water stress. We use two terms whose definitions apply to this paper and may not conform with certain usages in the literature. Water stress refers to water shortage in the plant and tissue. Drought is a period when rainfall deficit is substantial. Whether there is water stress for a particular crop during a drought depends on the pertinent soil and crop factors, discussed next.

THE SOIL-PLANT-ATMOSPHERE CONTINUUM

Crop water uptake and water balance

Only a fraction of 1% of the enormous amount of water taken up is retained in the plant tissue. Yet this minute fraction is all-important – even a small variation can make the difference between no growth and vigorous growth. The water retained is dependent on the balance between uptake and loss by transpiration. Uptake is the consequence of transpiration. Transpiration, in turn, is largely determined by the supply of energy to the crop, mostly from solar radiation.

The absorption and movement of water is a passive process, downhill in terms of the energy status of the water. Water energy status is commonly expressed as

water potential (ψ) which can be taken as the free energy or potential energy per unit volume of water. The potential of water at a particular site is the sum of all the factors that affect its free energy content.

In the soil-plant system, water moves passively from where its potential is high to where its potential is low. The steeper the water potential hill (water potential gradient), the faster the water moves, other things being equal. Another factor affecting movement is the ability of the pathway to conduct water. Commonly, the conductance of soil for water from the bulk soil to the root surfaces decreases sharply with decrease in soil water content. If roots are less dense, soil conductance is also lower, as is root conductance from its surface to the plant shoot. In addition, the intricacies of the vascular system, such as dimensions and numbers of xylem elements, affect the conductance of roots and shoots. Quantitatively, the rate of water movement Q between two points in a path is the product of conductance C of that path segment multiplied by the water potential difference ($\Delta\psi$) between the two points of the path. Conductance is often expressed as the inverse of resistance R. In equation form,

$$Q = C^{source \rightarrow sink} (\Psi^{source} - \Psi^{sink})$$

$$= \frac{(1)}{R^{source \rightarrow sink}} (\Delta\Psi^{source \rightarrow sink}) \qquad (1)$$

This means that to maintain a given water flow rate, only a small $\Delta\Psi$, corresponding to a gentle Ψ gradient, is needed across a path segment of high conductance but a large difference (a steep gradient) is necessary across a path segment of low conductance. Conductance as used here differs from conductivity in that the former incorporates the effects of path length and cross-sectional area as well as the intrinsic conductivity of the path.

As plant leaves transpire, water content is reduced as is Ψ. The reduction in leaf Ψ steepens the Ψ gradient from soil to roots to leaves and causes faster water uptake. Such increases in uptake result from the lowering of Ψ at the downstream end of the flow path. The plant pays the price of a lower leaf water status (a lower Ψ) to effect the faster uptake. Uptake can also be accelerated by increasing Ψ at the upstream end. Irrigating a dry soil steepens the Ψ gradient from the soil to the plant and increases soil conductance.

In the natural environment, water uptake and transpiration rates usually are not equal and the plant undergoes a daily cycle of net water loss and gain. The cycle is set primarily by solar radiation. From sunrise to midday, uptake lags behind transpiration because uptake depends on the Ψ gradient generated by transpiration, leading to a continuous decline in tissue Ψ. In the afternoon, transpiration slows, but the slowing of uptake lags and the plant recovers to a more favorable Ψ level in the evening. It follows that a plant experiences its lowest water status around noon on a sunny day.

The water storage capacity of most plants is small relative to the rates of water loss and uptake. Thus, a delicate balance must be struck between water

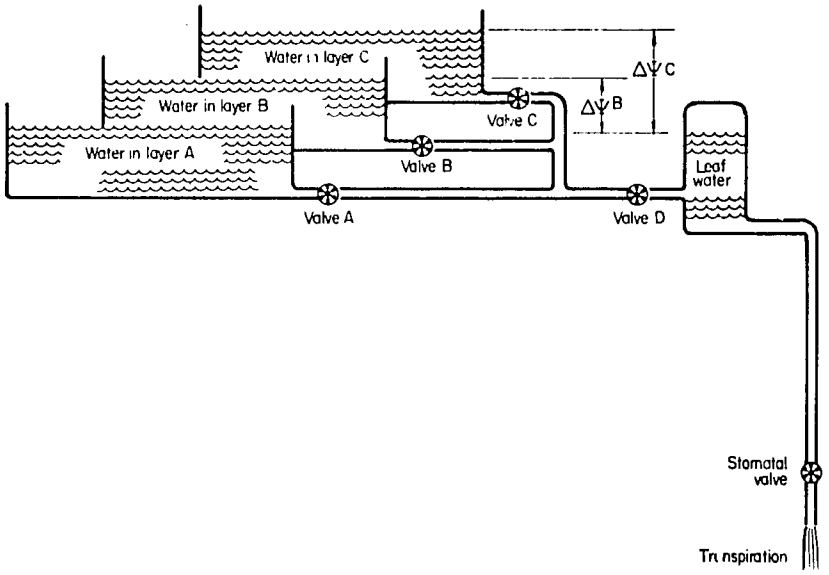
income and water expenditure all the time to avoid excessively low Ψ levels, which damage the tissue. Plants have evolved means to aid in the maintenance of this balance. The most important are the operation of stomata, and leaf rolling in some monocots. Stomata are the main ports through which water vapor is lost. Stomata are equally important as main ports through which atmospheric carbon dioxide is assimilated. During the day and when water deficiency is not severe, transpiration proceeds according to evaporative demand, while open stomata ensure adequate inward passage of carbon dioxide for photosynthesis. Water deficit in the leaves may develop up to a point without any effect on the stomata. When it becomes excessive, the stomata close partially to slow transpiration, with the unavoidable concurrent reduction in carbon dioxide assimilation. Thus, the stomata operate as safety valves in checking water loss and minimizing the development of severe water stress in the plant. The tradeoff, however, is that dry matter production also slows.

Soil as a water reservoir, rooting, leaf water status, and transpiration control: a hydraulic model

The water storage capacity of a soil profile is readily determined; but the proportion of the soil profile tapped by the crop is more difficult to ascertain. Still harder to assess is the level to which the reservoir water may be depleted before the crop suffers significantly from water stress. The traditional approach assumes a reasonable rooting depth and calculates the so-called *available* water as that held between field capacity (FC) and soil Ψ of -15 bars (permanent wilting percentage or PWP). Had this procedure been faithfully followed, much of irrigated agriculture would be ruined. It turned out that a fudge factor – *allowable depletion* – had evolved and is now in common use. Usually, the allowable depletion is chosen by trial-and-error, and sometimes even arbitrarily, to be a small fraction (e.g. 30%) of the total *available* water. To us, the need for this factor constitutes strong evidence for the abandonment of the *available* water concept based on a lower limit of water at -15 bars and points to the need to update the estimating procedure.

The danger of the traditional approach lies in the oversimplification of a problem that varies with crop rooting and development and is made even more complex by interaction with the atmosphere. For clarity, we resort to a hydraulic tank model (Fig. 1). The model aids in appreciating the roles played by 1) soil water-holding capacity, 2) rooting depth, 3) soil Ψ, 4) conductance or resistance of the soil and the plant, and 5) the minimum plant water status that must be maintained to avoid significant detrimental effects on the crop.

The model (Fig. 1) represents different soil depth layers as a series of tanks, each serving as a separate water reservoir. The tanks are connected through regulating valves to a tank representing plant (more specifically leaf) water. The valves (A, B, and C) connected directly to the soil tanks represent soil and root conductance (or resistance) at each of the soil layers. Valve D connecting directly to the leaf water tank represents plant shoot conductance. An increase in con-



1. A hydraulic model depicting a soil profile divided into depth layers as a series of reservoir tanks supplying water to a crop. Water levels in the tanks represent Ψ as well as the extent of filling. Differences in levels between the tanks for each soil layer and the leaf tank represent the driving force (ΔΨ's) for uptake. Note that the soil profile may be represented by as many layers (tanks) as appropriate, and the storage capacities (tank size) of the layers usually are not the same.

ductance (or decrease in resistance) would be thought of as some opening turns of the valves, and a decrease, some closing turns. There is a feedback link (not explicitly shown) between the stomatal valve and the water level in the leaf such that when the leaf water drops to a threshold level, the valve is triggered to shut and reduces transpiration. Above that threshold, leaf water level can fluctuate without any effect on the stomatal valve.

Figure 1 shows that the volume of soil water accessible to the crop depends on the size of the storage capacity (tank size) of each depth layer, its fullness, and the number of layers (soil tanks) *exploited* by the roots. The levels of water in the tanks reflect not only the volumes of water stored, but also soil Ψ and

leaf Ψ. The difference in water levels between the soil and leaf tanks is the $\Delta\Psi$ that drives the water flow from a soil layer to the leaves.

During a dry period, crop transpiration continues unabated as long as the stomata (stomatal valve of Fig. 1) of the leaves remain fully open. This in turn gradually depletes the water in the reservoirs and soil Ψ (water levels in tanks) drop. At the same time, soil conductances decrease because of soil drying (closing of valves A, B, and C). Yet water flow from the soil to the plant must remain about as before because transpiration remains the same and changes in tissue water content represent an insignificant quantity relative to the flow rate. How is this flow maintained in spite of the drop in the levels of the supply reservoirs and partial closing of the connecting valves? The answer is simple. Leaf Ψ (leaf tank level) must drop not only to a level to compensate for the drop in soil Ψ (soil tank levels) but further to a level to compensate for the decrease in conductances as well. In terms of equation 1, leaf Ψ must drop more than soil Ψ so that $\Delta\Psi$ increases to compensate for the drop in $C^{soil \rightarrow leaf}$.

As the soil water depletes further, eventually leaf Ψ drops to the threshold level for the activation of stomatal closure (stomatal valve). The closure restricts water loss from the crop and slows the further depletion of soil water.

The model emphasizes the importance of rooting depth in supplying water to the crop and allows the consideration of differential drying of the soil layers. Deeper rooting by the crop means connections to more soil tanks (e.g. increasing the tanks to six), and extremely restricted rooting, connection to only one. Connections to more tanks suggest not only a larger total reservoir to draw on, but also a smaller $\Delta\Psi^{soil \rightarrow leaf}$ for a given transpiration rate because the flow from each tank is a smaller fraction of the total flow or transpiration. Thus, $\Delta\Psi$'s to maintain the flow would be smaller and leaf Ψ can be kept higher for a given soil Ψ.

In reality, soil Ψ in the root zone is hardly ever uniform. A full soil profile usually dries first in the upper layers, and the dry zone descends through time if no recharge occurs (Hsiao et al 1976a, b). Hence, water supply is restricted to fewer and fewer layers, necessitating a drop in leaf Ψ and steeper Ψ gradients for uptake from the remaining moist deep layers to meet the evaporative demand.

The model also illustrates the importance of knowing the maximum allowable tissue water stress when considering the amount of soil water usable to the crop. As long as the water level in the leaf tank is lower than the level in one of the soil tanks, some water will flow from the soil to the leaf. So most of the soil water can be extracted by a crop, provided that the Ψ of the crop drops low enough. Clearly there must be a limit to the fall in leaf Ψ if productivity is to be maintained. To hold the leaf above that limit while maintaining the necessary flow to keep up with transpiration, soil Ψ must be sufficiently higher than the lower limit for leaf Ψ to account for the resistance to flow from the soil to the leaf. The sum of volumes held in the soil tanks between the lower limits for soil Ψ and the upper limits at the start of a drying cycle is the total water volume usable to the crop.

Soil as water reservoirs, rooting, and leaf water status: physical fundamentals

Our model (Fig. 1) relates to the mundane experience of water flow in daily living and is easily understood. We now discuss the physical fundamentals underlying the model.

The resistance of the flow path from soil to leaf consists of three components, arranged in series, and therefore additive. Applying equation 1 to the rate of uptake Q by the foliage of a crop,

$$Q = \frac{1}{R^{soil} + R^{root} + R^{shoot}} (\Psi^{soil} - \Psi^{leaf})$$

When the leaf water status is not changing rapidly, leaf water uptake must be nearly equal to leaf transpiration rate T. Substituting T for Q and rearranging,

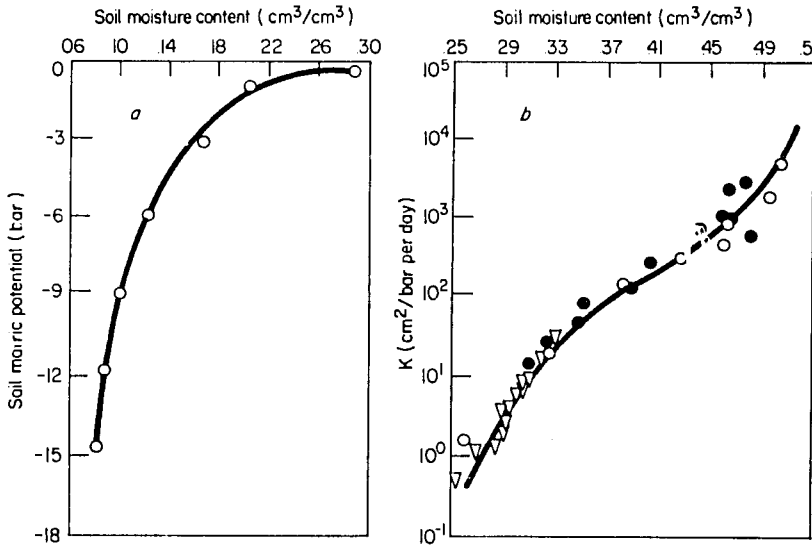
$$\Psi^{leaf} \simeq \Psi^{soil} - T(R^{soil} + R^{root} + R^{shoot}) \qquad (2)$$

The result shows that to maintain a given leaf Ψ, soil Ψ must be more positive by a factor of the transpiration rate times the sum of soil and plant resistances. This factor may be termed potential loss, analogous to the term *head loss* in hydraulics. The Ψ lost is that used to compensate for resistance(s). Equation 2 emphasizes the fact that there is no unique relationship between leaf Ψ and soil Ψ. Excessively low leaf Ψ can be caused by soil drying, high transpiration or high plant resistances, or any combination of those factors. Thus, searches for a widely applicable single soil Ψ value to maintain a desired leaf or plant Ψ level will fail.

When the crop is not short of water and is actively growing, T is largely determined by the evaporative demand. Space does not permit further elaboration here and pertinent references (Rosenberg 1974, Doorenbos and Pruitt 1977) should be consulted.

As for soil Ψ, two major factors affecting it are dissolved solutes and interactions with the solid soil matrix. In soils low in salts, Ψ consists of mostly the matrix potential Ψ_m, which is a function of soil water content and the pore size distribution of a soil. Its behavior during a wet-dry cycle is described by the soil moisture release or characteristic curve. As seen in Figure 2, as the soil moisture content (θ) declines, so does the soil Ψ_m. The shape of the curve varies from soil to soil because of variations in the pore size distribution. Hence, both texture and structure affect the shape of this curve.

Another soil parameter in equation 2 is soil R. Soil conductance, and therefore soil R, must depend on the hydraulic conductivity (K) of the soil. In addition, however, rooting density plays a critical role, as will be elaborated below. Hydraulic conductivity drops sharply with decreases in soil water content (Fig. 2b). Most significant is the fact that for every 0.1 cm^3/cm^3 reduction in θ, K decreases nearly a hundredfold. This drastic reduction in K is due mainly to the restriction of water flow to the close proximities of the surfaces of solid soil particles.



2. a) Soil moisture release curve (Tomar and Ghildyal 1973) and b) hydraulic conductivity curve (Tripathi and Ghildyal 1975) of Beni silty clay loam, a Mollisol, at Pantnagar, India.

Rooting density also affects soil R. This is because with more roots distributed in a given volume of soil, the effective cross-sectioned area of soil for conducting water to roots is increased and the effective flow path length is reduced. For a more quantitative approach, we use the treatment of Gardner (1960). Starting with Darcy's law, an equation can be derived for an idealized depth layer of soil-root system that relates the rate of water transport q (from the bulk soil to the root surface) to the Ψ gradient ($\Psi^{soil} - \Psi^{rs}$), the soil hydraulic conductivity K, and the root length density L_v (cm of roots/cm^3 of soil) in that soil layer,

$$q = \frac{4\pi L_v \Delta z K}{-\ln(\pi L_v) - 2\ln r} (\Psi^{soil} - \Psi^{rs})$$

$$= \frac{1}{R\ soil} (\Psi^{soil} - \Psi^{rs})$$

Here Δz is soil layer depth in cm (e.g. 20 cm), r is the mean root radius in cm, and Ψ^{rs} is Ψ at the root surface. The derivation of this equation involves several simplifying assumptions with their attendant uncertainties (Hsiao et al 1976b). Nonetheless, the equation is useful to show that soil R is a function of both soil K and rooting intensity in a given depth layer:

$$R^{soil} = \left[\frac{-\ln(\pi L_v) - 2\ln r}{4\pi L_v \Delta z}\right] \frac{1}{K} \qquad (3)$$

Thus, rooting geometry, as expressed by the terms enclosed in the brackets of equation 3, is as crucial as soil K in determining soil R. As an approximation, a given proportional increase in either L_v or K would reduce soil R by about the same proportion. It is important to point out, however, that in general K changes logarithmically with soil water content, as exemplified by Figure 2b. The drying of a soil can cause such a marked reduction in K as to obviate any increase in L_v brought about by growth.

Equation 3 is written for a soil layer nearly homogeneous in rooting density, soil Ψ, and soil K. The entire root zone may be divided into such layers, with roots in each layer connected more or less independently to the base of the plant shoot, as parallel pathways for conducting water from individual soil layers.

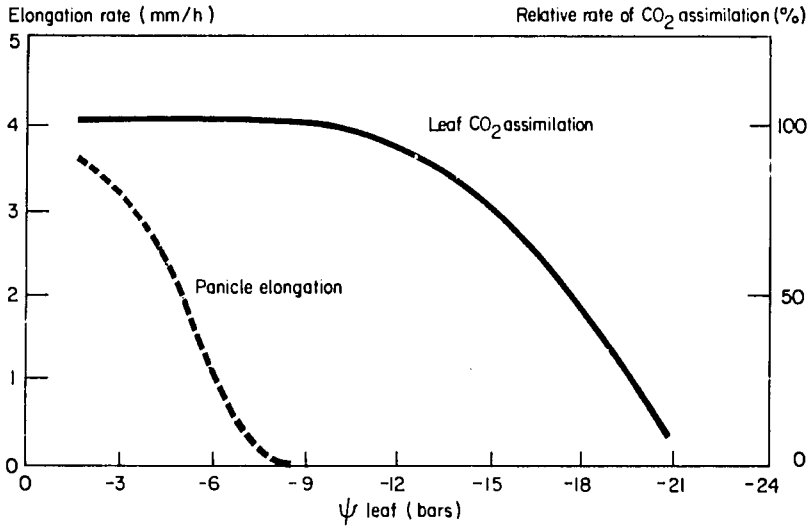
The remaining parameters in equation 2 are plant resistances. As may be expected, root development appears to affect root R markedly. In one study, increasing L_v reduced root R, apparently because more parallel root paths are created for radial and longitudinal transport (Hsiao et al 1976b). More quantitative data along this line are badly needed.

Our knowledge on shoot R is also sketchy. It is now certain that in many crops shoot R is not negligible relative to root R as erroneously assumed earlier. On the other hand, shoot R appears to vary markedly among species and even with crop ontogeny (Acevedo 1975). Again, more information is needed.

Returning to equation 2 and its three resistances in series, we emphasize that when rooting is extensive and the soil quite wet, soil R is estimated to be negligible relative to root R (Newman 1974, Greacen et al 1976) and relative to root and shoot R's (Acevedo 1975). In such cases, therefore, a partial drying of the soil, through reducing soil K and raising soil R severalfold, would hardly affect the total resistance to water flow.

The desired lower limit of leaf or shoot water potential

How far should leaf Ψ or shoot Ψ be allowed to drop during a drying cycle? One certainly wants to avoid restricting carbon dioxide assimilation per unit leaf area for any sustained duration since it is the basis of dry matter accumulation. Therefore, leaf Ψ should be kept at levels above the minimum level that induces stomatal closure. Indications, however, are that even such levels are too low, at least during some growth stages, if one desires high productivity. Ample studies have shown that the physiological process most sensitive to water stress appears to be expansive growth (Hsiao 1973). Apparently this is the consequence of turgor pressure in sustaining cell enlargement (Hsiao et al 1976a). In fact, expansive growth is so sensitive to water deficiency that, in some cases, any reduction in tissue Ψ reduces growth (e.g. Fig. 3). In other cases, especially in plants adapted to an arid environment, a few bars of reduction in tissue Ψ affect growth little, but further reduction has marked effects. In our experience, the first indication of water deficiency is often a reduction in size of plants in the field compared with plants on well-irrigated plots. Because of inherent variability, the difference in leaf Ψ becomes readily measurable only later, when stress becomes more intensive.



3. Panicle elongation and leaf carbon dioxide (CO_2) assimilation rates as related to leaf Ψ in sorghum. The curves were generalized from replicated plants grown in the field and moved to the laboratory on the day of measurements. Leaf Ψ was measured with an intact-leaf dewpoint hygrometer on the second leaf (flag leaf taken as first), covered to minimize Ψ gradients while the same plant was being monitored for panicle elongation with a linear variable differential transformer (Hsiao et al 1970) or for CO_2 assimilation by the same leaf with a gas exchange chamber linked to an infrared gas analyzer. Water status of the plants was lowered gradually by soil drying and, when necessary, by root pruning.

In comparison, stomatal opening and the related carbon dioxide assimilation and transpiration are considerably less sensitive to water stress (Fig. 3). The first decline in carbon dioxide assimilation and stomatal opening often occurs when leaf Ψ drops to −12 to −16 bars, depending on species and prior growing conditions. This threshold level usually corresponds roughly to the beginning of visible wilting or leaf rolling (Turner 1974, O'Toole and Cruz 1980), which is approximately at the point when cell turgor pressure approaches zero in some parts of the leaf tissue.

The fact that expansive growth is extremely sensitive to water stress has important ramifications. If mild stress develops in the early vegetative stage when foliage is sparse, a slowing of leaf growth would reduce the foliage surface available to capture sunlight and photosynthesize. Although foliage development may catch up with that of the unstressed plants later, the accumulative assimilation per unit land area for the stressed plants would be less for a given crop duration although stress has yet to reach the threshold level to affect the stomata. This would mean less total dry matter yield and possibly less harvestable yield as well (Hsiao et al 1976b). All other developmental processes are also underlaid by expansive growth because cell differentiation and expansion occur concomitantly.

It appears then that for high productivity, even mild water stress should be avoided, especially early in the vegetative stage. As the leaf canopy nears closure, assimilation per hectare would be limited by available light, not by the light-capturing surface. Larger water deficits may be permitted in that case because an additional foliage would be superfluous. During flowering and pollination, however, it is important to keep the tissue water status moderately high, especially if the crop is determinant in flowering habit (Hsiao et al 1976b). Throughout the growth stages, leaf Ψ should be kept above the threshold for stomatal closure.

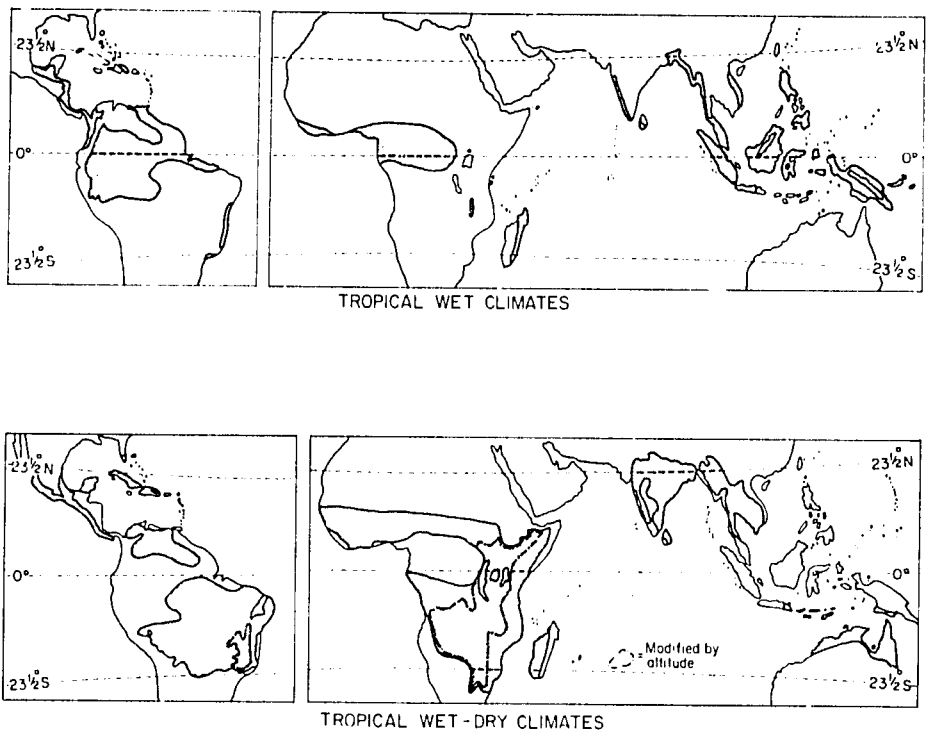
Returning now to the desired lower limit of soil Ψ for maintaining good productivity, and ignoring the early vegetative and pollination stages for the time being, we assume the crop in question has a stomatal threshold of −14 bars. Many measurements on sunny days have shown midday leaf Ψ to range from −7 to −12 bars for well-irrigated field crops and we will use a middle value of −10 bars. With the soil near field capacity, soil Ψ is close to zero. The 10-bar difference in Ψ is the water potential loss needed to compensate for the total resistance and sustain transpiration at midday. Assuming the soil then dries in the bulk of the root zone to −4 bars, and assuming that soil R remains small in spite of the reduced K and is still negligible relative to plant R, now leaf Ψ would drop to around −14 bars at midday, a level just triggering stomatal closure. In reality, soil R may become significant when soil Ψ is in the −4 bar range (Acevedo 1975). Therefore, to prevent stress-induced stomatal closure, the lower limit of usable soil water would have to be placed at a Ψ value more positive than −4 bars. If one is more concerned about expansive growth, or is dealing with a soil that restricts rooting so that soil R and root R are larger, this limit must be raised to a higher Ψ value still. The foregoing discussion shows that it is not possible to effectively use soil water down to −15 bars or PWP. The lowest limit at which to set the lower limit of soil Ψ should correspond to the first sign of wilting, recognizing that this point takes on different values depending on resistances and evaporative demand. While we emphasize the need to raise the lower limit of soil Ψ for good productivity, we appreciate that for crop survival during a drought and water stress, water held at −15 bars or even lower in the soil would be helpful. Some rice cultivars extracted soil water in levels lower than −30 bars, but the plant barely survived and leaf Ψ fell in the same range (O'Toole et al 1978).

AREAS IN THE TROPICS WHERE CROP WATER STRESS IS MODULATED BY SOIL AND ROOTING FACTORS

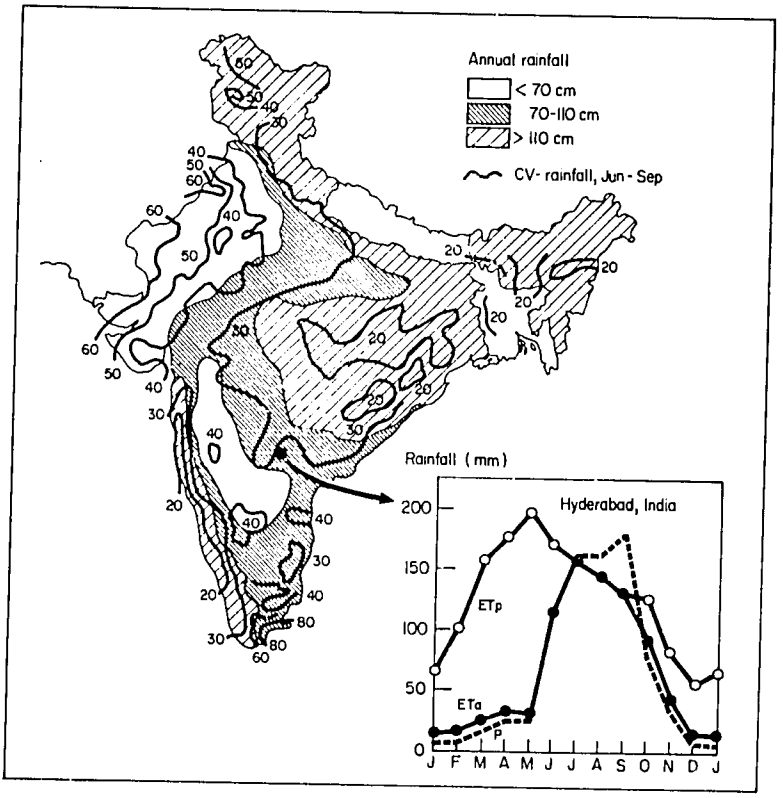
Our discussion will focus on areas within climatic regions where average total rainfall for the crop season is about adequate. Vagaries of rainfall within the season and from year to year, however, interact with soil and crop rooting characteristics to determine whether water stress imposes a productivity constraint. We will not discuss problems of water stress caused by grossly and chronically inadequate rainfall.

According to the annual rainfall distribution, the tropics may be classified into two climatic types. First, the tropical rainy or perennially wet climates as delineated in Figure 4. The equatorial proximity of these climatic types is obvious across the Americas, Africa, Asia, and the Pacific. These areas are not considered drought-prone. The other type consists of the tropical wet-dry climates (Fig. 4) characterized by a distinct dry season. This type is more relevant to our discussion. Areas within these climates have adequate total rainfall, but variability may be such as to cause water stress when combined with certain soil and rooting characteristics. Much of the variability is associated with the time of onset of rain at the start of the wet season and of withdrawal at the end. In addition, water stress is an obvious factor for the dry season crops grown on stored soil water and scarce rainfall. The soil's water storage capacity and plant rooting depth obviously are keys to the success of those crops.

We examine four sites in the tropics to illustrate the interaction of soil water storage and root development in mediating crop water stress.



4. Geographic representation of tropical wet and wet-dry climates (adapted from Money 1972).



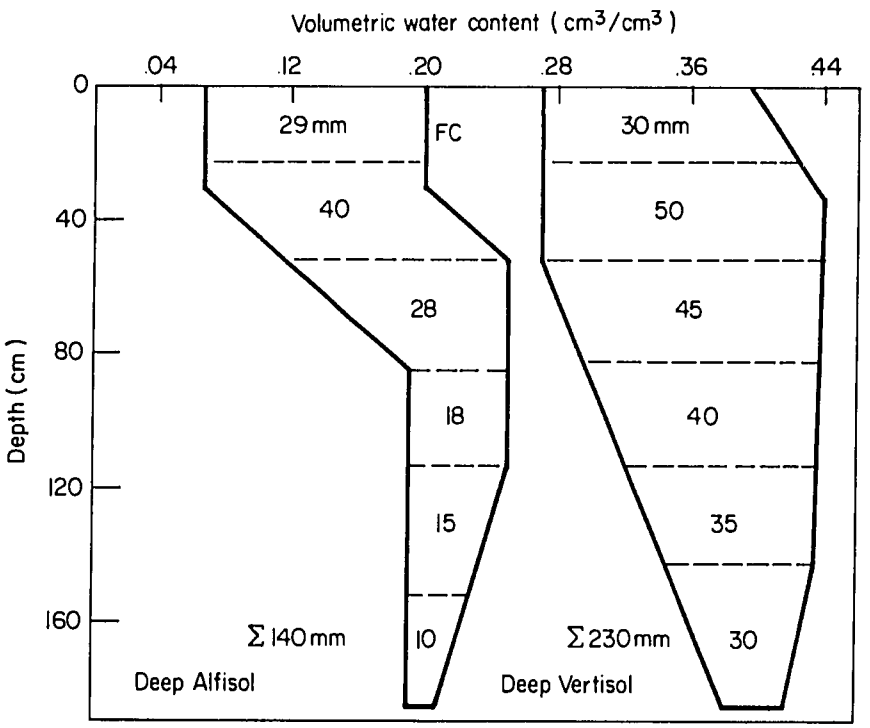
5. Rainfall amount and variability (cv, coefficient of variation) in the monsoon months, and water balance parameters for Hyderabad, India. Potential and actual ET (ET_p and ET_a) are those estimated by Thornthwaite. Monthly precipitation (P) represents means for 50 years (adapted from George et al 1974, Report of the National Commission on Agriculture 1976, and Thornthwaite and associates 1963).

Hyderabad, India

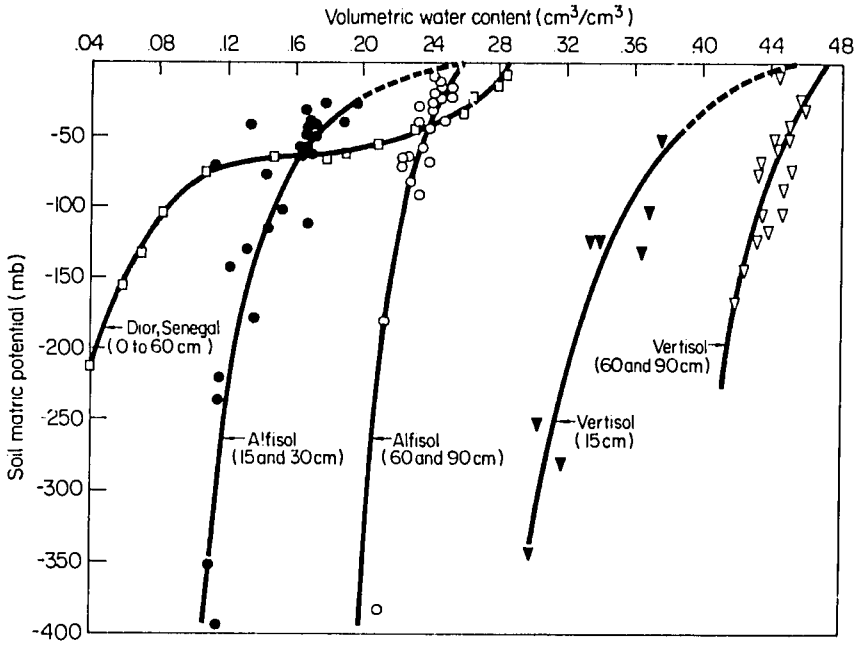
Hyderabad, India, is in a wet-dry zone receiving 70–110 cm annual rainfall that is monomodal in distribution (Fig. 5) and appears sufficient for sorghum or millet crops. However, the 30% coefficient of variation associated with the monsoon months of June–September, coupled with the fact that rainfall often consists of high-intensity storms resulting in percolation and runoff losses, attests to the importance of water retention characteristics of the soil and root development as determinants of crop success. Figure 5 illustrates the rapid decline in precipitation as the monsoon withdraws. The decline in potential ET, dictated largely by the seasonal cooling trend, is much slower. The actual ET during this period will determine the productivity of a crop grown on stored soil water. Hyderabad offers the researchers at International Crops Research Institute for the Semiarid Tropics (ICRISAT) the unique opportunity to observe two major soil types, a

coarse-textured Alfisol (red) and a fine-textured Vertisol (black), under the same climatic conditions.

By growing sorghum, pigeonpea, and chickpea under good management in the postrainy season largely on water stored in these two soils, M.B. Russell and associates (ICRISAT 1978) derived generalized estimates of crop extractable water for depth layers down to almost 2 m (Fig. 6). The upper limit of extractable water was set by field capacity (FC). For the topsoil layers (about 35 cm for the Alfisol and 50 cm for the Vertisol), it was assumed that crop removal stopped at −15 bar soil Ψ_m, although evaporation dried the surface soils to a more negative Ψ_m. Below these layers, the lower limit of extractable water corresponded to a more and more positive Ψ_m, accounting for the higher soil water contents in the lower depth at the end (Fig. 6). The ineffective use of water in the lower profile was attributed to low root densities and short durations of occupation by roots. It is interesting that the extractable water in the Alfisol is only about 60% of that in the Vertisol. The two soils' water contents from FC to −15 bars do not overlap. The differential behavior shown in Figure 6 has



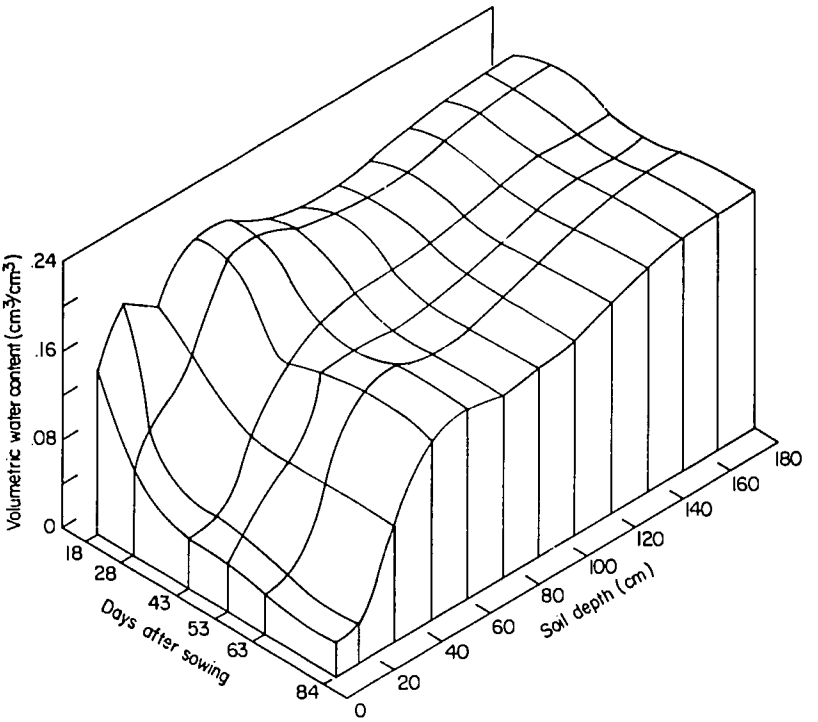
6. Generalized crop extractable water at different depths as determined by measuring extraction below field capacity for several long-duration and deep-rooted crops on an Alfisol and Vertisol at Hyderabad, India (adapted from ICRISAT 1978).



7. Soil moisture release curves for an Alfisol and a Vertisol at Hyderabad India, and for a Dior soil in Senegal (from ICRISAT 1978, Vachaud et al 1978).

basis in the moisture release curves of the two soils, depicted in Figure 7. Although the curves cover only the range from saturation to around FC, the differences in water contents at a given Ψ_m between the two soils are well illustrated. Presumably because Figure 6 was generalized from data obtained in a number of plots, corresponding water contents in Figures 6 and 7 may differ in value. For a more meaningful comparison of crop-soil interactions between these two soils, it is necessary to have more information on the crop. Such information is in the process of publication (M.B. Russell, ICRISAT, personal communication).

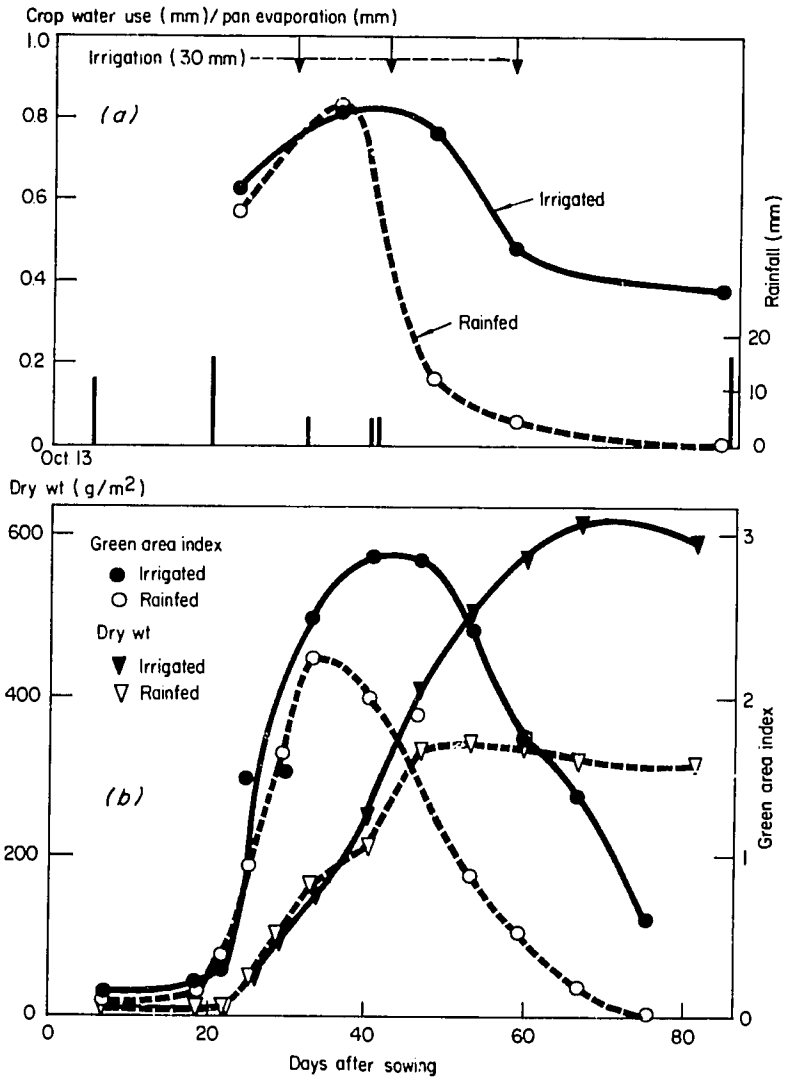
More data were reported by G. Squire, P. Gregory, and coworkers (ICRISAT 1978) on pearl millet grown at Hyderabad in the postrainy season. Unfortunately, only the Alfisol was used, so direct comparison of the two soils cannot be made. Figure 8 shows the progression of soil water extraction by the rainfed crop through time at various depths. In the first 40 days, water extraction was mainly from the upper 80 cm. Near the end of that period, roots were detected beyond 100 cm (ICRISAT 1978). Subsequent extraction was primarily from 60 to 150 cm until it nearly ceased in another 15 days. Compared with crop extraction in an irrigated control, total extraction (crop transpiration) in the rainfed crop was sharply restricted soon after da 36 (Fig. 9). Concurrently, dry matter production slowed and then ceased (Fig. 9). Early senescence of the rainfed crop is also



8. Soil water extraction by a rainfed pearl millet crop sown on an Alfisol on 13 October 1977 at Hyderabad, India (adapted from ICRISAT 1978).

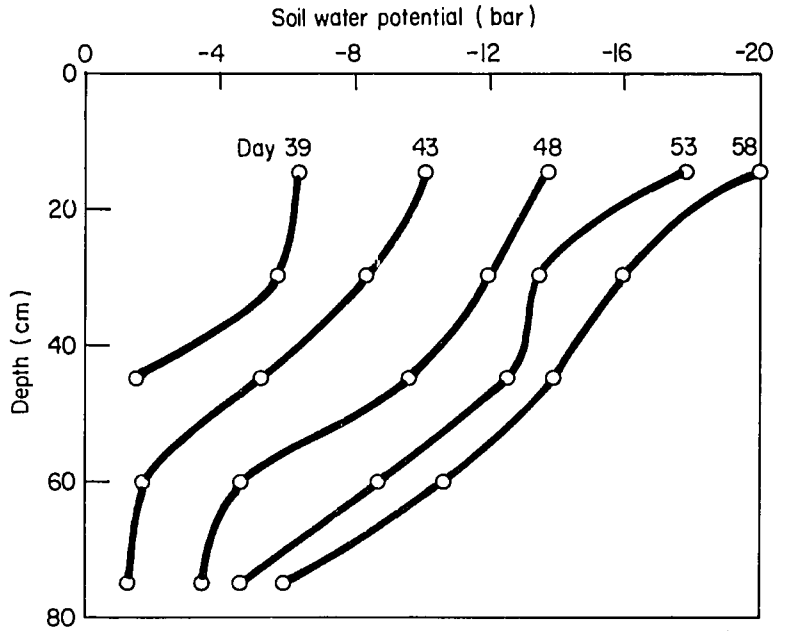
apparent from the decline in green leaf area, which started before day 40 (Fig. 9). By day 48, the daily minimum (midday) leaf Ψ of the irrigated crop was about −12 bars and that of the rainfed crop was about −19 bars (ICRISAT 1978). This substantial difference in leaf Ψ developed at the time the dry matter accumulation trend flattened, but at least 1 week after the start of the decline in transpiration and green leaf area. Thus, this level of daily minimum leaf Ψ must be considerably more negative than the threshold for stomatal closure and approximates a level at which carbon dioxide assimilation is drastically reduced. Of great interest are the values of soil Ψ at the time of decline in transpiration and green leaf area and at the time of virtual stoppage in dry matter production. Monitoring with soil psychrometers showed that at the time of declines (around day 40), soil Ψ was above - 4 bars in a substantial part of the root zone and only in the top 30 cm or so was it lower, −6 bars (Fig. 10). On day 48, when dry matter production had about ceased and leaf Ψ dropped to −19 bars at midday, soil Ψ reached −14 bars in the top 20 cm. Even then, at the 60-cm depth that was well populated with roots, it was about −5 bars.

Data combining soil, plant, and atmospheric water status with records of crop parameters are rare for tropical sites. The behavior observed at Hyderabad resembles that of corn (Acevedo 1975) and other crops at Davis, California, and



9. Ratio of crop water use to pan evaporation (a), and dry weight accumulation and green area index (b), for rainfed pearl millet (Fig. 8) and irrigated pearl millet sown 13 October 1977 at Hyderabad, India (adapted from ICRISAT 1978).

of cotton in Alabama (Klepper et al 1973). This example relates well to our hydraulic tank model, particularly to the drying of the tanks representing the upper soil layers, small tank sizes or storage capacity, the need for substantial differences in levels of the soil tanks and leaf tank ($\Delta\Psi$'s) to keep good flow rates or uptake, and reduction in outflow or transpiration presumably due to



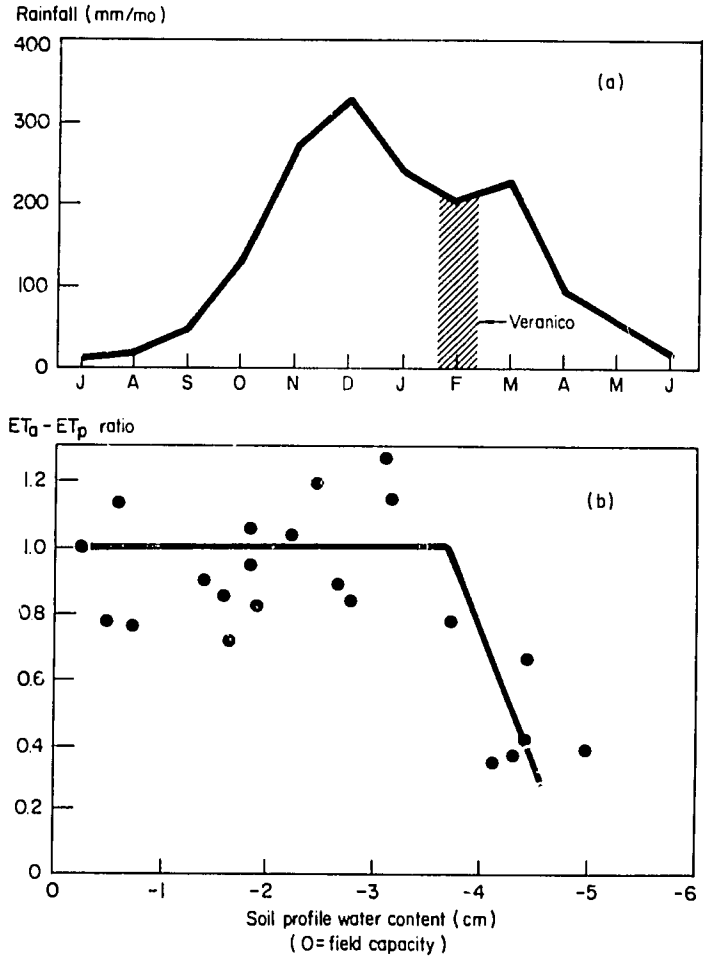
10. Soil Ψ at different depths on various days after sowing under the rainfed pearl millet crop represented in Figures 8 and 9 (derived from ICRISAT 1978).

the shutting of stomatal valves. It demonstrates the consequences of plant water deficit. Yields of the rainfed and irrigated crops were about proportional to the water used by each crop (ICRISAT 1978).

Brazil

The red Latosols of the *cerrado* region of Brazil are characterized by low fertility, low pH, low water-holding capacity, and excess aluminum. The aluminum toxicity and acidity often increase with soil depth. Rainless periods lasting 5 to 20 days occur with a high frequency (Moraes 1978) during the period labeled *veranico* in Figure 11a. Rainfed rice, which occupies about 3.7 million ha in the *cerrado*, is most adversely affected because the *veranico* period often coincides with the crop's reproductive growth stages.

Jones and Guimaraes (1979) estimated ET by following soil water extraction of a rainfed rice crop during a drought. Rooting depth was only 60 cm, consistent with the shallow rooting habit of rice in general. Figure 11b shows an abrupt change in ET_a:ET_p, coinciding with measured increases in stomatal resistance of the crop, as the soil dries out. Total extractable water, defined by them as the amount in the profile between field capacity and the lowest water content achieved by a crop in very dry conditions, was only 5.4 cm. Even so, 33% of the extractable water remained in the 60-cm layer when ET_a:ET_p fell below 1.0. Here, both low soil water storage capacity and limited rooting poten-



11. a) Mean rainfall distribution and identification of the chronically drought-prone period (*veranico*) in the *cerrado* of central Brazil (Moraes 1978). b) Relationship between the ratio of actual (ET_a) and potential (ET_p) evapotranspiration and soil profile (0-60 cm) water content (after Jones and Guimaraes 1979).

tial contribute to the early development of water stress. In terms of our earlier discussion, an increase in rooting depth would delay stress development by adding more tanks to the storage reservoir. This is feasible with other crop species and is potentially feasible with better adapted rice cultivars.

A further complication not investigated in the above study, but characterizing the soils in Brazil's central plateau, is widespread aluminum toxicity (Cline and Buol 1973). For many crops, toxic aluminum levels in the subsoil cause inhibi-

tion of root development and thereby reduce the number of storage tanks. This problem may be solved by screening crop cultivars for tolerance to aluminum (Howeler and Cadavid 1976), thus indirectly solving the problem of drought.

West Africa

The climate of sub-Saharan West Africa is diverse (Dudal, this volume). However, regardless of the total rainfall and distribution, poor physical properties of the highly weathered, coarse-textured soils of West Africa overshadow the climatic parameters and establish water deficit as a primary constraint to rainfed crop yields (Charreau and Nicou 1971, Lal 1979).

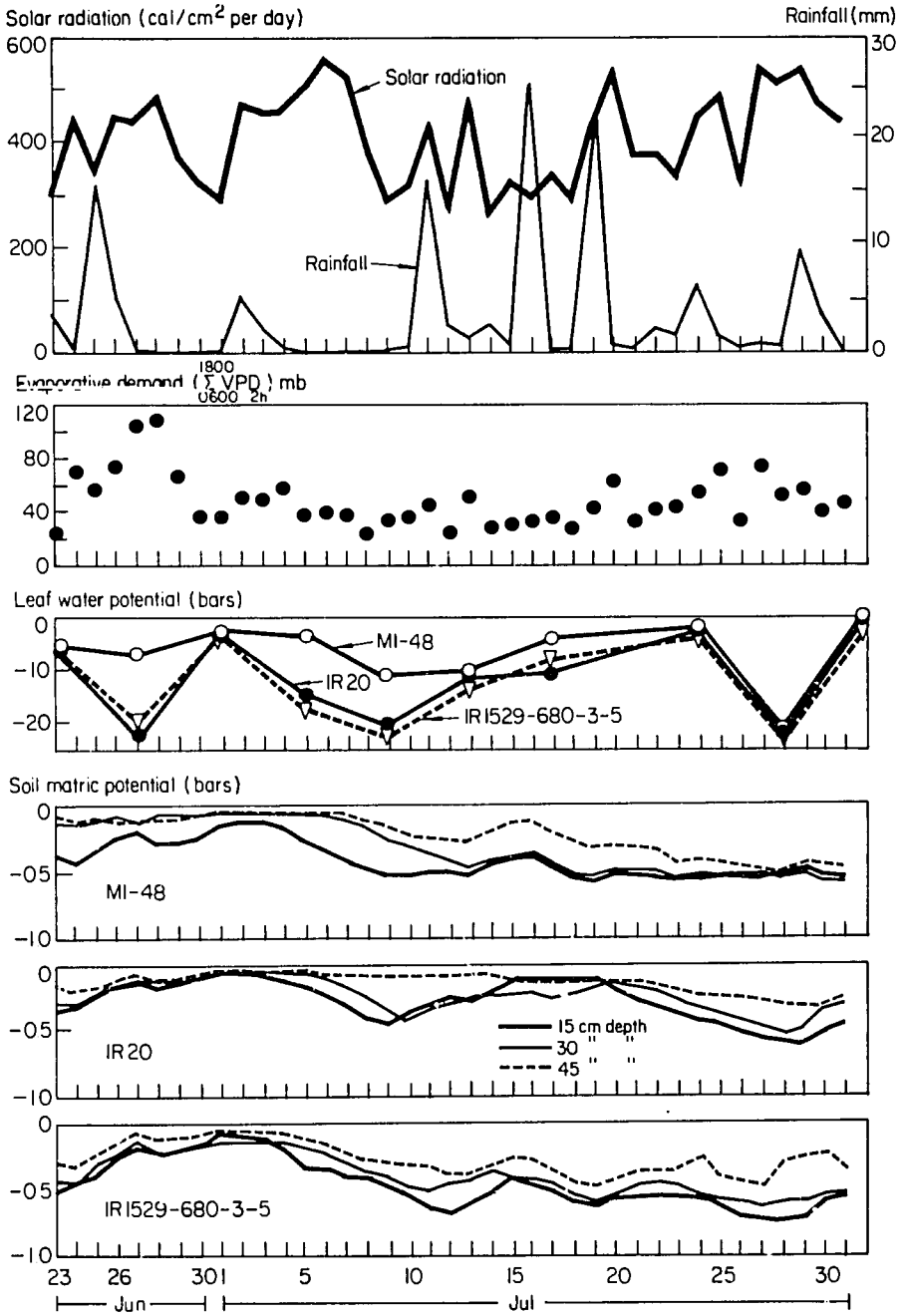
The Dior soil of Senegal is a ferruginous soil with 92% sand and about 0.4% organic matter. It is extremely poor in water-holding capacity (Vachaud et al 1978) compared with the Vertisol and Alfisol in Hyderabad (Fig. 6). The moisture content at −.1 bar Ψ *soil* is only 0.08 cm^3/cm^3. Although West African soils are quite heterogeneous, low water retention appears to be general. Thus the comment by Lal (1979) that they may provide only 5 to 7 days of water requirement for maize and 3 to 5 days for rice. This generalization implies that extensive root development is a prerequisite for crops to meet evaporative demand during drought periods and be agriculturally successful in West Africa. A review by Nicou and Chopart (1979) illustrated the relationship between yield and root development (root weight or density) for several crops grown on Dior soil and similar soils in Senegal.

Unfortunately, root development is often very limited because of another serious soil problem – poor structure. For example, Dior soil is very compact and relatively structureless. Its low porosity (about 40%) and high bulk density (1.5–1.8) impede root growth. Root development of rainfed rice and maize was enhanced markedly by small increases in porosity (Nicou and Chopart 1979). As is well known, porosity or bulk density interacts with soil water status to affect root penetration (Taylor, this volume). This was also the case for soils in West Africa (Maurya and Lal 1979). In upland soils there, there is a structural problem also with subsurface gravelly horizons which are often compacted and rigid because of a clay matrix and seriously limit rooting depth.

Philippines

Dryland rice in Southeast Asia is often relegated to more marginal lands. Typically, it is grown on sloping topography, on light-textured soil in fields without bunds. Thus, the soil is well drained and aerobic most of the season. Because of the inherent lack of deep root system development in this species, water stress occurs even in climatic zones with relatively high seasonal rainfall totals.

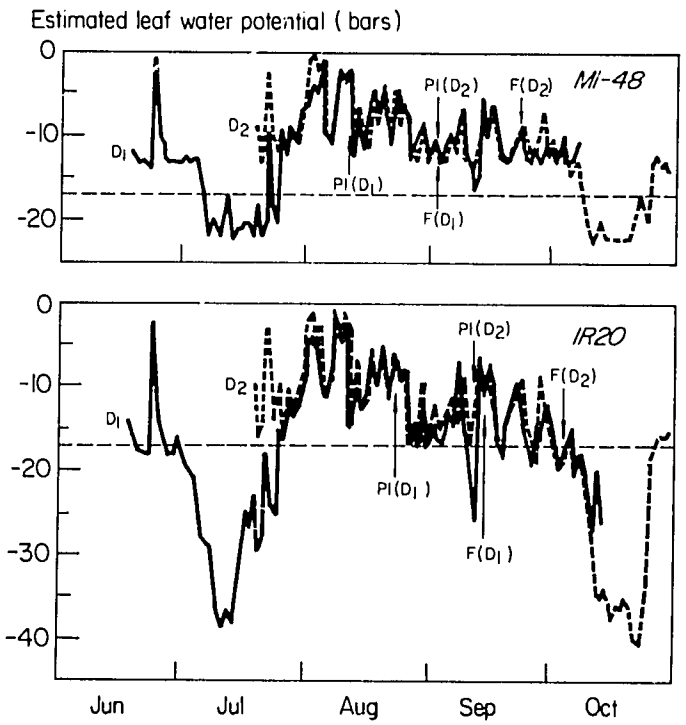
Attempts to monitor the soil-plant-atmosphere continuum in dryland rice in the Philippines (Fig. 12) have provided insight into its dynamics in this crop and allowed initial observations of intensity and duration functions of water stress and growth stage interactions. M1-48, the dryland adapted cultivar, maintained higher leaf Ψ than the other rices during periods of adequate soil moisture and



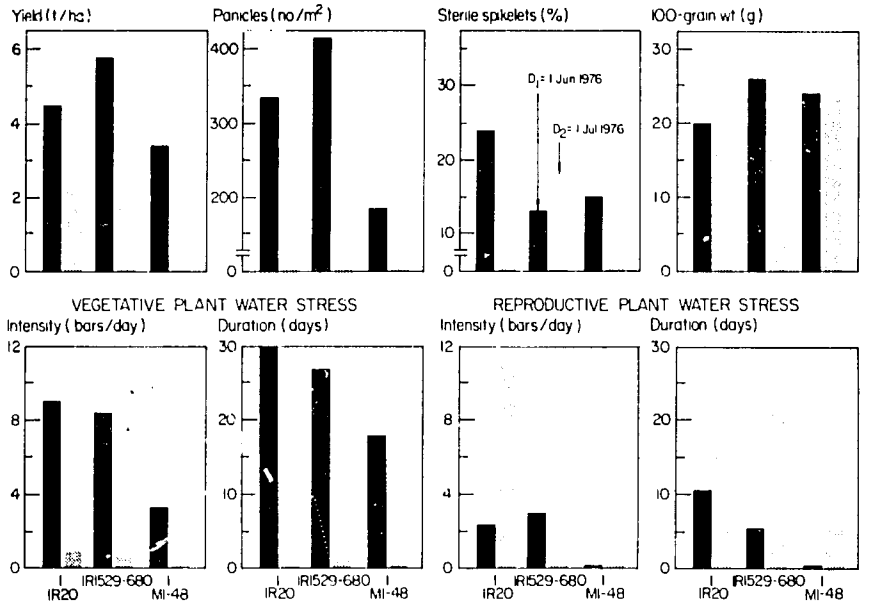
12. Soil, plant, and atmospheric water status for three rice cultivars during the wet season. Upland farmers' field, Batangas province, Philippines, 1975 (O'Toole and Moya, unpublished).

high evaporative demand. Later in the season when soil moisture became limiting M1-48 was more effective in extracting soil moisture at all soil depths. The poor soil moisture extraction ability exhibited by IR20 and IR1529-680-3-5 illustrates less root system development even at the 45-cm depth. Because of the shallow rooting depth, daily minimum leaf Ψ in all three varieties was highly correlated with atmospheric evaporative demand and soil Ψ_m at 15 cm during much of the season.

Regression equations were developed from these edaphic and atmospheric variables, and the daily minimum leaf Ψ for two dryland rice crops planted at different dates in 1976 were predicted (Fig. 13). Plants in the first planting date (D_1) experienced drought at the vegetative growth stage; those in the second (D_2) experienced severe stress during the reproductive stage. The varieties differed



13. Estimated daily minimum leaf Ψ during the growing season for M1-48 and IR20 (IR1529-680-3-2 and IR20 had identical responses) rice cultivars and two dates of planting (D_1 and D_2). D_1 = 1 Jun 1976, D_2 = 1 Jul 1976. PI = panicle initiation, F = flowering. Dashed line is −17 bar lower limit of leaf Ψ. Upland farmers' field, Batangas province, Philippines, 1976 (O'Toole and Moya, unpublished).



14. Yield and yield components of IR20, IR1529-680-3, and M1-48. Intensity and duration of plant water stress at vegetative and reproductive stages. Batangas province, Philippines, 1976 wet season (O'Toole and Moya, unpublished).

in leaf Ψ response to the drought period as noted when their extraction patterns were compared (Fig. 12). After determining −17 bars as the desired lower limit of leaf Ψ, the intensity of water stress was computed as the difference between the daily minimum and −17 bars. Duration of water stress was calculated as the sum of days within a growth stage when the estimated minimum leaf Ψ was less than −17 bars. Figure 14 illustrates how these values can be accounted for during the vegetative and reproductive stages of the two crops. The three varieties were not phenotypically matched, and the water stress calculations were done separately for each variety and date of planting. The trends for intensity and duration of plant water stress and the measures of growth and yield components show a close cause-and-effect relationship.

Figure 14 shows the crops' lower susceptibility to water stress during the early vegetative stage. All D_1 crops yielded well despite the high intensity and duration of vegetative stage water deficits. The D_2 crops in the reproductive stage showed characteristic sensitivity to water deficit in terms of affected yield components.

The response of dryland rice in the Philippines to water stress has shown the value of studying the soil-plant-atmosphere continuum as a unit. The value of deeper rooting was emphasized and the concept of a desired lower limit of leaf Ψ was used to quantify intensity and duration of crop water stress.

Our examples illustrate the primary soil-water related conditions that constrain crop growth and yield in the tropics: low soil water retention capacity,

physical impedance or chemical toxicity leading to impaired root development, and the inadequate capability of some crops and cultivars to exploit the soil water reservoir. These examples also demonstrate the great variability in edaphic and climatic complexes and emphasize the advisability of researching the soil-plant-atmosphere as a system rather than its discipline-oriented components within these complexes.

MEASURING CROP AND SOIL WATER STATUS AND ASSESSING SOIL WATER SUPPLY

With crop production the final objective, and with the plant acting as an integrator of soil water regimes, rooting effects, and evaporative demand, more attention must be directed to the crop when assessing soils for use where water is limited.

Measurements of plant water status

The parameter most frequently measured is leaf Ψ. Thermocouple psychrometry has often been thought of as the most definitive for Ψ measurements. The pressure chamber technique (Scholander et al 1965), however, is the only one that is rapid and suitable for routine field use. Two common procedural errors must be avoided: overly rapid pressurization (thereby overshooting the end point) and failure to protect the tissue from drying after excision and while in the chamber. Regrettably, leaves or branches of some species do not seal easily in the chamber and sap fills air spaces in the petiole or stem when pressurized, giving a negative error in leaf Ψ (Boyer 1967). Regarding thermocouple psychrometers, the Peltier-cooling or Spanner type is less accurate than the isopiestic type (Boyer and Knipling 1965). The use of either type involves a number of pitfalls (Brown and Van Haveren 1972) and is not recommended to the novice.

Another measure of plant water status is relative water content (RWC), the amount of water in the tissue relative to the amount the tissue holds at saturation. RWC is 100% when Ψ equals zero. Visible wilting occurs when RWC is in the range of 75 to 85%, corresponding to −12 to −16 bars in leaf Ψ (Gardner and Ehlig 1965). RWC is relatively simple to measure and requires no special equipment. The random error in the method, however, is large compared to the range of change of interest. References (Barrs 1968, Slavik 1974) should be consulted for details of these and other methods of measuring plant water status.

In the field, visual symptoms are often good indicators of plant water status, especially if the observers' eyes have been *calibrated* against measured leaf Ψ or measured changes in physiological processes effected by stress. A thorough familiarity with the crop is essential. For rice, the degree of leaf rolling correlated well with leaf Ψ (O'Toole and Moya 1978). As already mentioned, leaves of many crops wilt when their Ψ falls to −12 to −16 bars. The beginning of wilting corresponds roughly to the start of stomatal closure and the associated reduction in transpiration and carbon dioxide assimilation. Within that Ψ range,

some crop cultivars also exhibit a color change. Because these visual symptoms point to the start of a dropoff in important physiological processes, in one way they are even more useful than Ψ measurements. Unfortunately, above that Ψ range, when changes in water status may still affect expansive growth, visual symptoms are not so apparent.

Because plant Ψ is at a minimum around noon on a sunny day, midday measurements are imperative if crop growth and assimilation are of major concern. If leaf Ψ just reaches the stomatal threshold at midday, then carbon dioxide assimilation may only be slightly depressed for 1 or 2 hours that day. On the other hand, if midday leaf Ψ is 5 or 6 bars lower than the threshold, leaf Ψ is likely to remain below the threshold for most of the day, reducing assimilation and dry matter production to a small fraction of the daily normal.

When assessing soil water and rooting volume, leaf Ψ measured at dawn is also invaluable. As transpiration is greatly reduced (or eliminated) at night, the tissue refills with water until dawn. At that time, leaf Ψ approaches equilibrium with soil Ψ and hence is indicative of the soil water status in the rhizosphere.

Measurements of soil water status

To measure soil Ψ_m down to nearly -1 bar in the field, tensiometers are now widely used in the tropics. They are unequalled in accuracy when equipped with mercury manometers to measure tension. For Ψ_m or $\Psi \leqslant -1$ bar, there are several techniques; gypsum resistance blocks and thermocouple psychrometers are the most common. In our experience, commerical thermocouple psychrometry sensors have an unacceptably high failure rate when left installed in the field for more than a few days. The practical sensor for routine measurements in the field appears to be resistance blocks. Resistance blocks hold water by matrix forces exactly as the soil and require calibration, usually on a pressure plate. The blocks are said to be insensitive to changes in Ψ_m between FC and -1 bar. The fact is that blocks of appropriate design (D.W. Henderson, personal communication; Closs and Jones 1955) can be used to measure changes in that range, especially with an electric resistance meter covering both high and low ranges of resistance (Acevedo 1975).

For soil water content, the simple and direct method is core sampling, and weighing before and after drying the core in the oven. Indirect methods are many, the most popular in modern field research being the neutron scattering method (Gardner 1965). Once an access tube is installed, the instrument allows the repeated monitoring of soil water content in different depth layers. This is particularly advantageous for studies of water depletion by a developing root system. Calibration of the instrument is necessary for a given soil and may even vary with horizons (Lal 1974).

Assessing soil water usable by the crop

Direct experimentation is still necessary for accurate assessments of usable soil water, especially where knowledge of soil and crops is scant. Normally the crop

is started on a fully wetted profile or when sufficient rain is expected for the establishment of a good root system. A well-irrigated treatment is included as control. Soil θ at different depths and leaf Ψ or other indicative crop parameters (e.g. Fig. 9b) are monitored as the season progresses. The usefulness of the data is greatly expanded by accompanying soil Ψ measurements at the various depths. As the soil dries to the point when leaf Ψ of the exposed upper leaves of crop reaches the threshold for stomata, or when wilting is obvious and transpiration reduced substantially, the values of θ at different depths at this point represent the lower boundary of usable water in the profile for maintaining good productivity of the particular crop near or after full canopy development. Of course, rainfall must be deficient enough to dry the crop to the point of stomatal closure.

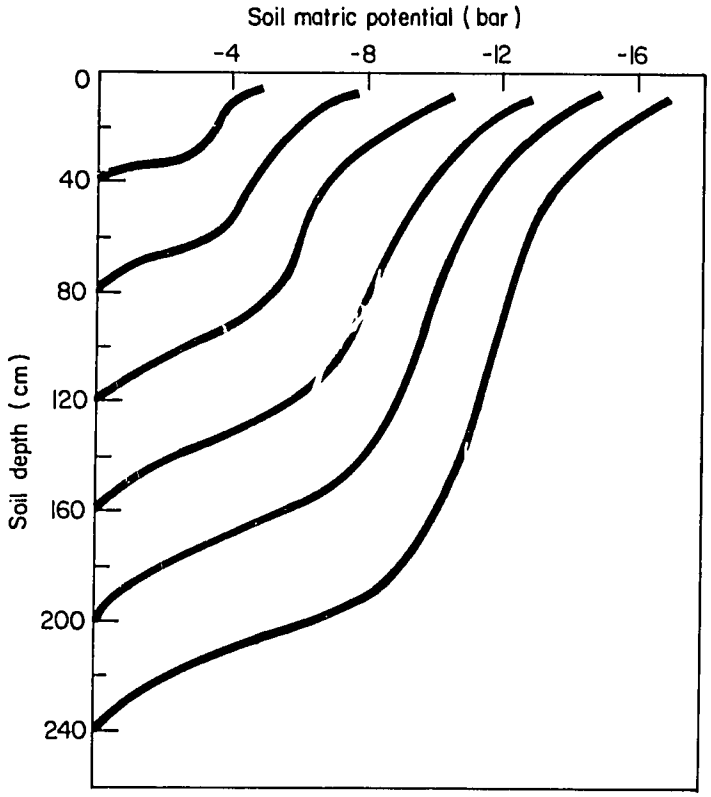
The water extraction front can also be used to estimate effective rooting depth at any one time. One potential source of error is vertical water flux in the soil due to deep drainage or to capillary rise from a water table.

A new procedure to estimate extractable soil water

Direct experimentation to assess usable soil water often is not feasible and quicker estimates must be resorted to in tasks such as land evaluation and productivity planning. Good estimation procedures should evolve from sound principles and be molded by the reality of direct experimentation. We propose a procedure to stimulate further studies and improvements. It is based on current understanding of water in the soil-plant-atmosphere system and relies on soil Ψ values obtained mostly in temperate zones.

The upper limit of usable water is traditionally taken as the FC. In most cases drainage for at least 2 or 3 days after a good rain is required before FC is approached. Because the crop takes up water held above FC during that period, the upper limit of the reservoir should be raised for situations where rainfall or irrigation is frequent. FC falls around a soil Ψ_m of -0.3 bar for many soils but is closer to -0.1 bar for sandy soils. For simplicity, the upper limit may be raised to a θ corresponding to -0.1 bar for all soils. An alternative is to take as the upper limit the water retained 1 day after the disappearance of standing water from the field.

The lower limits for θ is much more difficult to delineate. As mentioned, the corresponding soil Ψ are dependent on transpiration rate, resistances, desired lower limit of leaf Ψ, and soil depth explored by the roots. For now, we will deal only with situations where leaf Ψ threshold for stomatal closure, plant resistances, and ET (about 5–6 mm/day) do not vary markedly, and where canopy cover is nearly complete and expansive growth is not critical. Rooting is then the main variable affecting the lower limits of soil Ψ. In soils not affected by salinity, Ψ_m accounts for most of the Ψ value. We propose that the Ψ_m values be chosen for each depth layer on the basis of the total depth of the root zone, in accordance with Figure 15. Starting with the knowledge or estimate of the depth of the rhizosphere for the given soil, the curve with y-intercept closest to that rooting depth is chosen from Figure 15. The curve is then approximated by



15. Proposed tentative lower limits of soil Ψ_m for water usable by crops as a function of total rooting depth (Y-intercept) and depth layers in the rhizosphere.

a histogram, dividing the rhizosphere into a minimum number of depth layers consistent with accuracy of the supporting data. With the lower limit of Ψ_m estimated for each layer, the corresponding θ can be found from the determined or estimated moisture release curve for that layer. In this way, usable water in each layer can be calculated and summed to give the total for the whole profile. It is clear that in this procedure, the shallower the rooting, the more positive would be the lower limit for Ψ_m at a given depth. This is consistent with our hydraulic model. The position of the curves in Figure 15, especially those for shallow rhizospheres, however, are subject to improvement as more data develop.

FUTURE RESEARCH NEEDS

Interactive roles are clearly played by climate, soil, and crop in the occurrence and severity of plant water deficit and the consequent constraint on crop production. It follows that future research needs include work on climate and crops as well as soils.

I. Encourage interdisciplinary approaches to water stress problems. Data sets including soil physical properties; water extraction; crop growth, development, and water status; and atmospheric conditions are rare and obviously necessitate interdisciplinary cooperative efforts.

II. The above will necessitate development of data collection for soils, crops, and weather:

A. *Soil*

1. Collect more and better data on water-holding capacity and the presence of restrictive (both physical and chemical) layers in soils. At the minimum, field capacity (or moisture equivalent) and the volumetric water content at two lower values of soil Ψ_m should be determined, for depth layers down to 1.5 m or more. We tentatively recommend −2 and −8 bars as the two lower values. This departs emphatically from the traditional −15 bar value, for reasons discussed earlier. Water content at −0.1 bar would also be useful in estimating the water available to a crop after a rain. The data provide the basic information necessary for soil mapping according to water regimes.

2. Strive to include more hydroedaphological factors in the soil classification system. More attention should be directed to translating structural and texture information into water-related parameters pertinent to crop production.

B. *Crop*

1. Determine the rooting depth of tropical species. We need to ascertain the potential rooting of crops growing on deep and pliable soils well provided with nutrients and water on the one hand, and their rooting depth under low fertility and low-input agriculture on the other.

2. Evaluate germplasm of tropical crops for differential cultivar adaptability to drought, with emphasis on root parameters. Especially valuable are genetic variabilities in rooting depth, root tolerance for soil toxicities, and root penetration of soils of high mechanical impedance.

3. Evaluate the effects of flooding and high water table on rooting depth and root function and the resistance of crops to subsequent droughts. This is pertinent because much of the tropics is characterized by periods of excessive rainfall followed by dry spells.

C. *Climate-weather*

1. Collect more complete climatic data. The minimum set should include biweekly precipitation and pan evaporation. Inclusion of solar radiation, wind run, etc., would of course expand its usefulness.

III. Develop a better and more quantitative understanding of crop productivity as influenced by the soil-water-climate complex to construct process-based models and make more realistic predictions.

IV. Develop methods of estimating quantities of soil water extractable by the crop which have sound basis in theory and take into account rooting depth and effects of water stress on productivity. The estimation procedure proposed in a preceding section may be taken as a point of departure.

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Mechanical impedance related to land preparation as a constraint to food production in the tropics (with special reference to fine sandy soils in West Africa)

R. NICOU AND C. CHARREAU

Mechanical impedance to land preparation is a direct constraint to food production in the tropics, where the necessity of soil tillage has been ascertained. This necessity is dependent on:

- the soil,
- the climate,
- the number of years of cultivation, and
- the irrigation possibilities.

Land preparation is faced with a certain number of soil constraints related to:

- texture,
- clay mineralogy,
- structure, and
- soil moisture.

To study and measure mechanical impedance, the following parameters should be noted:

- particle size distribution,
- bulk density,
- penetrometry,
- draft requirements, and
- exchangeable iron, calcium, and sodium contents.

Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT)/ Groupement d'Etudes et de Recherches pour le Developpement de l' Agronomie Tropicale (GERDAT), B.P. 5035, Montpellier Cedex, France; and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), B.P. 3340, Dakar, Senegal.

Problems of mechanical impedance to land preparation have not been studied much in the tropics and references in the literature are scarce.

More detailed studies have been specially devoted to:

- hardening and cementation of sandy and sandy clay soils of the dry tropical regions of West Africa,
- crust in the subarid zones, and
- problems related to puddling in rice cultivation.

A lot of work still has to be done in this field, particularly on the influence of these factors on food production.

MECHANICAL IMPEDANCE to land preparation cannot be considered as a direct constraint to food crop production in the tropics. Mechanical resistance linked to the soil acts directly when it disturbs seed emergence, affects root development, or when, due to the effect of desiccation, shrinkage and superficial hardening phenomena cause damage at the root collar, thus allowing parasite and insect penetration.

But mechanical resistance often poses numerous problems when certain cropping operations related to the success of the crop are to be performed. In the harvest of groundnut, for instance, lifting out can be hindered by superficial soil hardening, which can lead to considerable losses in the harvest. It should first be noted that land preparation is essential to plant growth and agricultural production. However, the need for a thorough land preparation before sowing does not appear to be as evident in every situation.

Under such conditions, soil-related constraints occur at two levels:

- where the soil conditions are such that tillage is indispensable for optimum production, and
- where mechanical resistance makes soil tillage difficult.

Therefore, two questions need to be answered:

- What is the best type of tillage for each kind of soil?
- What are the constraints to this tillage?

SOIL TILLAGE IN THE TROPICAL ENVIRONMENT

Soil tillage in the tropical environment has long been discussed by two schools of tropical agronomy whose positions seem irreconcilable:

- those who consider the need for soil tillage to be naturally obvious,
- those who feel that it is useless and even harmful and, in any case, not economical.

As we are to discuss the major soil constraints that limit food crop production, we thought it interesting to take stock of the question by bringing out the

factors that support one theory or the other, or more precisely, those constraints that do or do not call for tillage. The problem is complex and cannot be definitively resolved by either school alone.

EFFECTS OF SOIL TILLAGE

Much has been written about the effects of soil tillage in a tropical environment. Arakeri et al (1962) in India, Charreau and Nicou (1971) for the dry tropical West African zone, Greenland and Lal (1977) for the humid tropical zone, Van Wambeke (1974) in a synthesis on Ferralsols, Sanchez (1976) treating a group of tropical countries with special reference to flooded rice farming, and many other authors have analyzed the effects of soil tillage, emphasizing one characteristic or another, depending on the case.

Generally speaking, three major specific effects of soil preparation are recognized:

- it induces an alteration in the soil's physical conditions, especially of the superficial layers,
- it ensures seedbed preparation and thus guarantees good grain germination and seed emergence, and
- it permits some weed control before sowing and during the first stages of plant growth.

Alterations in the soil physical conditions

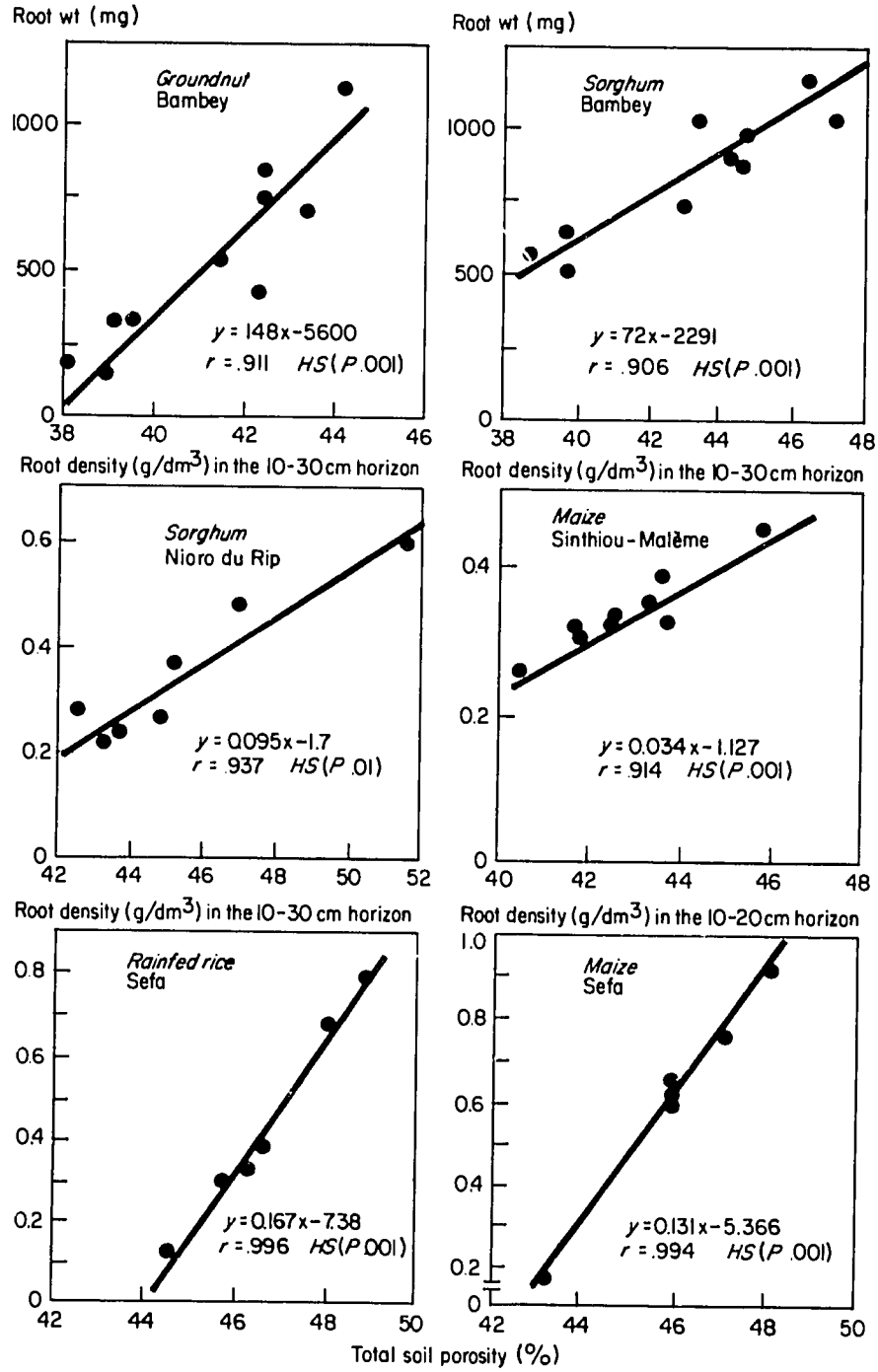
The first result of soil tillage in general and plowing in particular is the complete alteration of the structural state of the tilled layers. This alteration significantly affects a number of characteristics:

- total porosity and also pore size distribution,
- water regime,
- erosion susceptibility, and
- microbial activity and decomposition of organic matter.

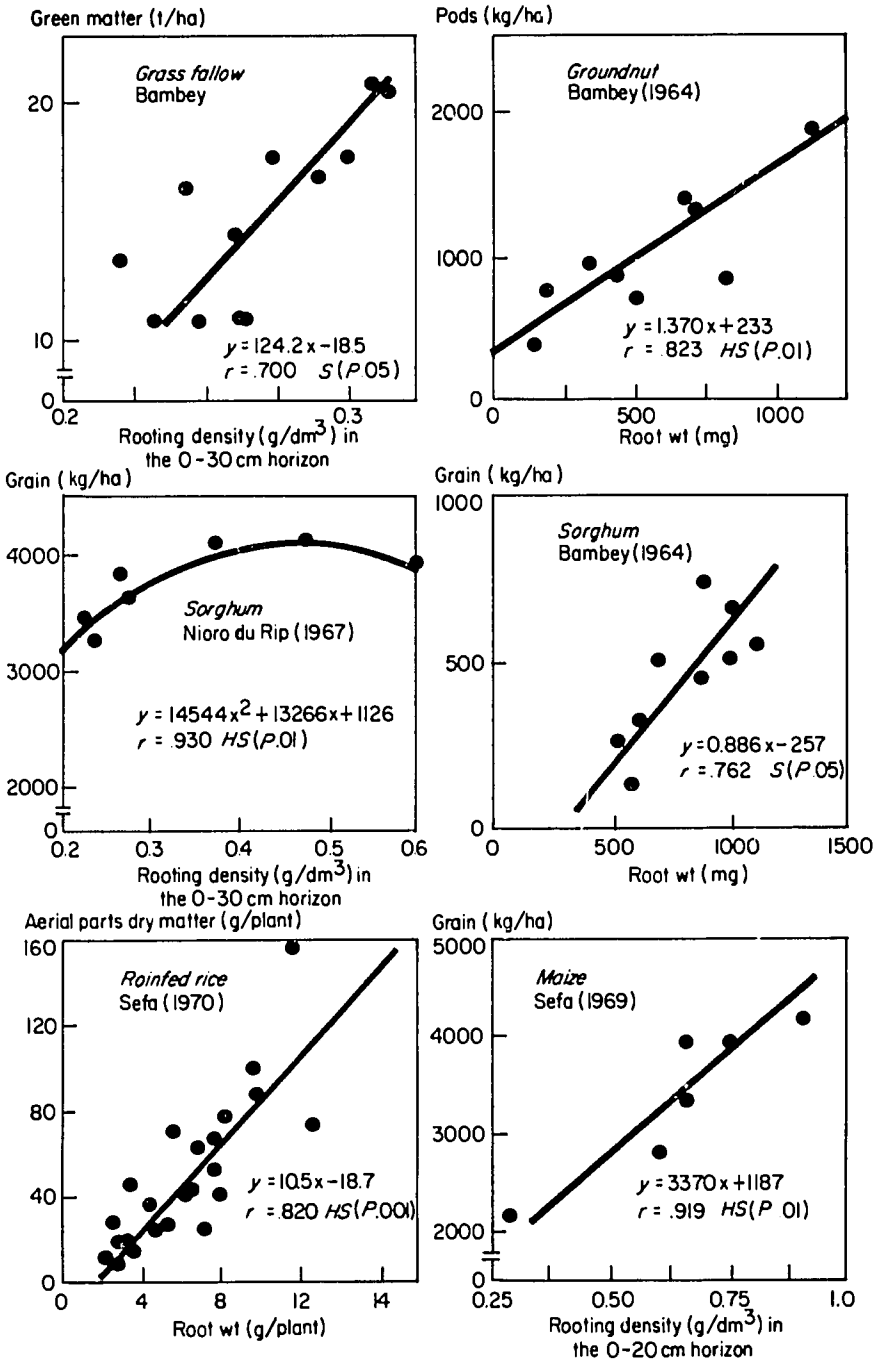
Depending on the soil's initial state, its particle size distribution, clay mineralogy, and climatic parameters, tillage can affect plant growth either favorably or unfavorably.

Soil porosity. Alterations of structure initially cause an increase in total porosity (Charreau and Nicou 1971) and a change in pore size distribution (Van Wambeke 1974). Thus where porosity is limiting, tillage decreases mechanical resistance to root penetration and rooting develops more quickly and more deeply. This has very important consequences on vegetative growth and yields.

For example, Figure 1 shows a direct relationship between development of the root system in the superficial layers and soil porosity on ferruginous soils (Alfisols) in the dry, tropical West African zone (Nicou and Chopart 1977). The relationships between root densities and yields of food crop (Fig. 2) show the need to increase the root mass which, under natural conditions, is insufficient. In Figure 1 the initial soil porosity of about 40% is often considered the limit



1. Relationships between soil porosity and rooting for different crops in the dry tropical West African zone.



2. Relationships between rooting and yield for different crops in the dry tropical West African zone.

for good root growth. After root development has reached a certain level, this relationship is no longer linear as in the case of Nioro du Rip sorghum. This variety has reached its ceiling at a yield of 4,100 kg/ha, and additional roots are not essential. After a certain level of porosity and root development has been attained, it is perhaps no longer necessary to alter the soil physical state.

Water regime. Soil tillage can influence water regime in three ways:

- improving water infiltration in the soil either by affecting soil porosity, or by creating a microrelief,
- reducing evaporation and conserving water in the soil during the dry period, and
- increasing the soil water uptake as it permits the root system to develop better in depth.

These effects are not of equal merit, nor are their results necessarily the same for different soil types and climatic conditions.

Erosion susceptibility. By increasing porosity and producing clods that create a superficial microrelief, proper soil tillage limits runoff and can be a good means of controlling water erosion. Supportive data have been obtained on tropical ferruginous soils (Alfisols) in Senegal (Charreau and Nicou 1971) and on ferrallitic soils (Oxisols) in the Ivory Coast (Kalms 1977). But this is not always the case when the slope is too steep or precipitation too intense. Soil tillage can be harmful when it is done poorly, e.g., with disk plows working at a fast speed in the direction of the slope. Other techniques, which appear to be more adapted to certain areas, have been developed (Greenland and Lal 1977).

Experience has shown that in the dry tropical zone, plowed soil is more resistant to wind erosion due to the formation of clods. Here again poor tillage performed with disks can be more harmful than leaving the soil as it is after harvest.

Microbial activity and the decomposition of organic matter. Soil tillage is first a good means of incorporating harvest residues, mineral fertilizer, and green manure in the soil. It is not always necessary that the soil be turned over, and good techniques of soil preparation with teeth or chisels can assure a satisfactory superficial mixture. Tillage increases soil aeration and, therefore, contributes to the decomposition of organic matter and nitrification. Soil aeration can be undesirable when there is considerable leaching, as may be the case in recently cleared Ferralsols (Van Wambeke 1974). But it is an advantage for groundnut on sandy soils because rhizobial activity may be substantially increased as in Senegal (Wey and Obaton 1978).

Preparation of seedbeds

The objective of seedbed preparation is the creation of an environment that is favorable to seed emergence. It is necessary to ensure good contact between grain and soil so that moistening occurs. At the same time, the soil should not become so compacted that anaerobic conditions are created or mechanical resistance to root penetration and to seed emergence is increased. This is parti-

cularly true with Vertisols, and is also important for sandy soils where any superficial tillage after plowing should not offset the favorable effects created by plowing.

Depending on the initial soil conditions, the size of the aggregates in the surface soil should be either highly or slightly reduced by plowing. The optimum will be determined by the intensity of rains; too much pulverization can result in splashing, sealing, and finally, crusting.

Superficial waterlogging can cause a significant problem at seed emergence. In that case a device that will assure satisfactory drainage should be developed. Such a device is the system of broad ridges at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (Krantz et al 1978).

Weed control

Soil tillage, especially plowing, is an excellent means of controlling weeds, at least at the beginning of the cycle. In many tropical countries it has enabled the farmer to spend less time in controlling weeds. Van Wambeke (1974) cites results obtained by Jurion and Henry in Zaire where plowing reduced by 60 days/ha the labor necessary to control *Imperata cylindrica*. In dry tropical zones it is generally estimated that good plowing eliminates at least one weeding operation.

The use of herbicides obviously alters the situation. But they are expensive and have not been demonstrated to be effective under all soil and climatic conditions. Here, too, it is important not to generalize. Much progress remains to be achieved in weed control; all too often manual labor is the most widespread means of controlling weeds.

FACTORS THAT MAKE SOIL TILLAGE NECESSARY

Evidence from many tropical sites shows that the necessity of soil tillage for food crop production is not the same everywhere. A recent Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT) study on corn indicated a good response to plowing in Senegal (Ustalfs), a moderate response in the maritime region of Togo (Oxisols), and only a slight response in the Ivory Coast (Oxisols). IITA at Ibadan has also found no response to plowing; in South America the responses were variable.

The effects of soil tillage can also differ for the same location depending on the crop. Rainfed rice, for example, calls for more tillage than does sorghum or maize. Generally speaking, it depends on the plant's ability to adapt to the physical environment. Therefore, the necessity of soil tillage seems to depend on the following four factors, which in some cases can be considered as constraints.

Soil

One of the main effects of soil tillage is alteration of the soil physical conditions, particularly in the superficial layers. When the soil's natural physical properties

are poor, they represent a constraint to the growth and development of food crops.

This is true where the soil structure is not sufficiently developed (hard and massive when dry, breaking into single grains), sizes are too small to favor root penetration, infiltration is insufficient, or there is too much percolation. This is also the case when the fine particles in upper layers tend to disperse making them susceptible to erosion, when microbial activity is weak, when organic matter decomposition is slow, or when the humus content is low.

Soil structural characteristics are particularly dependent on texture and clay mineralogy. The fine particles play an essential role in structure formation, as swelling and shrinking greatly affect the formation of aggregates and the presence of cracks and cavities. This effect depends not only on the quantity of fine particles (0–2 μm) but also on the clay mineralogy. It is known that kaolinite alone does not favor the creation of good structure. In most tropical soils the fraction less than 2 μm is often made up solely of kaolinite and iron sesquioxides. It is only when some 2:1 minerals are present that an oriented clay structure forms.

In this regard, the 18% clay content threshold in the USDA textural triangle, which delineates coarse loamy and fine soils, may be a significant limit. Above this limit, when the clay fraction includes 2:1 minerals, the soil can be considered structurally active. The seasonal shifts between swelling and shrinking create or regenerate structural units. In these conditions plant roots, especially those of gramineae, are able to improve the structure.

Below this threshold, particularly if the fraction contains little or no 2:1 clays, the soil is generally structureless. Plant roots by themselves cannot improve soil structure. It is possible that with more than 18% clay, deep soil tillage may not be necessary or may be less frequently needed. With less than 18% clay and particularly with no 2:1 clays, deep soil tillage seems necessary to compensate for insufficient natural mechanisms to create soil structure (Charreau 1974). Most soils in the African dry tropical zone belong to this second category because of the fine sand or sandy-clayey texture of the surface layers and the predominance of kaolinite in the clay fraction. These soils belong to the following units:

- "isohumic class", in particular those formed on eolian deposits: modal brown and reddish brown soils situated in the north between the 200 and 500 mm isohyets (Camborthids in *Soil taxonomy* USDA 1975).
- gray ferruginous soils subdivided into two subclasses:
  - slightly leached soils formed on old eolian deposits, with 500–900 mm rainfall (Ustropepts),
  - leached soils, which are found on rocks of various origins (Ustalfs);
- ferrallitic soils associated with tropical ferruginous soils. In this zone they are impoverished, slightly unsaturated ferrallitic soils (Alfic Eutrustox).

On the other hand, Vertisols, Hydromorphic, and Halomorphic soils found in this zone do not present the same problems at all, particularly because of the

presence of 2:1 clay minerals and also because of their water regime.

Coarse material also has a significant role: the proportion of fine sand and coarse sand can affect pore size distribution and overall porosity, and can affect mechanical resistance to root penetration as will be seen later.

Finally, presence of gravel in the soil profile can create some discontinuities, thus assuring aeration and favoring water penetration and good root systems.

The effect of humus on soil structure should also be considered. Its role in structural stability is well known and the rapid drop in humus content in the upper layers is often the initial cause of soil degradation. The nature of humus and the proportion of the different fractions present in the soil profile also have some influence on mechanical resistance to penetration.

The K index to erosion susceptibility (Wischmeier scale established for American soils) ranges from 0.10 for the most resistant to erosion to 0.50 for the most susceptible. In the West African dry tropical zones values are between 0.04 and 0.17. In the USA such values refer generally to sandy and sandy-clayey soils, which are considered relatively resistant to erosion.

The very damaging erosion witnessed in West Africa can be explained by the considerable erosive power of rains. Topography is often a predominant factor in erosion. Steep slopes require specific means of controlling erosion and much care in the use of soil tillage. This is especially the case in Central America and South America (Greenland and Lal 1977).

Climate and vegetation

Climate is an essential constraint since it conditions cropping possibilities. It can affect the need for soil tillage in several ways:

- by the rainfall pattern, which controls the frequency of alternating periods of wetting and drying and, therefore, the possibilities of swelling and shrinking in certain soils;
- by the periodicity and length of seasons. A long dry season severely limits the permanent presence of active soil fauna, such as earthworms. The type of erosion (wind or water) varies with the season, and the means of control are different;
- by the intensity of the rains, one of the principal causes of runoff and erosion; and
- by natural vegetation, which is closely associated with the climate. When it is abundant, it can provide some protection to the soil, and can make plant residues available as effective and protective mulch during the cropping season. This is not the case in the dry tropical zone, however, where even harvest residues are partly used as building material or as fuel.

Time of clearing

A common observation is that in tropical zones soil fertility after a recent clearing is often better than that in a formerly cultivated soil. The improvement of food crop production should, therefore, be based on whether it involves culti-

vating areas which have previously been under natural vegetation or, possibly, sporadic shifting cultivation, or lands which have been cropped for a long time with decreased fallow periods because of population pressure.

When an area is cultivated for the first time, some precautions must be taken so as not to destroy the soil structure and humus.

In hot and humid areas, on very clayey Ferralsols, soil organic matter decomposes rapidly. It is advisable that the superficial humic layers be protected by tilling them as little as possible (Van Wambeke 1974).

Inadequate clearing methods have produced many harmful effects on soils. Some mechanical operations can cause damage to soil physical properties and lead to compaction and erosion. The traditional slash-and-burn method does not cause such problems and even adds fertilizers in the form of ashes. Under these conditions the combination of minimum tillage and mulch can maintain the natural properties (Sanchez 1976). The operations should be evaluated, however, after sufficient time has lapsed, to make sure that in the long run they do not result in soil packing and decreased root development. There should also be enough vegetative growth to provide an effective mulch. Where the soils have been cultivated for a long time, or natural vegetation has disappeared, there is often no alternative to a well-executed soil tillage for creating an adequate soil structure.

In general, any land development operation should consider, when choosing cropping techniques, the important part which the initial characteristics of the environment play in soil behavior during the first cropping cycles (de Blic 1976).

Irrigation possibilities

The problem of soil tillage in irrigated cultivation is different as it very often concerns other soil units, and water layer alters the initial conditions.

Most of the irrigated land in the tropical zone, particularly in Asia, is used for rice cultivation. One of the most widespread land preparation practices is puddling. In most cropping systems puddling is an accidental result of soil tillage carried out under inadequate soil moisture and leads, in general, to serious decreases in yield. In lowland rice systems puddling destroys the superficial structure so as to decrease water losses and to increase nitrogen availability by limiting leaching. The operation is highly beneficial to soils that readily leach. It is particularly important for sandy soils, Oxisols and Andepts, where puddling is indispensable to successful irrigation. It is less important for soils with an impermeable layer or a groundwater table near the surface, or in already dispersed sodic soils.

In most cases, puddling diminishes the effects of a temporary drought and increases yields. But it can be harmful in a rainfed lowland system. When severe drought follows transplanting, the soil hardens and restricts root development. When drought occurs at a later stage, the root system is well developed and water stress can no longer cause irreversible damage (Sanchez 1976).

Another unfavorable effect of puddling is the time required for the soil to dry out in preparation for other crops in rotation with rice. The time is long for

soils high in 2:1 clay minerals, but is considerably reduced for kaolinitic, allophanic, and oxidic families (Sanchez 1976).

CONSTRAINTS TO SOIL TILLAGE IN A TROPICAL ENVIRONMENT

Soil tillage, even when necessary, cannot always be performed in a tropical environment. The constraints can be economic, sociological, or climatic; most are related to the soil.

Problems of mechanical resistance to land preparation according to soil types seem to have been well studied in temperate environments, but not in tropical environments. The bibliographical research for this paper was not very profitable. Data processing systems had numerous references to *mechanical impedance* or *land preparation*, but gave no response when the terms *tropics, tropical agriculture*, or *tropical soils* were introduced. It is recognized that difficulties have been encountered in implementing soil tillage for different categories of soils. But to the best of our knowledge, only few studies provide quantitative data that allow characterization of the phenomenon.

It is well known that Vertisols present special difficulties because they are sticky when wet and hard when dry. An interesting approach – graded broad ridges and furrow system – has been made at ICRISAT, Hyderabad, to alleviate the constraint.

A detailed study of mechanical resistance to land preparation in rainfed cropping was carried out in the dry tropical zone on sandy and coarse loamy soils by IRAT. We present the results obtained in this area and the characteristics to be measured.

A CASE STUDY: HARDENING AND CEMENTATION OF COARSE LOAMY SOILS IN THE SEMIARID WEST AFRICAN ZONE

Most of the sandy and sandy-clayey soils of the dry tropical West African region are very loose in a wet state, but become hard as soon as they dry out. They then become difficult, if not impossible, to till – mechanical resistance is too strong for cropping instruments to overcome, no matter what traction power is used. This phenomenon is especially important when the rainy season is short because cropping operations are limited to a short period of time.

Hardening and cementation were studied on three soil types whose textural characteristics are given in Table 1.

Characterization of the phenomenon

Soil hardening and cementation can be characterized in several ways:

- *by thoroughly observing the upper layers of the soil profile ("cultural profile")*

When the soil is dry, fragments taken out of the profile present a uniform and massive aspect throughout and do not have a definite form. Depending on texture the fragments become powdery when subjected to some hard pressure.

Table 1. Principal textural characteristics of soils (0 to 20-cm horizon) susceptible to hardening.

	Northern Senegal ferruginous, tropical slightly leached soil (Ustropept)	Eastern Senegal ferruginous, tropical, leached soil (Ustalf)	Southern Senegal ferrallitic slightly desaturated soil (Alfic Eutrustox)
Clay <2 μ (%)	3.1	7.1	11.7
Fine silt 2–20 μ (%)	1.5	3.5	5.5
Coarse silt 20–50 μ (%)	4.7	15.7	8.5
Fine sand 50–200 μ (%)	69.7	34.9	42.5
Coarse sand 200–2000 μ (%)	20.8	38.4	31.3
Carbon (%)	0.25	0.50	0.70

• *by measuring the bulk density of soil fragments of different sizes.* When clod size decreases, porosity decreases only slightly, which means an absence of individual structural elements.

• *by measuring resistance to penetration*

– in the field: a metal rod terminating in a cone is plunged into the soil by a weight falling from a given height. The work carried out for a given depth is directly proportional to the number of blows. The work (or number of blows) is plotted against the depth to which the rod is driven. The average force of resistance to penetration may be determined on the curve for a given depth.

– in the laboratory: the force necessary to drive a needle with a 2-mm diameter at the rate of 1 cm/minute into a standard size sample is measured.

Data on resistance to penetration and rupture forces in two Senegalese soils are shown in Table 2.

• *by measuring traction efforts*

Plowing soil that is dry (moisture content less than 2%), ferruginous, tropical, and slightly leached (Ustropept) requires a force averaging between 80 to

Table 2. Resistance to penetration and breaking force for two Senegalese soils.

	Resistance to penetration in the field (F, kg to 20 cm)	Resistance to rupture in the laboratory			
		Core samples		Reconstituted samples	
		F, g force	Pressure (kg/cm^2)	F, g force	Pressure (kg/cm^2)
Bambey (3% clay), ferruginous tropical slightly leached soil (Ustropepts)	225	960	30	1910	61
Sefa, ferrallitic slightly desaturated soil (Alfic Eutrustox)	634	5715	182	6645	212

145 kg/dm^2; in moist soils the figures are nearer 30 to 35 kg/dm^2.

Recently and, to our knowledge, for the first time a direct relationship was established between mechanical resistance to penetration measured with a percussion penetrometer and the specific traction effort measured throughout plowing (Chopart 1978) (Fig. 3).

$$T = 0.079\,F + 20.153$$

with $r = 0.90$ HS (P.01)

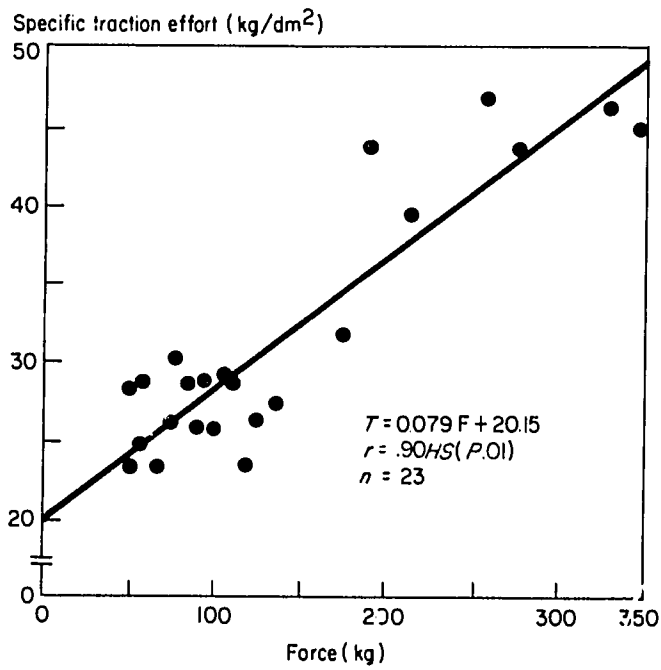
where T = specific traction power in kilograms/square decimeter

F = average resistance force to penetration between 5 and 20 cm deep, in kilograms

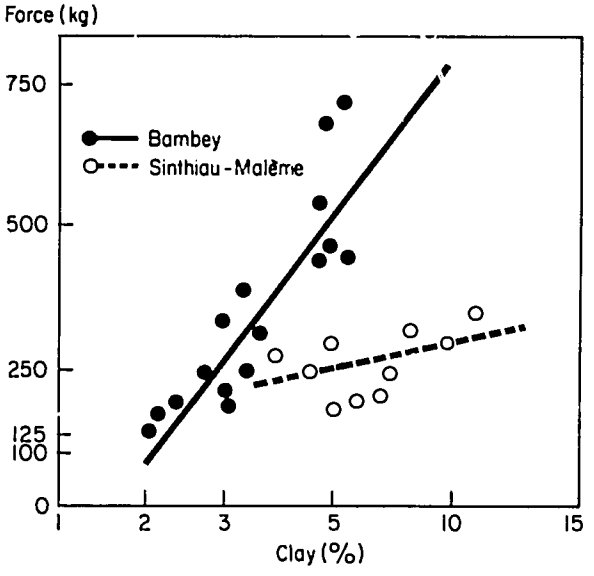
Factors affecting soil hardening and cementation

Mechanical resistance to penetration depends on numerous factors, which are often interrelated:

Texture. Some relationships between resistance to penetration force and soil content of clay (particle size less than 2 μm) were established in the field and in the laboratory (Fig. 4).



3. Specific traction effort measured during plowing versus mechanical resistance to penetration.



4. Soil hardening (resistance to penetration) versus clay content (field trials).

Assuming that $x = sin^{-1}A$

A = % clay content,

y = average force of resistance to penetration between 0 and 20 cm deep, in kilograms,

Bambey (Ustropepts) has $y = 71x - 474$ with $r = 0.849$ *HS* (*P*.01); Sinthiou-Malème (Ustalfs) has $y = 9.9x - 109$, $r = 0.636$ *S* (*P*.05).

The curves, systematically established in the laboratory by varying the clay content while keeping the original skeleton (sands and silts), are exponential (Fig. 5).

Bambey (Ustropepts) $Fg = 1252e\ 0.17A$ $r = 0.995$ *HS* (*P*.01)

Sefa (Alfic Eutrustox) $Fg = 1713e\ 0.0756A$ $r = 0.962$ *HS* (*P*.01)

The curves obtained differ perceptibly according to the soil type, showing two influences:

- the composition of the sand and silt fractions

Thus if $x = sin^{-1}T$, where $T = \frac{A}{LG + SG} \times 100$

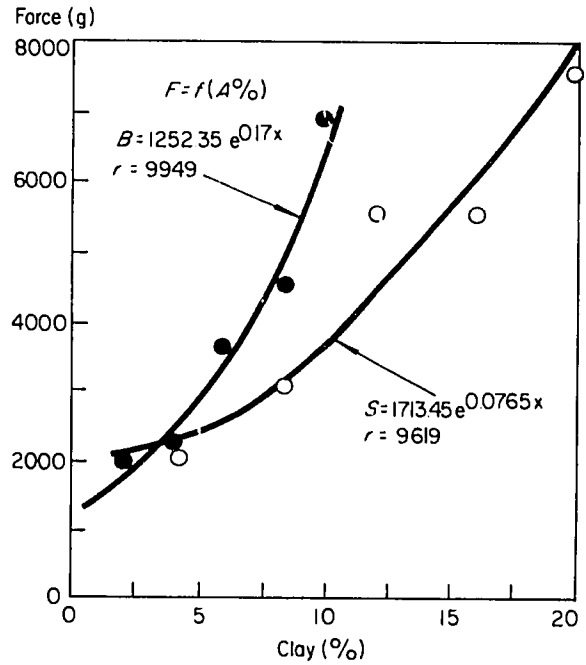
A = % clay content

LG = % coarse silt content

SG = % coarse sand content

The coefficient of correlation is improved compared to the use of only the variable clay content in the equation.

- the iron oxides present: 60% in fractions less than 2 μm at Bambey, and 35% at Sefa.



5. Soil hardening (resistance to penetration) versus clay content (laboratory test).

Porosity. There is often a close relationship between porosity and force of resistance to penetration. The connection can be represented by an exponential curve (Fig. 6). But if the clay content is not the same, forces for the same total porosity will be different.

Soil moisture. In the areas under consideration, the variations in the force of resistance to penetration as a function of soil moisture contents can be described by the power function $Y = X^m$ with $m < 0$.

Possible extension of findings to other problems of mechanical resistance

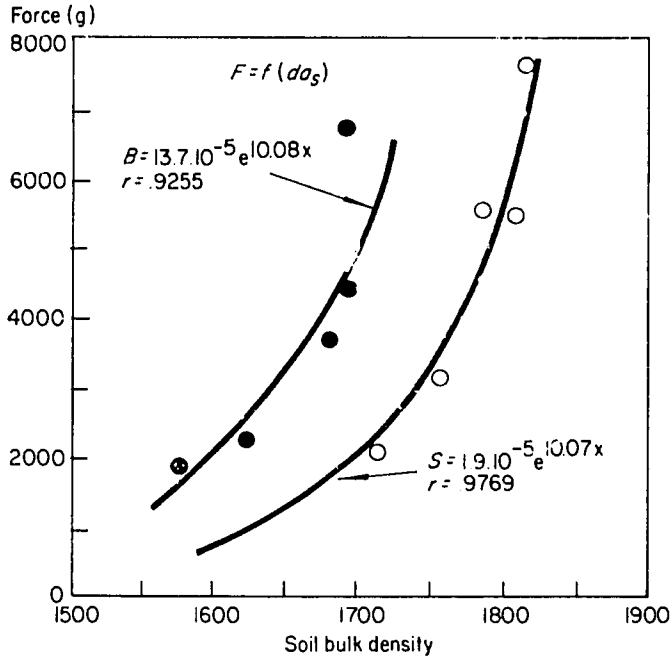
Soil hardening is a serious constraint to land preparation in the dry tropical region. Although plants can grow and produce without mechanical intervention, their production is severely limited by the soil's physical properties. Proper soil tillage increases crop yields by 20 to 100%.

Constraints involving the soil are the same. Therefore, the same problem will have to be resolved wherever mechanical intervention is incompatible with the economic means available to farmers.

OBSERVATIONS AND MEASUREMENTS IN STUDYING PROBLEMS OF MECHANICAL RESISTANCE TO LAND PREPARATION

Most factors that need measurement have been touched on:

- Textural characteristics:



6. Relationships between resistance to penetration and soil bulk density.

– analysis of particle size distribution, particularly a thorough division of sands

– mineralogical nature of clays

- Structural characteristics:

– measuring the soil bulk density in situ. Clod density and porosity curves as functions of the size of structural elements

– determining classes of pore sizes

- Water characteristics:

– pH curves

- Mechanical characteristics:

– penetrometric measurements in the field and in the laboratory,

– Atterberg limits

– Proctor curves

- Measuring traction efforts and correlations with water and mechanical characteristics
- Analyzing soil organic matter and its different forms
- Analyzing certain mineral elements:

– Iron and aluminum – role of the sesquioxides present in the particle fraction whose size is less than 2 μm

– Calcium and sodium responsible, in particular, for certain crusting phenomena.

Obviously not all determinations are essential in every case, but it is often necessary that they be connected.

Resistance to penetration measurements cannot be separated from soil moisture measurements. Everything seems to revolve around the following four data:

- particle size distribution
- soil moisture
- resistance to penetration force
- traction effort.

Studies of the connections among the four parameters are presently pursued by IRAT and the Institut Senegalese de Recherches Agricoles (ISRA) in Senegal for the sandy and sandy-clayey soils of the dry tropical zone.

CONCLUSION

In this attempt to analyze the problem of mechanical impedance to land preparation in the tropical zone for food crop production we can be criticized for not having followed the suggested guidelines and for having somewhat strayed from the subject. Actually, we have approached a much larger problem – that of soil tillage in a tropical environment. This focus seemed indispensable to us for two reasons:

- The necessity of soil tillage in a tropical environment has not been unanimously accepted. If it is decided that the soil will not be touched, the problem of mechanical impedance to land preparation does not arise.
- Few researchers have touched on the problems of mechanical resistance in the tropical zone. Some like Muchena (1979) speak of classifying soils according to their workability, but this is more of a subjective observation than a rigorous determination of certain characteristics that allow soil appraisal.

Two other important aspects are related to mechanical impedance to plant growth.

- the soil's mechanical resistance to root penetration, a subject to be discussed by Dr. Taylor, and
- seed emergence when superficial hardening phenomena occur. The latter seems to us to be too limited and is closely related to seedbed preparation.

At present, problems of land preparation are often empirically resolved by use of heavy mechanical equipment which can penetrate the soil regardless of soil moisture conditions and without concern for economizing on energy, profitability, or, unfortunately, conserving soil fertility.

Willcocks' (1979) study in Botswana is original and interesting because it shows the very tool for economical use of the maximum amount of energy for a given condition.

We feel that it is in this direction that studies should be directed. What type of soil tillage should be and could be performed for a soil type, taking into account cropping history and the climate? What is the average traction-tool combination which, for the same energy, is the most economical? The question of soil tillage assumes much importance in the tropical environment because it concerns food crops with little profitability.

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Mechanical impedance to root growth

H. M. TAYLOR

This paper reviews basic principles of mechanical impedance, geographical locations where root impedance is a problem, methods for measuring impedance, techniques for determining when impedance is a constraint on root growth and on crop yield, and methods for alleviating, tolerating, or evading mechanical impedance.

Mechanical impedance has no direct effects on food production. It affects yield by reducing water consumption or use of essential minerals. Often, however, it distorts the plant's rooting pattern without reducing yield.

Much research has to be accomplished before the significance of mechanical impedance can be predicted for any specific site. The overall importance of mechanical impedance to food production in the tropics has not yet been evaluated, but the constraint probably reduces yield more often in the semiarid tropics than in other moisture regimes.

MECHANICAL IMPEDANCE is only one of several soil constraints that can cause altered rooting patterns (Carson 1974), e.g. marked reduction in concentration of plant roots at the normal depth of plowing, or scarcity of roots in vehicular traffic paths between plant rows. Therefore, given situations must be analyzed carefully before mechanical impedance is established as the restrictive agent. This article discusses the:

- basic principles of mechanical impedance,
- geographical location of soils that mechanically impede plant roots,
- qualities of soils where mechanical impedance is most likely to occur,
- methods for measuring mechanical impedance,
- techniques for determining if mechanical impedance is a constraint on crop yield,

USDA, Iowa State University, Ames, Iowa 50011, USA.

- methods for alleviating or evading mechanical impedance, and
- future research on mechanical impedance.

BASIC PRINCIPLES OF MECHANICAL IMPEDANCE

Plant roots elongate when the turgor pressure inside new cells is sufficient to overcome the constraint of the cell walls and any external constraint caused by the surrounding soil matrix. The difference between turgor pressure and cell wall constraint, defined as root growth pressure by Gill and Bolt (1955), must be greater than the impedance acting upon the cross section of the root if the root is to elongate. Maximum root growth pressure values were first measured by Pfeffer (1893) - 7 to 25 bars for horsebean (*Vicia faba* L.), corn (*Zea mays* L.), common vetch (*Vicia sativa* L.), and horse chestnut (*Aesculus hippocastanum* L.). Since that time, Stolzy and Barley (1968), Eavis et al (1969), and Taylor and Ratliff (1969b) have confirmed that the maximum axial (longitudinal) root growth pressures of several crops range between 9 and 15 bars. Kibreab and Danielson (1977) have shown that radish (*Raphanus sativa* L.) roots also cease to enlarge in diameter when subjected to radial constraints of about 8.5 bars.

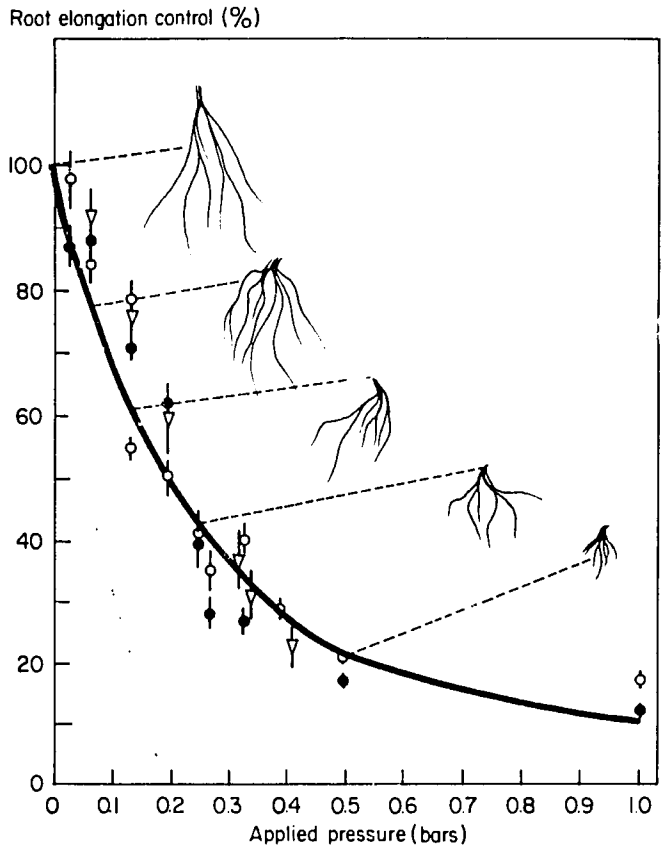
Russell (1977) suggested that agriculturists be more concerned with the relative effects of partial constraints on root elongation and development than with the maximum root growth pressures that plants can exert. Russell and Goss (1974) showed that 0.2-bar pressure applied to a glass bead system reduced the elongation rate of barley (*Hordeum vulgare* L.) roots by 50% and that a 0.5-bar pressure reduced the rate by 80% (Fig. 1). As the pressure increased, the roots became shorter and larger in diameter. Pore diameters between 16 and 157 μm did not affect the relationship between root elongation rate and applied pressures.

Pore diameters sometimes affect root elongation rates. If the pore is larger than the root tip, the root can enter even a rigid matrix (Wiersum 1957; Aubertin and Kardos 1965a, b). If a material is easily deformable, roots enter and grow until some factor other than mechanical impedance stops elongation rate (Taylor and Gardner 1960). In most situations, roots grow partly through existing pore spaces and partly by moving aside soil particles.

Root growth is affected by many interacting soil factors (Russell 1977). Some factors affect the maintenance of turgor pressure, some affect cell wall constraint, and some affect the size of the root tip.

GEOGRAPHICAL LOCATIONS OF MECHANICAL IMPEDANCE

Mechanical impedance of plant roots occurs in areas where soil structure is destroyed during tillage operations. Sometimes, destruction is caused by heavy equipment on several trips over the fields each year. Unless special management techniques are used, a large proportion of the land surface is compacted to some degree by the weight of these vehicles, and compacted soils resist root entry and elongation.



1. Effect of applied pressure on rate of elongation of seminal axes of barley plants grown for 6 days in ballotini beads. Open circles: pore diameter 157 μm. Closed circles: pore diameter 69 μm. Triangles: pore diameter 16 μm (Russell and Goss 1974).

Soil compaction by modern machinery is not the only cause of mechanical impedance, however. The footprints of animals (even man) exert significant contact pressure on the soil surface. The resultant pressure can be enough to compact the soil layer near the soil surface. When an animal's feet sink deeply into the soil, compaction can occur there and in some cases that compacted soil may mechanically impede roots.

Finally, much of the world's rice crop is grown under puddled-flooded conditions. Puddled soil layers often have low porosity and, thus, a low percolation rate (Sanchez 1976). Such layers cause the severely distorted root systems of upland rainfed crops that follow the rice crop (Syarifuddin and Zandstra 1978).

Various root-impeding soil horizons, e.g. duripans, ortstein layers, petrocalcic layers, and placic layers (all terms are defined in *Soil taxonomy*, USDA 1975), occur naturally in the tropics. These layers nearly always severely impede root

growth, but other soil qualities, such as lack of aeration, and ion imbalance also constrain rooting. When the layers are near the soil surface, they sometimes can be destroyed by deep tillage. The best management technique, however, is retaining the land in permanent vegetation.

DEVICES FOR MEASURING MECHANICAL IMPEDANCE

Various devices have been used in studies on the effects of mechanical impedance on root growth. They include soil penetrometers, shear vanes, unconfined compressive strength machines, triaxial load cells, and bulk density samplers. Because all results are empirical, the values must be correlated with actual root growth measurements before the devices are useful for prediction purposes.

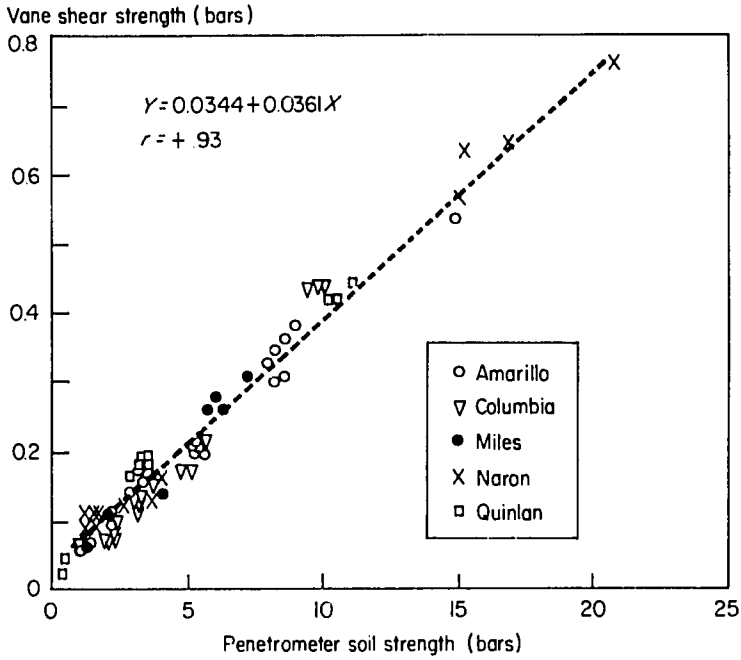
Penetrometers fall into three main groups: a) those which record the pressure necessary to push the tip a specific distance into the soil volume (static-tip penetrometers), b) those which measure the pressure (or force) required to move the tip through the soil at a more or less constant rate (moving-tip penetrometers), and c) those which record the number of blows required to drive the penetrometer tip through a specific depth of soil (impact penetrometers).

Shear vanes (Freitag 1971) also have been used to measure mechanical impedance. The vane is forced into the impeding layer and then rotated. The maximum torque (force times lever arm) required to rotate the vane is divided by the surface area of the sheared cylinder of soil. The vane shear strength increases as soil cohesion or soil bulk density increases, or as soil water content decreases. This technique is slower than, but highly correlated with, penetrometer resistance measurements (Fig. 2).

Unconfined compressive strengths (Sallberg 1965) have also been used. A soil core is removed from the impeding layer and placed on the platen of the machine, and then a vertical force is applied. The force required to break the core is divided by the cross-sectional area to get a value for unconfined compressive strength. Compared with penetrometers or shear vanes, this technique gives distorted results on brittle soils because of horizontal cleavage planes, formed either by differential settling velocities of particles after sedimentation or by passage of a tillage tool at that specific depth.

Triaxial load cells (Sallberg 1965) are devices in which a hydrostatic pressure can be applied radially and an additional force can be applied to a soil sample in the vertical direction. Soil cohesion and friction angle are then determined from a Mohr diagram (Yong and Warkentin 1966). This device has been useful in understanding the basic mechanics of root growth (Barley 1963, Russell and Goss 1974) but usually is too slow for field evaluation of mechanical impedance.

Static or moving-tip penetrometers sometimes can be combined with bulk density measurements (Blake 1965) to characterize the impedance of a soil layer. Soil cores are compacted to a series of soil bulk densities while at high but unsaturated water content. The cores are then dewatered to specified soil water potentials. A family of curves is obtained by relating penetrometer resistance



2. Relation between soil strength as measured with a static-tip penetrometer and vane shear strength (Taylor et al 1966).

(soil strength) to soil bulk density and soil water potential (or water content). Although soil strength (mechanical impedance) is the most accurate measurement to use in mechanical impedance studies, bulk density measurements are sometimes used because elongating roots often encounter the impeding layers at the field capacity moisture contents; therefore, the soils' strengths more or less depend only on bulk density changes at the time that root penetration first occurs. Bulk densities that stop *most* roots of *most* crops depend upon soil texture. In the southern United States, the bulk densities for clay loam, loam, sandy loam, and loamy sand soils are about 1.55, 1.65, 1.80, and 1.85 g/cm^3. These values are general guidelines only and should be checked in the field for accuracy in the tropics, especially since the type of the clay mineral, iron cementation, and particle density can greatly alter the critical bulk densities.

LIMITING VALUES OF MECHANICAL IMPEDANCE

Limiting values for root growth

Plant roots are less likely to enter soil layers with massive structure as soil strengths increase (Taylor et al 1966). Almost all cotton (*Gossypium hirsutum* L.) roots penetrated soil cores with low strengths, but the proportion of penetrating roots decreased with increasing strength until no roots penetrated at 30 bars

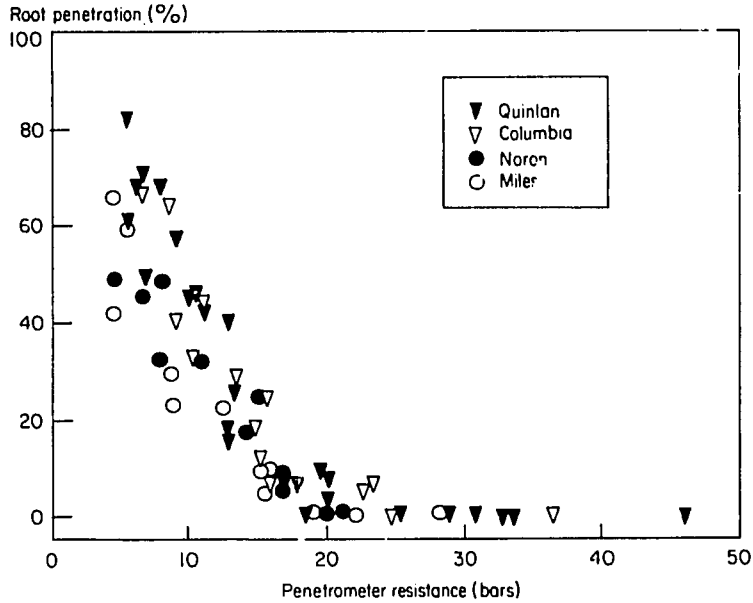
soil strength (static-tip penetrometer), regardless of whether the high soil strengths were caused by increased soil bulk densities or by reduced soil water contents. The cores were derived from four soils that ranged in texture from loam to loamy sand. One general relationship seemed to exist between cotton root penetration percentage and soil strength (Fig. 3).

Penetrometers also can be useful devices in correlating soil strength with rate of root elongation. Taylor and Ratliff (1969a) found that the elongation rates of cotton and peanut (*Arachis hypogaea* L.) taproots progressively decreased with increasing penetrometer resistance (moving-tip penetrometer). A penetrometer resistance of 7 bars reduced cotton penetration rate by 50%, while 20 bars was required to reduce the peanut rate by 50%. Soil water potential between −0.17 and −7.0 bars had no effect on the elongation of cotton roots; that between −0.19 and 12.5 bars did not affect the elongation of peanut roots. Cockroft et al (1969) found that a penetrometer resistance of about 11 bars in a wet clay soil was sufficient to reduce pea (*Pisum sativum* L.) root elongation rates by 50%.

Studies have shown that the quantity of roots growing in field soil profiles is reduced by high-strength soil layers. The studies were on corn and soybean in the Philippines (Syarifuddin and Zandstra 1978); corn in Florida, USA (Fiskell et al 1978); peanut, grain sorghum, corn, and rice in Senegal (Nicou and Chopart 1979); cotton and grain sorghum in the Southern Great Plains, USA (Taylor and Burnett 1964, and Taylor et al 1964a); asparagus in The Netherlands (Reijmerink 1973); rice in India (Kumar et al 1971); grapes in Israel (Cohen and Sharabani 1964); sugarcane in Queensland, Australia (Monteith and Banath 1965); cantaloupe in California (Davis et al 1968); wheat and cotton in Orange Free State, Republic of South Africa (Bennie and Laker 1975); wheat in Libya (El-Sharkawy and Sgaier 1975); and sugarcane in Hawaii, USA (Trouse 1965). The works cited illustrate the widespread occurrence of high strength soils and their effects on root development.

Limiting values for crop yield

For several reasons the relationship between mechanical impedance and crop yield does not easily show a direct cause-effect relationship. First, mechanical impedance does not, of itself, reduce yield. Plants require water, essential minerals, and anchorage from the soil. If the impeding layers do not increase plant stresses for these items at *any time between emergence and physiological maturity*, mechanical impedance will not affect yield. Second, the definitive experiments that show mechanical impedance reduces root growth were conducted in the laboratory under closely controlled conditions. These conditions usually are not achieved in fields where most yield trials are conducted. Finally, all commonly used strength-sensing devices integrate their measurements over soil volumes substantially larger than the size of the plant root. In addition, the devices either follow a rigid path (penetrometers) or cause a pre-ordained failure pattern (shear vanes and compressive strength machines). The small and flexible plant roots are



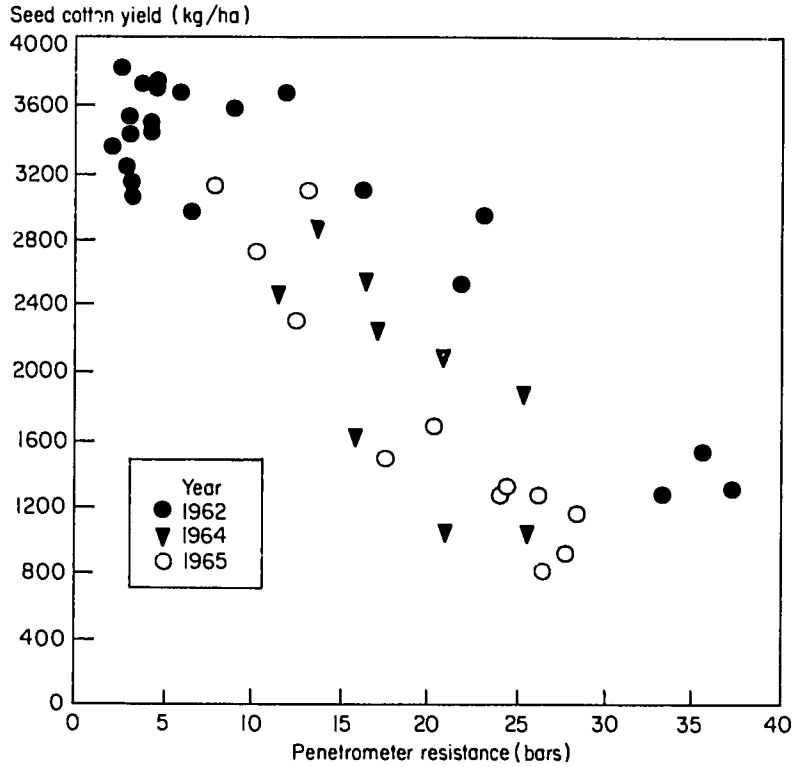
3. Relation between penetrometer soil resistance and the percentage of cotton taproots that penetrated through cores of 4 soils (Taylor et al 1966).

able to penetrate soil layers through soil cracks, worm holes, root channels, and other voids that do not substantially affect results obtained with the strength-sensing devices (Nash and Baligar 1974, Davis et al 1968).

Despite the difficulties, many experiments have shown that crop yields are reduced as the strength of soil layers or volumes increase. In an irrigated experiment, Carter et al (1965) found that seed cotton yield decreased linearly from 3,600 kg/ha, where penetrometer resistance measured at *field capacity* (cone penetrometer) was 3 bars, to 1,450 kg/ha where resistance was 40 bars (Fig. 4). Thus, yields of irrigated cotton grown in the arid environment of San Joaquin Valley of California increased as mechanical impedance was reduced. Grimes et al (1975) showed that water uptake rates (cm^3 H_2O/cm^3 soil a day) increased with rooting density on San Joaquin Valley soils; plant water stress probably was reduced, even under irrigated conditions, as mechanical impedance was reduced.

In the arid environment of the Al-Kufra Oasis of southeastern Libya, El-Sharkawy and Sgaier (1975) increased rooting depths of wheat by 24% from no tillage by disking to 15 cm, by 48% by disking to 30 cm, by 100% by subsoiling to 50 cm, and by 132% by subsoiling to 70 cm. Yields increased from 3.0 t/ha for no tillage to 3.9, 4.1, 4.2, and 4.7 t/ha for the four tillage treatments.

In the semiarid environment of the Southern Great Plains, the yield of non-irrigated cotton was reduced as penetrometer resistance (static-tip penetrometer)



4. Relation between penetrometer resistance and yield of seed cotton. Drawn from data of Carter et al (1965).

increased. The yield of lint cotton was 560 kg/ha where no soil pan existed and 280 kg where penetrometer resistance was 25 bars. Yields were not further reduced as penetrometer resistance were increased above 25 bars (Taylor et al 1964a). The yields of grain sorghum tops (Taylor et al 1964a) also decreased curvilinearly as soil strength increased, but were substantially lower on a Pratt fine sandy loam than on Amarillo fine sandy loam when soil pans were created in the former at Bushland, Texas (Fig. 5). Reseeded range grasses (Barton et al 1966) and sugar beets (*Beta vulgaris* L.) (Taylor and Bruce 1968) followed the same general trend of decreased yield with increased soil strength.

In semiarid Senegal, Nicou and Chopart (1979) found a linear increase of rooting density within the 10- to 30-cm soil layer as total soil porosity increased within that layer. Yields of peanut, sorghum, corn, and rainfed rice showed a linear increase as rooting density increased.

In the subhumid environment of Alabama, seed cotton yield was reduced from 180 g/cylinder (an oil drum buried in field soil) when no pan existed, to about 70, 45, and 35 g when soil pans with 80 bars penetrometer resistance existed at 30, 20, and 10 cm (Lowry et al 1970). Soybean [*Glycine max* (L.)

Merr.] followed the same general pattern of reduced yields as penetrometer resistance increased (Rogers and Thurlow 1973). Plant water stresses induced by soil pans were thought to be the reason for reduced yields in both cases.

A soil profile that contains an impeding layer of only moderate thickness is less likely to reduce yield in perennial than in annual crops. Barton et al (1966) found that the first year of giant cenchrus (*Cenchrus myosuroides* H.B.K.) grown on a fine sandy loam soil at Big Spring, Texas, was about 3,400 kg/ha where no soil pan existed, and about 1,050 kg/ha where a pan with a penetrometer resistance of 34 bars existed. The rooting pattern also was severely distorted (Fig. 6). In time, however, grass roots found planes of weakness in Amarillo fine sandy loam soil and permeated most of the soil volume (Fryrear and McCully 1972).

ALLEVIATING OR EVADING IMPEDANCE

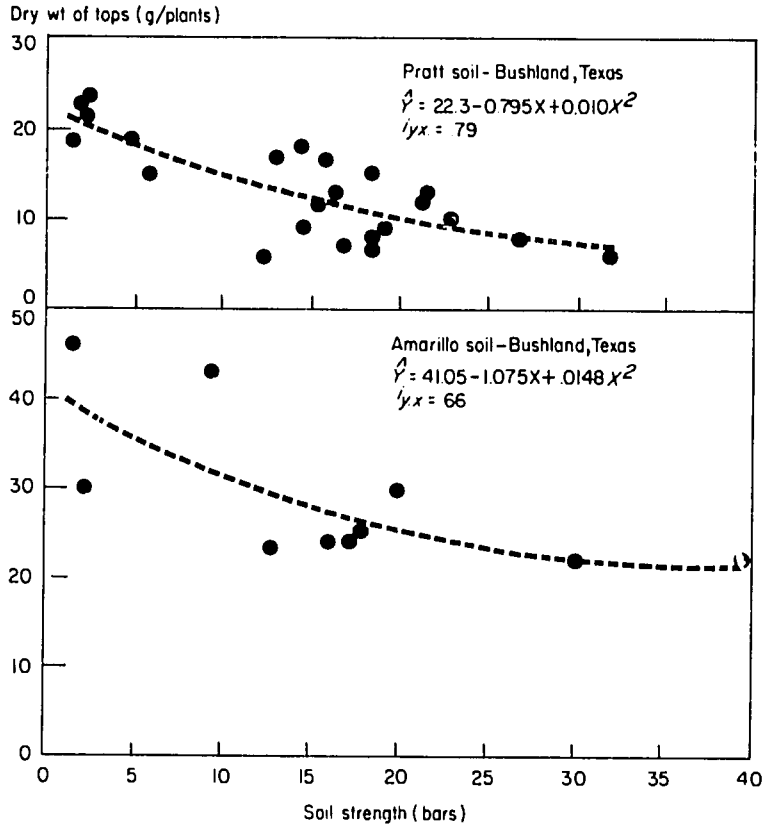
Several methods have been used to reduce the effects of mechanical impedance on crop production. Each must be evaluated for cost, equipment availability, operator expertise, timeliness of operations, and social acceptance.

Controlled traffic has achieved some success in evading mechanical impedance on most of the land surface (Dumas et al 1973). Narrow strips of the field are set aside for all vehicular tire traffic. These areas often become so compact and develop such high strength that no plant roots can grow in the surface soil of the strips. Consequently, water and fertilizer nutrients contained in these soil volumes are not available for crop use (Trouse et al 1975). In a 3-year study on a sandy coastal plain soil in Alabama, Young and Browning (1977) found that seed cotton yields averaged 2,335 kg/ha when tractor and sprayer traffic was not controlled, and 2,540 kg/ha when the vehicles were confined to traffic strips. Dumas et al (1973) found that cotton yields in Alabama were increased by the controlled traffic concept. Sheesley et al (1974) found that alfalfa (*Medicago sativa* L.) yields and stand longevity decreased as the proportion of ground surface covered by tire traffic increased. Even though controlled traffic increased infiltration of irrigation water in California (Abernathy et al 1975), cotton yields were not increased in the San Joaquin Valley (L.M. Carter cited by Chancellor 1977).

Considerable success has been achieved in increasing crop yields by deep tillage of soils that contain a high strength layer, especially if the tillage operation completely penetrates the impeding layer. Data from Lund and Elkins (1978) illustrate the problem of predicting just when crop yields will be increased by deep tillage. Cotton yield data were obtained at 8 sites in Alabama where mechanically impeding layers were present (penetrometer resistance >15 bars at field capacity). Planting directly over the chisel slot both increased and decreased yield compared to a normal no-chiseling treatment (Table 1).

Burnett and Hauser (1967) surveyed the literature to find out how long the effects of deep tillage will persist. They concluded that the effects will be short-lived if:

- soils were medium to coarse-textured (silt loam or coarser),



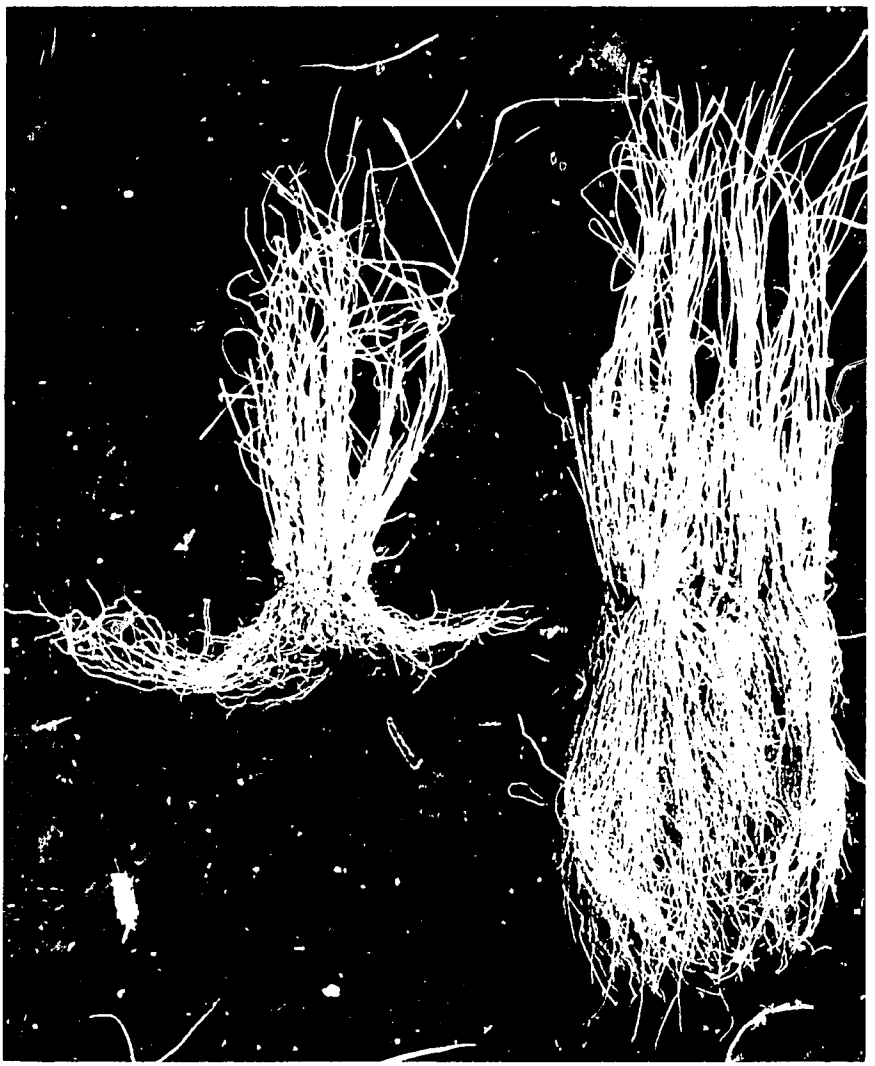
5. Effect of soil strength (penetrometer resistance) on yield of sorghum tops on Pratt and Amarillo fine sandy loam soils (Taylor et al 1964a).

- the impeding layer was caused by farm machinery operations, or
- the deep tillage implement was a subsoiler or chisel.

Beneficial results from deep tillage persisted for several years if:

- soils were either fine-textured (high clay content) throughout or there was a dense layer of fine-textured soil within the profile,
- the tillage operations were drastic, such as with use of trenching machines, slip plows, huge moldboard or disc plows that drastically disturb the entire soil mass, or
- the dense zones were essentially genetic in nature (although probably aggravated by cropping).

Crops grown in semiarid and arid parts of the world often are planted when the water content of the soil in the plow layer is less than field capacity but still high enough for germination. Mechanical impedance is a function of both soil bulk density and soil water content. Layers with low water content sometimes will impede plant roots until a rain occurs (Taylor et al 1964b) or until



6. Roots of giant cenchrus growing in Amarillo fine sandy loam soil. The plant at left grew on soil with a high-strength soil pan. The plant at right grew on soil where the pan was removed by chiseling. The greater top growth reflected greater utilization of water and nutrients from the larger soil reservoir (Barton et al 1966).

irrigation water is added. Soil strength decreases and root penetration increases when water is added. Additional irrigation or runoff water diverted onto a cropped area are management tools that tend not only to increase the water supply in the profile but also to make that water more available by increasing root penetration through high strength soil layers.

Table 1. Effect of subsoiling in the row before planting on seed cotton yields in Alabama, USA, 1966.[a]

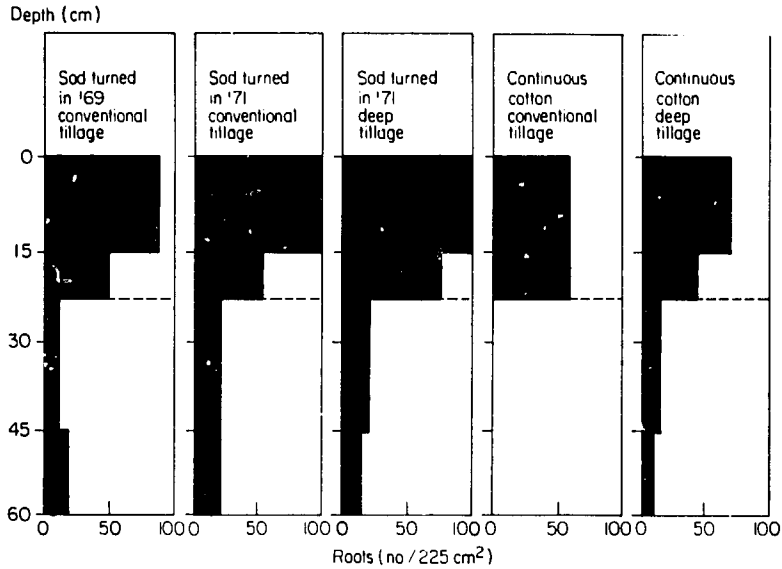
Site	Yield (kg/ha)		Yield increase (kg/ha) from subsoiling
	Conventional treatment	Subsoiled treatment	
Headland	2260	2260	0
Normal	1470	1165	−305
Prattville (east location)	2250	2250	0
Prattville (west location)	1825	1905	+80
Sand Mountain	2400	2060	−340
Monroeville	2205	2150	−55
Auburn (Field 17)	1525	2060	+535
Auburn (Field 19)	1490	2005	+515
Tallassee	1210	1850	+640

[a]From Lund and Elkins 1978.

The research literature contains many references to the pan-shattering ability of various plants such as alfalfa, sweet clover (*Melilotus alba* Medik.), and guar (*Cyamopsis tetragonolobus* L.). The reports usually clarify the effects of these plants on succeeding crops, but not the exact mechanism that causes the yield increase, e.g. increased root penetration, increased nitrogen supply, increased aeration, or increased infiltration, etc. for the succeeding crop. Elkins et al (1977), however, have produced unambiguous results showing that bahia grass (*Paspalum notatum* Flügge "Pensacola") roots will penetrate soil layers that mechanically impede cotton roots. They found that bahia grass increased the number of pores greater than 1.0 mm in diameter and thus increased cotton rooting densities to at least the 60-cm depth (Fig. 7). Cotton following bahia grass sod plowed under 3 years before still yielded more than cotton grown where the soil had been chiseled to 35 cm deep. C.M. Peterson (quoted by Elkins et al 1977) found that bahia grass roots possess a fibrous sheath beneath the epidermis. This sheath, which is absent in most plants, probably is responsible for the additional penetrating ability of bahia grass roots.

RESEARCH NEEDS

Major gaps exist in our knowledge about the effects of mechanical impedance (soil strength) on crop yield, especially in the tropics. First, information is needed about the ease with which tropical and subtropical soils develop high-strength layers when they are subjected to the heavy weights of modern farm equipment. The information will allow national or regional planners to impose some soil management restrictions. Second, soil maps, profile descriptions, and land evaluation descriptions of the areas where field experiments have been conducted are needed. Third, reconnaissance land resource surveys are needed to allow extrapolation to wider areas of the field and laboratory information obtained at the



7. Effect of Pensacola bahia grass and deep tillage on cotton root penetration of a high-strength layer in Cahaba loamy sand soil, Tallassee, Alabama. The dotted line shows depth to the high-strength layer (Elkins et al 1977).

specific experimental site. This information will allow national planners to determine the national significance of the mechanical impedance problem. Fourth, more plant species should be examined for their ability to penetrate high-strength soil layers. Fifth, much more information on the interactions of mechanical impedance with other soil factors and their effects on root growth is needed. Finally, much information is needed on the effects of root growth (whether constrained by mechanical impedance or by some other soil factor) on the water or nutrient supply to the plant tops. Some progress has been made in developing simulation models for water and nutrient uptake, but much more research is needed. The models will enable national and international planners to forecast, with reasonable accuracy, the consequences of a proposed land development scheme.

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Soil erosion as a constraint to crop production

R. LAL

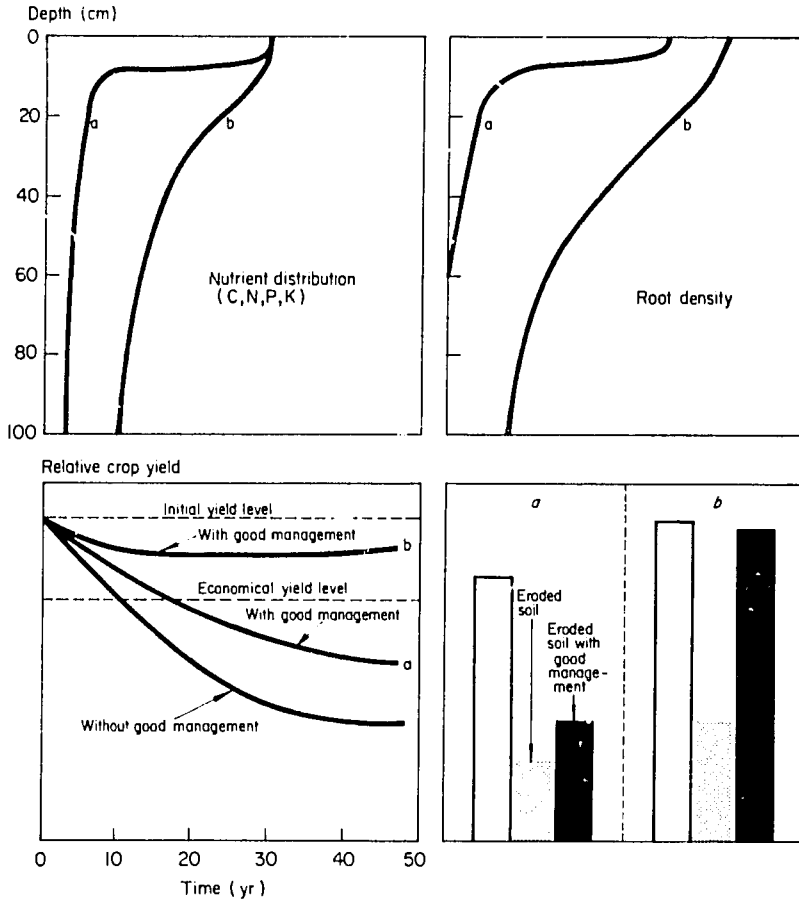
If not adequately managed, soil erosion can be a serious constraint to food production in the tropics. Research priority must be given the quantification of soil loss (wind and water erosion) in relation to the loss of productive potential for a range of soils and crops. Basic information on parameters affecting rainfall and wind erosivity and soil erodibility is also needed. Continuous ground cover provided by appropriate cropping system (relay and mixed cropping), crop residue mulches, and no-tillage systems are better as erosion control measures than engineering systems of contour terraces and diversion channels adopted in isolation. Methods of new land development and forest clearing must be evaluated for their effects on soil, environments, and crop production, and for socioeconomic acceptability.

SOME SOIL EROSION is inevitable whenever natural vegetation is replaced by commercial farming. Whether or not soil erosion is a constraint to crop production in the tropics depends on soil, climate, and crop to be grown. Wischmeier and Smith (1965) defined *soil loss tolerance* as the maximum rate of soil erosion that will economically and indefinitely permit sustained crop productivity. Baver (1950) observed that soil erosion is very serious if the land productivity cannot be restored even by introducing improved systems of management. Soil characteristics that affect soil loss tolerance are nutrient profile, rooting depth, and physicochemical properties of the subsoil horizons.

In addition to the economic and indefinite maintenance of crop productivity, it is important to consider soil erosion's off-site damage to the natural resource base. Such damage, which includes abrasion or burial of young seedlings, water pollution, siltation of rivers and harbors, etc. is difficult to quantify.

Erosion caused by mismanagement has rendered many soils in the tropics unproductive. In category *a* in Figure 1 are soils whose productivity cannot be

International Institute of Tropical Agriculture, Ibadan, Nigeria.



1. Range of soil loss tolerance in relation to profile characteristics and crop response to management.

restored, even with improved management. A majority of the Alfisols in West Africa, characterized by gravelly horizon at shallow depth and with structure that is unstable to raindrop impact, are prone to severe degradation as a result of surface soil removal. On the other hand, deeply weathered well-structured soils with good water and nutrient holding capacities can sustain crop yield indefinitely with proper management. Soils of volcanic origin and some Oxisols of the Congo and Amazon basin fall in this category. Soil *b* of Figure 1 fits this description. Similar soils in Hawaii and Puerto Rico suffer a minimal loss in productivity by some removal of surface soil.

Some well-structured Oxisols and Ultisols with deep profile are severely affected by gully erosion and by subterranean or pipe erosion. Gully erosion is serious in many regions of Brazil, West Africa, and India. In those areas, the subsoil has little strength and gullying, once it starts, is difficult to control.

EROSION HAZARDS IN THE TROPICS

Results of experiments on soil erosion by water in tropical Africa are shown in Table 1. The data indicate that:

- In ecological regions where the erosivity factor (R) exceeds 400 foot-ton/annum and for soil slope greater than 5%, an annual soil loss of 100 t/ha is not uncommon.
- An increase in R does not necessarily result in an increase in erosion, because of other intervening factors. Soil erodibility, landform (slope steepness and shape), and management systems are important factors affecting the magnitude of soil loss.

The magnitude of soil erosion in different ecological zones in Asia has also been investigated (Joshua 1977, Vasudevaiah et al 1965, Tiwari 1964, Rama Rao 1966, Singh et al 1967, Srivastava 1973, Leigh 1973, Bols 1978) and in Latin America (FAO 1954; Yamamoto and Anderson 1973; Ahmad and Brechner 1974; EMBRAPA 1975, 1978; Benatti et al 1977; Bertoni et al 1975; Amezquita and Forsythe 1975).

The soil and climatic parameters that affect erosion by water are shown in Table 2. If R exceeds 1,000 foot-ton/annum, erosion is serious only if natural vegetation is removed. These are the regions of potential erosion hazard. Erosion by water is a serious problem in the regions where R is between 400 and 800 foot-ton and the natural vegetation is savanna. Similar type of ratings can be made for wind erosion. Skidmore (1976) gives the basic information on different parameters for the ratings.

Soil erosion by water – commonly rill or sheet – is a serious problem on Alfisols in West Africa. These soils are characterized by unstable structure that forms a crust when exposed to raindrop impact. The effect of erosion on their productivity is seen in a short period (5 to 7 years) after forest removal because of the shallow depth of the surface horizon and unfavorable characteristics of the subsoil. The effect of cumulative soil erosion on crop yield on these soils is shown in Table 3. Maize yield declined exponentially with cumulative soil loss and could not be economically increased by fertilizer use.

SOIL AND CLIMATIC FACTORS THAT AFFECT EROSION

Rainfall erosivity

The force required for particle detachment is provided by rainfall and is a function of intensity, drop size, and wind accompanying a rainstorm. The kinetic energy of rain has been recognized as a major causative factor (Wischmeier et al 1958, Hudson 1976), although momentum may also be correlated with soil loss (Elwell and Stocking 1973, 1975). The high intensity of tropical rains is associated with large drop size. Medium drop size (D_{50}) exceeding 3 mm is not uncommon (Kowal and Kassam 1976, Aina et al 1977).

The direct measure of rainfall erosivity can be made by monitoring sand splash, and simultaneously measuring kinetic energy, momentum, and drop size

Table 1. Runoff and soil loss data from different agroecological zones in tropical Africa.

Country	Location	Mean annual rainfall (mm)	Approx. value of *R* (foot-ton per acre-inch)	Plot size	Slope (%)	Treatment	Runoff (%)	Soil loss (t/ha per annum)	Reference
Cameroun	Bafoussam	–	–	10 × 5 m^2	25.0	Bare soil	24.8	122.0	Rochette 1959
Cameroun	Dachang	1970	810	–	–	–	–	–	Saguy 1971
Dahomey	Agonkamey	1300	750	30 × 8 m^2	4.5	Bare soil	–	–	Alders 1975
Dahomey	Boukombe	875	550	42 m	3.7	Millet, conventional tillage	11.7	1.3	Verne and Williams 1965
Ghana	Kwadaso	1200	600	25 × 4 m^2	5	Bare soil	30–35	140–150	Mensah Bonsu and Obeng 1979
Ghana	Ejura	1200	600	25 × 4 m^2	3–5	Bare soil	20–30	20–40	Mensah Bonsu and Obeng 1979
Guinea	Central Guinea	1870	–	14 × 14 m^2	6.0	Bare soil	9.2	18.9	Dugain and Fauck 1959
Ivory Coast	Abidjan	2100	1000	–	4.0	Bare soil	15–30	18–30	Roose and Birot 1970, Roose 1973
Ivory Coast	Bouake	1200	600	–	7.0	Bare soil	38	108–170	Betrand 1967
Madagascar	Alatora	1200	–	–	6–8	Groundnut-cassava forage	6.9	15.6	Roche and Dubois 1959
Madagascar	Ankaratra	1700	–	–	12.0	Oats	38.1	32.9	Roche and Dubois 1959
Madagascar	Bofandriana	2000	1800	–	–	–	–	–	CTFT 1971
Madagascar	Nanisana	1260	–	15 × 5 m^2	13–14	Potatoes	13–14	14–15	Roche and Dubois 1959
Niger	Allokoto	452	280	70 m	3.0	Sorghum, cotton	16.3	8.6	Roose and Betrand 1971
Nigeria	Ibadan	1100	600	25 × 4 m^2	10.0	a. Bare soil b. Mulch 6 t/ha	37.0 2.8	142.0 0.2	Lal 1976

continued on opposite page

Table 1 continued

Country	Location	Mean annual rainfall (mm)	Approx. value of *R* (foot-ton per acre-inch)	Plot size	Slope (%)	Treatment	Runoff (%)	Soil loss (t/ha per annum)	Reference
Nigeria	Ife	1500	800	25 X 4 m^2	8.0	Bare soil	2.8	72.0	Wilkilson 1975
Nigeria	Samaru	1062	500	180	0.3	Bare soil	25.2	3.8	Kowal 1970
Rhodesia	Henderson Res.	–	–	27.5 X 1 m^2	4.5	a. Bare fallow b. Plot covered by gauge	–	0.94 126.6	Hudson and Jackson 1959
Senegal	Sefa	1300	650	40–50 m	1–2	Bare soil	39.5	21.0	Charreau and Nicou 1971
South Africa	Natal	436	–	36.6 X 11.0 m^2	11	Burning	6.65	15.7	Fournier 1967
South Africa	Natal	436	–	36.6 X 11.0 m^2	27	Burning	15.1	101.5	Fournier 1967
South Africa	Pretoria	600–800	–	30 X 2 m^2	4–7	Bare soil	12–36.5	112–173[a]	Manne 1959
Tanzania	Lyamungu	1660	–	30.5 X 4.54^2	17.3	Clean weeding	29	20.25	Mitchell 1965, Temple 1972, Rapp et al 1972
Tanzania	Mpwapwa	620	–	27.7 X 1.8 m^2	6.4	Bare soil	50.4	120–130	Staples 1934, Temple 1972
Tanzania	Tengeru	1300	–	–	32.9	a. Coffee – clean cultivation	5	30–35	Mitchell 1965, Temple 1972
Uganda	Namulonge	1410	–	3 m^2	1–2	Bare soil	30–40	–	Hutchinson et al 1958
Uganda	Namulonge	1410	–	3 m^2	1–2	Grass mulch	4.5	–	Hutchinson et al 1958
Uganda	Namulonge	1410	–	3 m^2	1–2	Bare soil	40.6	81.5	Sperow and Keefer 1975
Upper Volta	Niangoloko	1140	650	40–50 m	1–2	Millet, conventional tillage	7.5	6.4	Christoi 1966
Upper Volta	Ouagadougou	850	400	–	0–5	Bare soil	40–60	10–20	Roose and Birot 1970, Charreau and Seguy 1969, Charreau and Nicou 1971

[a]Soil loss relative to protected plots.

Table 2. Soil and climatic parameters that affect erosion by water.

Erosion category	Depth (cm)	Organic carbon (%)	Erodibility (*K*)	Slope (%)	Erosivity (*R*) (foot-ton/acre per annum)
Very serious	<10	0.5–1.0	0.6	>10	>1000
Serious	10–20	1.0–1.25	0.2–0.6	5–10	600–1000
Moderate	20–50	1.25–2.0	0.05–0.2	2–5	400–600
None to slight	>50	>2.0	<0.05	<1	<400

of the storm. Indirectly, different empirical formulas (Table 4) have estimated erosivity. The widely used index of Wischmeier et al (1958) needs to be evaluated prior to its use in the tropics.

Soil erodibility

Permeability, texture, structure, and organic matter content affect soil erodibility by water. In the Universal Soil Loss Equation, erodibility is defined as the annual soil loss from a *unit plot* per unit of erosivity factor *R*. Erodibility is therefore a soil property that should be determined in natural field environments. Indirectly, erodibility has been related to various parameters that can be determined in the laboratory (Table 5). These indirect estimates may not, however, be good indicators of soils' field behavior. Wischmeier et al (1971) have prepared a nomograph to estimate erodibility from soil properties such as texture, structure, organic matter content, and permeability. The application of this nomograph should be verified for a range of soils before it is used in the tropics.

Landform also affects soil erosion. Whether the slope is regular, concave, convex, or complex has an important effect on the magnitude of soil erosion.

Wischmeier et al (1958) have combined into an empirical equation most parameters affecting water erosion. The equation, used for predictive purposes, is referred to as the *Universal soil loss equation.*

Table 3. Coefficient of linear correlation and regression equations of maize grain yield (t/ha) with cumulative soil erosion (t/ha) and other soil properties.

Independent variable	Correlation coefficient[a]	Regression equation
Soil loss	−0.87**	$Y = 5.95 - 0.009x$
Moisture retention (%) at zero suction	0.61**	$Y = -4.18 + 0.227x$
Moisture retention at 0.1 bar suction	0.61**	$Y = -2.48 + 0.309x$
Soil pH (1:1)	0.56**	$Y = -6.23 + 2.034x$
Organic carbon (%)	0.75**	$Y = 0.28 + 2.875x$
Soil nitrogen (%)	0.67**	$Y = 1.11 + 25.20x$
Extractable potassium (meq/100 g)	0.55**	$Y = 2.06 + 4.929x$
Extractable sodium (meq/100 g)	0.55**	$Y = 0.046 + 74.6x$

[a]**Significant at the 1% level.

Table 4. Empirical formulas for estimating erosivity by rainfall.

Formula	Description	Reference
EI_{30}	E = kinetic energy of rain I_{30} = max 30-min intensity	Wischmeier et al (1958)
$KE > 1$	Kinetic energy of rains with intensity exceeding 25 mm/h	Hudson (1965)
$C = p^2/p$	C = climatic coefficient P = mean monthly rainfall during wettest month of the year, and P = annual rainfall	Fournier (1956)
$\Sigma_1^2\ p^2/p$	Modified Fournier's index	FAO (1977)
AI_m	A = amount of rainfall per storm (cm) I_m = max intensity over 7.5-min time interval	Lal (1976)

$$A = RK(LS)CP \tag{1}$$

where A is annual soil loss (t/acre), R is climatic erosivity (foot-ton), K is soil erodibility, LS is length and steepness of slope, and C and P are management factors. Although this empirical relation is widely used, the determination of individual parameters must be experimentally determined for different ecological regions of the tropics.

Wind erosion

The aggressivity of wind (C) is estimated by an empirical relation that involves wind velocity and precipitation effectiveness.

$$C = V^3/2.9\,(PE)^2 \tag{2}$$

where V = wind speed and PE = precipitation effectiveness of Thornthwaite. Recently, FAO (1977) has used a modified index of wind aggressivity.

Table 5. Indirect measures of soil erodibility (detachability).

Index	Reference
Instability index	De Leenheer and De Boodt (1959)
Structural stability	Henin et al (1953)
Wet sieving	Yoder (1936)
Raindrop technique	Bruce-Okine and Lal (1975)
Dispersion ratio	Middleton (1930)
Heat of wetting	Collis-George and Lal (1971)
Clay ratio	Bouyoucos (1935)
Colloid content per moisture equivalent	Middleton (1930)
Erosion ratio	Middleton (1930)

$$C = \frac{1}{100} \sum_{1}^{12} V^3 \times \frac{PET\text{-}P}{PET} \times n \qquad (3)$$

where V = mean monthly wind speed at 2 m height in m/s,
P = precipitation in mm,
PET = potential evapotranspiration in mm, and
$\frac{PET - P}{PET} \times n$ refers to number of erosive days in a month.

A general functional relationship between different parameters that affect wind erosion has been developed into *the wind erosion equation* (Chepil and Woodruff 1963, Woodruff and Siddoway 1965, Skidmore and Woodruff 1968, Lyles et al 1969, Skidmore et al 1970, Skidmore 1976).

$$E = f(I, K, C, L, V) \qquad (4)$$

where I is a soil erodibility index, K is a soil-ridge roughness factor, C is a climatic factor, L is field length along the prevailing wind erosion direction, and V is equivalent quantity of vegetative cover.

Although wind erosion is a serious problem in many semiarid regions of the tropics, the equation has not yet been widely used. Research emphasis on wind erosion in the tropics has been considerably less than that on water erosion.

EROSION CONTROL

The basic principle of control for wind and water erosion is a continuous vegetative cover. Detailed methods of wind erosion control are discussed by Woodruff and Lyles (1977) and Chepil and Woodruff (1963). Erosion by water is discussed here.

Research results obtained from a range of soils and climatic environments have indicated that the best method of erosion control is *good soil and crop management.* Preference is given to soil and crop management techniques that minimize water runoff through improvement in soil structure and water infiltration. Some engineering practices, based on safe disposal of runoff, involve heavy initial capital investment that is beyond the means of small farmers. Moreover, the structures may fail if they are not properly constructed and regularly maintained, and thus increase the erosion hazard (Fig. 2, 3).

Cropping sequences

Cropping sequences that provide early and continuous ground cover permit less erosion than those with less or delayed cover. Research at IITA (Lal 1976) indicated that cowpea, a quick-growing crop with a good canopy cover, permits less soil erosion than maize, an open-row crop. Maize following cowpea permitted more erosion than maize following maize. Cultural practices (e.g. balanced fertilizer, insect and pest control, optimum plant population, early planting, etc.) that favor good crop growth also minimize losses due to runoff and erosion.

2. Soil erosion on contour ridges that are unstable under high intensity rains.

Similar results were reported from Rhodesia by Hudson (1965) and from India by Vasudevaiah et al (1965).

Crop combinations

Mixed and relay cropping, widely practiced in the tropics, provide a continuous ground cover. A crop combination with multistory canopy structure should be effective against erosion control. Data in Table 6 indicate that a maize-cassava cropping pattern had significantly less soil and water loss than monoculture cassava. In other trials 50% ground cover was attained in 50 days by mixed cropping and in 63 days by monoculture cassava. However, 50% ground cover was attained in 38 days for soybean and 45 days for pigeonpea.

Traditionally, farmers in West Africa may have as many as 10 crops planted simultaneously in the same plot. With a continuous ground cover provided by crops and weeds, erosion problems are usually minimal. Mixed cropping, however, cannot be followed on large-scale mechanized commercial farms because seeding and harvesting operations are difficult to perform. Moreover, the *land equivalent ratio* with mixed cropping is about one when inputs of farm chemicals are made in monoculture as recommended.

Residue mulch

Crop residue mulch is one of the most effective measures against soil erosion. Mulch prevents the direct impact of raindrop on soil aggregates, maintains pore space continuity and high infiltration rate, and enhances crop growth to provide

3. Conventionally tilled maize grown on land without a graded channel terrace can make soil highly susceptible to erosion.

Table 6. Soil and water losses in cassava monoculture and mixed cropping of cassava with maize.[a]

Slope (%)	Soil loss (t/ha)		Runoff (% of rainfall)	
	Cassava	Cassava + maize	Cassava	Cassava + maize
1	3	3	18	14
5	87	50	43	33
10	125	86	20	18
15	221	137	30	19
Mean	109	69	28	21

[a]Source: Aina et al 1977.

an early ground cover through improvements in soil temperature and moisture regimes and other physicochemical properties. The effects of different mulch rates on runoff and soil loss from a newly cleared land with 10% slope measured on 10-m^2 plots are shown in Table 7. Runoff and soil loss decreased exponentially with an increase in mulch rate. Rate of crop residue mulch application had a significant positive correlation with total porosity, macroporosity, infiltration rate, saturated hydraulic conductivity, and with earthworm activity. On the other hand, the correlation was significantly negative with bulk density, penetrometer resistance, and structural instability index.

Table 7. Effect of mulch rate on soil and water loss on 10% slope of an Ibadan soil series (Oxic Paleustalf) monitored on 10-m^2 runoff plots.[a] Total rainfall = 430 mm.

Mulch[b] rate (t/ha)	Runoff (% of rainfall)	Soil loss (t/ha)
0	17.4	9.6
2	10.0	2.3
4	3.5	0.5
6	1.2	0.1
12	0	0

[a]Unpublished data of Lal, De Vleeschauwer, and Malafa. [b]Rice crop residues.

No-tillage farming

Although residue mulch is an effective tool, in practice it can be achieved for annual crops only with reduced tillage methods. Weeds are controlled by appropriate herbicides and soil disturbance is minimal. Excessive tillage destroys soil structure in the long run. Moreover, a thin impermeable soil layer formed just beneath the plow layer decreases the infiltration capacity, which in turn increases water runoff. Crust formation is also an important factor in decrease of infiltration rate of a plowed bare soil surface. Table 8 shows regression equations of soil loss and water runoff with slope for different systems of soil management. The coefficients of exponential equations for runoff and soil loss decreased several hundredfold for no-tillage and mulch treatments compared with those for bare soil surface.

For the no-tillage system to be effective for crop production, considerable information is needed for different soils, crops, and ecological regions. Special requirements of the no-tillage system are economical methods of weed control, suitable planting equipment, balanced fertilizer application, suitable crop combinations and cropping sequences, and an adequate amount of crop residue for mulch.

Cover crops

Cover crops have an important role in erosion control for plantation crops and for annual crops. A suitable cover crop used in a crop rotation helps improve soil physical and chemical properties. Infiltration rate of a structurally degraded soil can be rapidly improved with 1 or 2 years of a deep-rooted cover crop such as pigeonpea (*Cajanus cajan*), stylo (*Stylosanthes guianensis*), velvet beans (*Psophocarpus palustris*), etc. (Lal et al 1978, 1979). Through improvements in soil physical properties and prevention of raindrop impact, cover crops prevent runoff and erosion during their growth cycle and for food crops grown on the same land in rotation.

Land development and soil management on watershed basis

The conclusions drawn from a critical appraisal of erosion on the large-scale mechanized crop production schemes in Africa and elsewhere in the tropics are

Table 8. Slope-soil loss and slope-runoff relationships for different systems of soil management, 1973 data.[a]

Treatment	r	Regression equation[b]
	Soil loss	
Bare fallow	0.86**	$E = 9.57\,S^{1.21}$
Maize-maize (conventional tillage)	0.52*	$E = 0.59\,S^{1.13}$
Maize-maize (no-tillage)	0.17	$E = 0.04\,S^{0.16}$
Maize-maize (mulch)	0.47	$E = 0.02\,S^{0.66}$
	Runoff	
Bare fallow	−0.03	$R = 46.4\,S^{-0.02}$
Maize-maize (conventional tillage)	0.39	$R = 4.86\,S^{0.38}$
Maize-maize (no-tillage)	0.53*	$R = 1.23\,S^{0.24}$
Maize-maize (mulch)	0.92**	$R = 0.0008\,S^{3.35}$

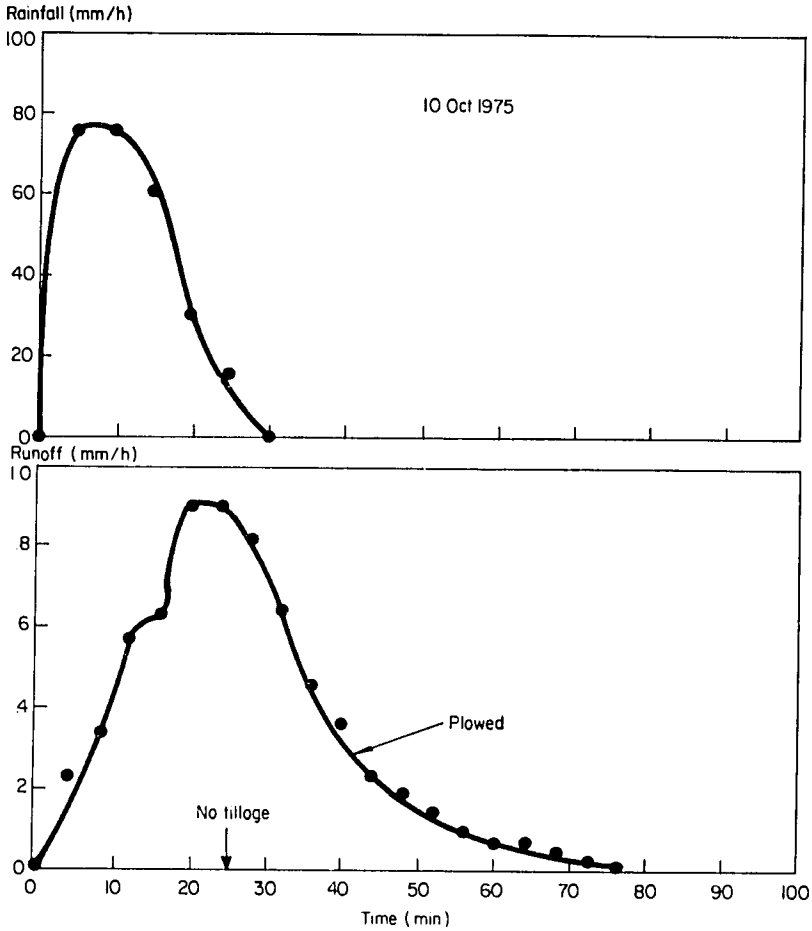
[a]Source: Lal 1976. [b]S = slope (%), E = soil loss (t/ha per mm rain), R = water runoff (% of rainfall).

not encouraging (Wood 1950, Wild 1967, Baldwin 1957). The failure of the schemes has not, however, deterred similar ventures. Planning and execution of such schemes, without accompanying planning and development on a watershed basis, have led to widespread barren and unproductive lands where lush green forest once prevailed (Greenland and Lal 1977).

But food production must substantially and immediately be increased. It is estimated, that to meet the demands for food production in the tropics, the rate of arable land development may have to be as much as 6–10 million ha/year (Boerma 1975). For adequate soil and water conservation and management, such land development must be planned on a watershed basis. Some steep slopes should not be cleared of natural cover, but should be left in suitable tree crops. Valley bottom soil should be developed primarily for rice cultivation, and middle slopes should be used for dryland crops grown with a no-tillage system. Runoff and erosion from a terraced watershed planted to maize with a conventional tillage system are compared with that from an unterraced no-tillage watershed in Figure 4. There was no runoff from the no-tillage watershed.

RESEARCH NEEDS

Before planning elaborate research, it is essential to obtain an estimate of the extent and severity of the problem. This information is not available in many countries of the tropics. FAO (1977) has attempted to prepare a soil degradation map of the present and potential erosion hazard for Africa north of the equator and for the Middle East. Once the extent or severity of the damage has been estimated, it is important to know the present rate of degradation wherever arable farming has intensified. In this connection, a survey of soil, vegetation, and climate is necessary prior to undertaking large-scale land development schemes for arable farming.



4. Runoff-rainfall relationship from 5 ha no-tillage and conventionally plowed watersheds under maize (unpubl. data of R. Lal).

Gaps in our knowledge to successfully address the problem of soil erosion in the tropics are in basic and applied research. Most of the basic research information currently used in the tropics is that developed in temperate regions. Because the soil and climate of the tropics are drastically different, it will be a mere coincidence if empirical relations developed in one climatic region can be directly transferred to the other. There are specific research needs for soil erosion and its control.

Wind erosion

There is little research information on basic and applied aspects of wind erosion in the tropics. Whereas wind erosion is a serious problem in semiarid and arid regions of Africa, and in parts of West and South Asia and South America, little or no research is being conducted on basic aspects of wind erosion. Some work

has been done on shelter belts and afforestation for control of wind erosion.

There is a need to evaluate the applicability of the wind erosion equation in tropical regions. Different parameters of the equation need to be determined for a range of soils and crops. The use of reduced tillage systems with crop residue mulch should also be evaluated.

Water erosion

Compared with wind erosion, substantial research information is available on both basic and applied aspects of water erosion and its control in the tropics. However, there are vital gaps in knowledge of its basic aspects. The following should be given research priority:

- *Erosivity.* Studies on rainfall parameters affecting erosivity are needed. Important parameters are drop size distribution, kinetic energy, and momentum of tropical storms. Energy load of a rainstorm should also be evaluated in relation to wind velocity. The rainfall information should be related to splash characteristics with Ellison's splash cup technique. The information can best be obtained through a worldwide network of stations that would follow a common program and use standard equipment to monitor erosivity.

The equipment available to monitor drop size and energy load of rainstorm is expensive. Relatively inexpensive and simple-to-use equipment must be developed. Such equipment could be based either on the acoustic principles or on the use of pressure transducers. Equipment based on these principles has been locally used for isolated experiments.

- *Erodibility.* Basic aspects of erodibility of soils in the tropics are not understood, certainly not as much as are those of erosivity. It is necessary to understand various aspects of erodibility in relation to detachability (resistivity) and transportability. Which soil parameters (structure, permeability, organic matter content, texture, clay mineralogy, and the amount of iron and aluminum oxides) are directly related to erodibility? Can any one parameter or a combination of several parameters be used to estimate erodibility? Can erodibility be estimated from soil physical parameters that can be routinely determined in the laboratory?

In addition, direct measurements of erodibility (using unit plot as described in the Universal Soil Loss Equation) of major soil groups should be undertaken as a coordinated research with similar field plot design and specific observations.

- *Slope characteristics.* Even though the effects of slope length and degree of slope are well recognized, the effects of irregular slopes (convex, concave, complex) on erosion are not well understood and are difficult to quantify. Although difficult to establish, field-scale experiments on natural slopes are required to quantify such effects.

- *Soil management.* Appropriate soil management techniques are more adaptable for soil and water conservation than engineering techniques that are expensive to install and difficult to maintain. In this connection, the use of no-tillage or reduced tillage system with crop residue mulch has a potential for wider application on a range of soils and crops in the tropics. Adaptive and

applied research is needed for using this technique for soil and water conservation. No-tillage systems can be adopted for diverse soils and crops, provided relevant information is available on adequate weed control, fertilizer application, crop rotations, and other agronomic practices that make the system work.

- *Land development.* Bringing new land into cultivation still constitutes the most widely practiced method of increasing productivity in many developing countries of the tropics. Vast areas of forested land will be cleared in the near future in the tropics of West Africa and South and Central America. Information is needed on methods of forest clearing and land development that cause a minimum of soil degradation. Due to a shortage of manual labor, the use of heavy machinery may be inevitable. However, research is needed to develop agronomic and soil management techniques that minimize the degradative effects of these machines on fragile soils of the tropics.
- *Watershed management.* Information on the effect of integrated watershed management and development on soil erosion and productivity is scarce. In this connection, the role of tree crops for appropriate soil and slope characteristics cannot be minimized. Runoff and erosion measurements should be made on a watershed basis.
- *Gully control.* Gullying is a serious erosion hazard in many regions of the tropics. Research on simple, inexpensive, and effective gully control measures is needed. Practical research work on reclamation of land that has been degraded by severe gully erosion should also be undertaken.

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Constraints to soil fertility evaluation and extrapolation of research results

S. W. BUOL AND J. J. NICHOLAIDES III

Technical soil classification systems are necessary to interpret the data included in natural classification systems for extrapolating soil fertility research results to users. Each group of potential users – research workers, land-use policy planners, extension workers, and farmers – has different requirements for soil fertility extrapolation. Experience with one such technical system, the FCC (Fertility Capability Classification), which was designed to enhance communication among research workers, is discussed. The development of additional technical groupings designed to address the needs of specific user groups is suggested.

CONSTRAINTS TO SOIL FERTILITY EVALUATION AND EXTRAPOLATION OF RESEARCH RESULTS

> "One can transfer the results of research and experience on named kinds of soil between countries and continents in order to estimate potentials for use. But farming systems are developed and used by people, and what they can and should do also depends on their social habits and goals." (Kellogg 1975)

Soil fertility is a term so frequently used in written and verbal communication that its meaning has taken on numerous connotations. Frequently, a *fertile soil* connotes no need for fertilizer additions. In this sense the term is always vague until some limit is placed on the level of expected production. Soil that has sufficient fertility to produce maize yields of 2 t/ha is infertile when yields of 10 t/ha are anticipated. There are also expressions of infertility related to soil

Professor and Assistant Professor, Soil Science Department, North Carolina State University, Raleigh, N.C. 27650. This work was supported in part by Contract #AID/ta-C-1236 of the U.S. Agency for International Development.

water conditions, toxic salt concentration, a root-restricting hardpan, nematodes, or low soil temperatures.

In its broadest sense soil fertility connotes the ability of soil to grow plants beneficial to man. Soil fertility does not connote, in specific terms, what is right or wrong with a soil. It should be stressed that soil fertility is only one of the many factors that influence plant growth. Fitts (1959) stated that crop yields are a function of at least four major factors – crop, soil, climate, management – and each factor has numerous variables that must be considered. Improvements in one factor or one variable can, but will not necessarily, result in realization of potential yield.

Evaluation of a soil's fertility should address, in specific terms, the variables that will affect the uses of that soil for growing plants beneficial to man. Evaluation should specify what steps must be taken to make the constraining variables nonlimiting to plant growth.

Extrapolation is a term that also has different connotations. To us, extrapolation as related to soil fertility connotes a projection of successful soil and crop management technology in one area into similar soil-crop-climatic areas where less research has been performed. Such extrapolation assumes similarity of the soil-crop-climatic conditions under similar social and economic constraints and can only be done when sufficient data exist, or are developed, to corroborate the similarities. Successful extrapolation of soil and crop management practices can shorten the time lag between development and transfer of agronomic technologies to the farmer.

USER GROUPS OF SOIL FERTILITY EVALUATION AND EXTRAPOLATION

To some extent, knowing the audience simplifies the identification of the soil fertility parameters. There are four principal audiences for soil fertility evaluation and its extrapolation:

- *Research workers.* Research workers are listed first because all other user groups rely on the information developed by researchers. Research workers need a systematic, technical grouping of surface soil properties that is used to define the limits of the uncontrolled variables within which field fertility research can be extrapolated. Lack of such data is the most critical constraint to soil fertility evaluation and its extrapolation today.

The controlled factors in the research must be identified specifically, and quantitative limits must be placed on the interacting uncontrolled variables that influence plant response. To interpret the benefits of liming a soil, for example, a researcher must know if the soil had an initial aluminum saturation of 80 or 20% and whether an acid-tolerant cultivar was used. He must also be aware of a multitude of other interacting parameters to properly assess the limits within which the results are valid.

- *Land-use policy makers.* Perhaps more than the researchers, the land-use policy makers have a desperate need to understand the limited range of uncon-

trolled variables in each individual experiment. Whereas the limits of the uncontrolled variables in an experiment are often rather easy to define for researchers, they must be explained to nonscientists in less sophisticated terms. In the absence of information relating the results in terms of soil properties, research is frequently interpreted in terms of political boundaries. Thus, the failure in province B of an experiment that was successful in province A is interpreted as the failure of the scientist, the social system, or the administrator, when in reality the results were obtained on sandy textured soils (Quartzipsamments) in province A and on clayey textured soils (Chromuderts) in province B.

Land-use policy makers need a methodology for evaluating land-use potential, especially as related to economic impact. With such a methodology the long-term effects of soil fertility innovations can be evaluated in terms of probability, and adequate infrastructure can be planned. Certainly there are successful models for land evaluation (Beek 1978); however, communication of the methodologies must be improved.

• *Extension workers.* Because of the enormity of communicating information from soil fertility evaluation and extrapolation to the farmer, intermediate technicians or extension workers are employed. Communication with such individuals becomes the first step in communication with the farmer.

Extension workers need technical guides for specific farming systems. The guides should list specific requirements for each cropping system. Development of the technical guides, however, must follow the alleviation of the primary constraint — the need of research workers to define boundary conditions of uncontrolled variables within which field research can be extrapolated.

• *Farmers.* The ultimate user of information from soil fertility evaluation and extrapolation is the farmer. The overall purpose of any worthwhile soil fertility evaluation and extrapolation program is "to obtain information which can be transmitted to farmers and guide them in the proper use of fertilizers, lime, and other soil amendments" (Fitts and Nelson 1955).

A multitude of categories could be devised to classify farmers or, more precisely, farming systems (Evenson et al 1973, Ruthenberg 1971). At least two broad categories of farmers must be considered when planning the extrapolation of soil fertility research.

One is the commercial farmer who is interested in maximizing his profits by increasing the margin on each unit of input. The native chemical fertility of the soil is [illegible]mportant to him if he can make a satisfactory profit on each unit of fertil[illegible] [illegible]plies. The inherent lack or excess of water is not of concern if he can profitably irrigate or drain. Thus, his real interest is a monetary evaluation of each management practice.

The second group includes farmers with few resources other than their own labor. They are mainly concerned with reducing their risks. The native soil fertility, in the broadest sense of the word, has to be considered, not only for its quantitative value, but also for its reliability. Incremental increases of production

from inputs of fertilizer, water, and varieties are relevant only if they do not increase the farmer's risk.

Both categories of farmers, however, are interested in increasing the probability of obtaining a response to any soil amendment they may use. Thus, the value of the technical guides developed for extension workers is apparent, although the subsequent use of such guides could be different for the two groups.

PRIMARY CONSTRAINT TO SOIL FERTILITY EVALUATION AND EXTRAPOLATION

The primary constraint to soil fertility evaluation and extrapolation is lack of a systematic technical grouping of surface soil properties by which research workers can define the limits of the uncontrolled variables within which field fertility research can be extrapolated. The alleviation of the constraints listed for land-use planners, extension workers, and farmers is contingent on the alleviation of this primary constraint. Hence, this paper deals with it and a potential means for its alleviation.

It is important to note a factor that contributes to the issue raised. Because of limited knowledge or traditional thinking, laymen – and many soil scientists – often do not distinguish between soil classification and soil mapping. Soil classification records quasi-permanent soil pedon features, while soil mapping delineates the geographical distribution of natural landscapes at reduced scales and uses the classification name(s) to help identify the soil(s) within each mapping delineation. However, almost no mapping unit is composed of a single kind of soil and not one has the entire range of soil properties defined in a taxonomic class of soil. Consequently, we are "compelled to acknowledge that soil taxa and mapping units identified by the same name are two distinctly different things" (Cline 1977). With such acknowledgment, it is obvious that "mapping is not necessary for transfer of information, although classification is" (Moore 1978).

Additionally, extrapolation via a combination of soil classification and soil mapping is further complicated by the fact that:

1) the results to be extrapolated are developed within a narrower range of boundary conditions than is present in mapping or taxonomic units;

2) because of the scale reduction, the mapping unit usually includes soil conditions that are not identified; and

3) extremely broad ranges of soil properties are included intentionally in the upper horizon of named kinds of soil, even though these surface horizons often are the most significant for crop production.

Cause

The underlying cause of the existence of the primary constraint is the fact that, for all practical purposes, soil classification and soil fertility management are most often at cross purposes. Because the basic goal of soil classification is to

record soil features that are at least quasi-permanent and not subject to management alteration, soil properties in the surface horizons are usually considered only at the lowest categories of most soil classification systems. Surface soil chemistry, of the type directly related to fertilizer manipulation, is not usually included in soil classification criteria to avoid the confusion that may result from the transient nature of the values encountered when soils are subjected to management. Thus, soil properties considered for taxonomic purposes (Dudal 1973, USDA 1975) are not necessarily relevant for soil fertility management purposes. Nor should they necessarily be.

Conversely, approaches utilized for soil fertility evaluation and improvement purposes (Cate and Nelson 1971, Waugh et al 1973, Fitts 1974, Colwell 1974, Pesek 1974), although valuable, have not always related the numerous analytical data to kinds of soils via any classification system. Several such approaches have implied wide applicability over many soils although the soil classification information usually is not given (e.g. Cate and Nelson 1971).

Effect

The upper 20 cm of soil is not only the place where most management practices for cultivated crops take place but also the layer that reflects the effects of these management practices. For those reasons soil taxonomic systems often do not use surface soil criteria. Soil fertility evaluations likewise do not utilize the classification systems because they do not reflect soil management practices. Thus, neither group provides a strong basis for consequent extrapolation of soil fertility evaluation and improvement.

It should be reemphasized that subsoil properties do not have as great an effect on crop yields as do the surface soil properties. For example, Sopher and McCracken (1973) found in a survey of 441 field trials in North Carolina that properties of topsoils, individually (Table 1, 2) or collectively, better explained crop yield variability than did those same properties of subsoils.

Alleviating the primary constraint

Cline (1949) stated 30 years ago that some problems related to soil fertility evaluation and extrapolation could be overcome by technical groupings or classifications for specific, applied, practical purposes. We now examine one such

Table 1. Yield relationship to pH in 441 soil profiles.[a]

Horizon	Udults			Aquults		
	Mean pH	pH range	r	Mean pH	pH range	r
Ap	5.6	4.8–6.5	0.41	5.7	5.0–6.5	0.35
2d	5.1	4.4–6.3	0.20	5.1	4.5–6.8	0.20
3d	4.9	4.2–6.6	0.24	4.8	4.4–6.8	ns
4th	4.9	4.1–6.5	0.17	4.8	4.4–6.9	ns

[a]Source: Sopher and McCracken 1973.

Table 2. Yield relationship to base saturation (BS) in 441 soil profiles.[a]

Horizon	Udults			Aquults		
	BS (%)		r	BS (%)		r
	Mean	Range		Mean	Range	
Ap	78	10–100	0.38	91	44–100	0.41
2d	45	5–100	0.33	49	13–98	0.38
3d	39	4–100	0.27	36	7–93	0.28
4th	33	4–98	0.20	38	9–98	0.26

[a]Source: Sopher and McCracken 1973.

technical classification specifically related to soil fertility evaluation and extrapolation, namely the Fertility Capability Classification (Buol et al 1975). Technical classification systems do not replace soil taxonomic information and soil surveys, but rather build on them to become useful in practical agricultural development initiatives (Johnson, this volume).

The Fertility Capability Classification

The Soil Fertility Capability Classification (FCC) system was designed to group soils having similar limitations of fertility management (Buol 1972). It provides a guide for the extrapolation of the fertilizer response experience (Buol and Couto [1980]). The FCC focuses attention on surface soil properties most directly related to management of field crops and is best used as an interpretative classification in conjunction with a more inclusive natural soil classification (Appendix A). Appendix B and C outline the proposed technical classification system and suggest some interpretations that can be made of the parameters in the system.

A worldwide survey using published descriptions and analytical data of 244 soil profiles representing a broad geographical and morphological range resulted in a grouping of the soils into 117 fertility capability classes (Buol et al 1975). Types L, C, LC, and S represented 92% of the population, while 10 condition modifiers accounted for 51% of the population. Five modifiers (v, n, s, x, i) never occurred alone, reflecting the fact that several fertility-related parameters occur together in many soils. Soil profiles of 678 Brazilian soils were grouped into 84 fertility capability classes (Buol et al 1975).

When the FCC was used to group soils from potato fertilization trials (McCollum and Valverde 1968) in Peru, the soils of the 73 sites were grouped into 5 classes (Buol et al 1975). Gross returns to fertilizer applications were evaluated after the soils were grouped by FCC and by soil test results (Table 3). Gross returns were higher when recommendations were based on a combination of the FCC and surface soil test results. This strongly emphasizes that there is no substitute for on-site reporting of the soil properties, including both soil characteristics and soil test determinations, to arrive at the most accurate fertilizer recommendations.

Table 3. Comparisons of gross returns to fertilizer applications by various methods.[a]

Fertilizer recommendation	Gross returns (US$/ha) to fertilizers
Single blanket fertilizer recommendation based on average fertilizer needs	770
Fertilizer recommendations based on P, K, and pH surface soil tests	860
Fertilizer recommendations based on estimates of optimum fertilizer rates from average group response curves by FCC	920
Fertilizer recommendations based on combination of estimates of optimum fertilizer rates from average group response curves by FCC and P, K, and pH surface soil tests	965

[a]Source: Buol et al 1975.

A combination of the FCC, using data from soil survey reports and standard soil test results following on-site sampling, allowed Nicholaides et al (1978) to extrapolate proper fertilization practices for peanut and soybean from a Haplustox with a clayey textured surface soil (Brazil) and a Paleudult with a loamy surface soil (Peru) to a Paleustult with a loamy textured surface soil (Bolivia).

The FCC, or some modification thereof, can serve as the basis for grouping soils for specific soil management evaluations and land-use planning such as CIAT's computerized land resource study of tropical America, which also utilizes climatic data and satellite and side-looking radar imagery (Cochrane et al 1979).

The essential prerequisite to any technical classification is a quantitative definition of the variables critical to the specific or applied objective. As it is, the FCC addresses fertilizer-plant-soil interactions only from the standpoint of an *average* plant. Species or cultivars with distinctly different requirements, such as flooded rice, or tea, may require specific technical groupings that utilize soil parameters most critical to the need of that cropping system.

Every classification system reflects the *state of the art* in that particular field. Classifying soils with respect to their natural occurrence and total soil properties is different from classifying soils with regard to their response to technological fertility practices. Also, within the soil fertility field it is probably safe to say that soil science knows more about the fertility of certain crops and management systems than about some other crops and management systems. A technical classification system that reflects the known interactions of soil fertility in each cropping system can greatly facilitate extrapolation. Technical groupings to reflect the probability of risk for certain soil uses (Cochrane et al 1979) are a logical extension of this concept and of potential use to farmers with limited resources.

CONCLUSIONS

Technical classification systems, built upon quantitative natural soil classification systems, are suggested as the most immediate, obtainable tools in the extra-

polation of soil-related research results. Each technical classification system has to be organized using quantitative criteria of practical significance to the applied technology. No single technical classification will equally serve all soil fertility practices. Where specific requirements can be defined quantitatively within any physical, social, or economic framework, a technical grouping would be helpful for the extrapolation of soil-related research results.

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APPENDIX A
The Soil Fertility Capability Classification System
(after Buol and Couto [1980])

The proposed system consists of three levels:

Soil type is texture of surface soil (20 cm).

Substrata type is texture of subsoil if within 50 cm of surface.

Condition modifiers are specific properties noted if a specific range of conditions is encountered.

Thus, every soil is named at the highest category by the surface texture present and further properties are noted as needed in a systematic fashion. Sample interpretative statements for specific soils are given in part C of Appendix C.

APPENDIX B. Description of type, subtype and modifier classes

Type:

Texture of plow layer or surface 20 cm (8"), whichever is shallower.

S = sandy topsoils: loamy sands and sands (by USDA definition).
L = loamy topsoils: <35% clay but not loamy sand or sand.
C = clayey topsoils: >35% clay.
O = organic soils: >30% O.M. to a depth of 50 cm (20") or more.

Substrata type: (texture of subsoil)

Used only if there is a textural change from the surface or if a hard root restricting layer is encountered within 50 cm (20").

S = sandy subsoil: texture as in type.
L = loamy subsoil: texture as in type.
C = clayey subsoil: texture as in type.
R = rock or other hard root restricting layer.

Condition modifiers:

Where more than one criterion is listed for each modifier, only one needs to be met to place the soil. The first criterion given is preferred, but additional criteria are selected to facilitate semiquantitative use in the absence of desired data.

g = (gley):
Soil or mottles ≤2 chroma within 60 cm (24") of surface and below all A horizons, or
saturated with H_2O for >60 days in most years.

d = (dry):
Ustic or xeric environment (dry >90 cumulative days/year within 20–60 cm depth).

e = (low CEC):
(applies only to plow layer or surface 20 cm, whichever is shallower).

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APPENDIX B continued

<4 meq/100 g soil by Σ bases + KCl extractable Al, or
<7 meq/100 g soil by Σ cations at pH 7, or
<10 meq/100 g soil by Σ cations + Al + H at pH 8.2.

a = (Al toxic):
>60% Al saturation of CEC by Σ bases + KCl extractable Al within 50 cm (20"), or
>67% EA (exch. acidity) saturation of CEC by Σ cations at pH 7 within 50 cm (20"), or
>86% EA saturation of CEC by Σ cations at pH 8.2 within 50 cm (20"), or pH <5.0 in 1:1 H_2O except in organic soils.

h = (acid):
10–60% Al saturation of CEC by Σ bases + KCl extractable Al within 50 cm (20"), or
pH in 1:1 H_2O between 5.0 and 6.0.

i = (Fe-P fixation): (used only in clay (C) types)
% Free Fe_2O_3/% clay >0.15, or
hues of 7.5 YR or redder and granular structure.

x = (X-ray amorphous): (applies only to plow layer or surface 20 cm (8"), whichever is shallower).
pH > 10 in 1N NaF, or
positive to field NaF test, or
other indirect evidence of allophane dominance in clay fraction.

v = (Vertisols):
Very sticky plastic clay: >35% clay and >50% of 2:1 expanding clays; COLE >0.09. Severe topsoil shrinking and swelling.

k = (K deficient):
<10% weatherable minerals in silt and sand fraction within 50 cm of soil surface, or
exchangeable K <0.20 meq/100, or
K <2% of Σ bases, if Σ bases <10 meq/100 g.

b = (basic reaction):
Free $CaCO_3$ within 50 cm of soil surface (fizzing with HCl), or pH >7.3.

s = (salinity):
≥4 mmho/cm of saturated extract at 25°C within 1 m depth.

n = (natric):
>15% Na saturation of CEC within 50 cm.

c = (cat clay):
pH in 1:1 H_2O is <3.5 after drying and jarosite mottles, with hues of 2.5 Y or yellower and chromas 6 or more are present within 60 cm.

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APPENDIX C. Sample management interpretations of FCC nomenclature.

(A) *Interpretation of FCC types and substrata types:*

L : Good water-holding capacity, medium infiltration capacity.

S : High rate of infiltration, low water-holding capacity.

C : Low infiltration rates, potential high runoff if sloping, difficult to till except when *i* modifier is present.

O : Artificial drainage is needed and subsidence will take place. Possible micronutrient deficiency, high herbicide rates usually required.

SC, LC, LR, SR : Susceptible to severe soil deterioration from erosion exposing undesirable subsoil. High priority should be given to erosion control.

(B) *Interpretation of FCC condition modifiers:*

When only one condition modifier is included in the FCC class nomenclature, the following limitations or management requirements apply to the soil. Interpretations may be slightly modified when two or more modifiers are present simultaneously or when textural classes are different.

Modifier	*Main limitations and management requirements*
g	Denitrification frequently occurs in anaerobic subsoil and tillage operations and certain crops may be adversely affected by excess rain unless drainage is improved by tiles or other drainage procedures.
d	Soil moisture is limited during the growing season unless irrigated. Planting date should take into account the flush of N at onset of rain.
e	Low ability to retain nutrients – mainly Ca, K, Mg – for plants. Heavy applications of these nutrients should be split. Potential danger of overliming.
a	Plants sensitive to aluminum toxicity will be affected unless lime is deeply incorporated. Extraction of soil water below depth of lime incorporation will be restricted. Lime requirements are high unless an *e* modifier is also indicated.
h	Strong to medium soil acidity. Requires liming for most crops.
i	High P fixation capacity. Requires high levels of P fertilizer. Sources and method of P fertilizer application should be considered carefully.

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APPENDIX C continued

x	High P fixation capacity. Amount and most convenient source of P to be determined.
v	Clayey textured topsoil. Tillage is difficult when too dry or too moist but soils can be highly productive.
k	Low ability to supply K. Availability of K should be monitored and K fertilizers may be required frequently for plants requiring high levels of K.
b	Basic reaction. Rock phosphate and other nonwater soluble phosphate should be avoided. Potential deficiency of certain micronutrients, principally iron and zinc.
s	Presence of soluble salts. Requires special soil management practices for saline soils.
n	High levels of sodium. Requires special soil management practices for alkaline soils.
c	Potential acid sulfate soil. Drainage is not recommended without special practices. Should be managed with plants tolerant of flood and high level of water table.

(C) *Sample interpretations of FCC units:*

Classification	*Main limitations and management considerations*
Lehk	*L:* Good water-holding capacity, medium infiltration capacity. *e:* Low ability to retain nutrients, mainly Ca, K, Mg, for plants. Heavy applications of these nutrients should be split. *h:* Requires liming for most crops. Potential danger of overliming because of low CEC. *k:* Low ability to supply K. Availability of K should be monitored and K fertilizers may be required frequently for plants requiring high levels of K.
Lgh	*L:* Good water-holding capacity, medium infiltration capacity. *g:* Limitations in drainage so that tillage operations and some crops may be adversely affected unless drainage is improved by tiles or other procedures. *h:* Strong to medium acid soil. Liming required for some crops.
LCgeak	*LC:* Removal of surface soil will expose undesirable clay-textured subsoil. *g:* Drainage is limited so that tillage operations and some crops may be adversely affected unless drainage is improved by tiles or other procedures. *e:* Low ability to retain nutrients, mainly Ca, K, Mg, for plants. Heavy

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applications of these nutrients should be split. *a:* Plants sensitive to aluminum toxicity will be affected unless lime is deeply incorporated. However, deep liming practices are difficult because of clay-textured substrate and because of low CEC in the surface there is a danger of overliming. *k:* Low ability to supply K. Availability of K should be monitored and K fertilizers may be required frequently for plants requiring high levels of K.

Discussion summary

Session III, Subsession 1: Acidity, Salinity
P. Sanchez, chairman; A.S.R. Juo, reporter.

In the discussion following the papers by Kamprath, van Breemen, and Ponnamperuma and Bandyopadhya, a consensus on priorities was developed:

1. *Priorities for alleviating soil acidity constraints in dryland soils*

- Use of *N* KCl extractable aluminum is the most practical criterion for determining lime rates (application of technology). Use of pH, buffered solutions, etc., as criteria should be abandoned.
- Research to determine the most appropriate factor to translate milliequivalents of exchangeable aluminum to tons of lime per hectare for specific soil-farming systems situations is needed.
- Research to determine the critical percentage levels of aluminum saturation for main crops and cultivars is needed.
- There is a need to expand the number of long-term lime trials to properly evaluate its residual effects as a function of time and its effects on downward movement of calcium and magnesium.
- Cultivars tolerant of high levels of aluminum saturation should be developed both to reduce lime requirements (and eliminate them altogether in certain cases) and to improve root development into acid subsoils. The latter improves water utilization and reduces the impact of short-term droughts.
- The absence of lime in certain areas must be recognized as a major constraint; in such cases emphasis should be on developing more effective cropping and fallow systems, which may involve some tree crops.
- Knowledge about critical levels of manganese toxicity and the soils where it occurs needs to be developed.

2. *Priorities for alleviating acidity constraints in wetland soils*

- The wetland Sulfaquepts and deep ombrogenous Histosols should be eliminated from consideration where the possibility of payoff is extremely low. Chemical-physical criteria should be developed to separate hopeless soils from those that have potential, such as Aquults, ferrolysed soils, shallow Histosols, Sulfic Tropaquepts, Sulfic Haplaquepts, and others.
- The soil factors important for the production of rice, taro, and sago palm in acid wetland soils, both for short-term and long-term productivity, should be quantified.
- Studies on the effects of temporary drainage and oxidation on acid wetland soils are needed.
- The acid wetland soils where experiments are conducted should be better characterized.
- Flooded Oxisols often present iron toxicity problems so serious that flooded rice is better grown elsewhere. In Sierra Leone where there is no such choice, appropriate technology has been developed.

3. *Priorities for relieving soil constraints in saline soils in the humid tropics*

- Varieties tolerant of different saline soil conditions should be selected.
- Soils where the soil solution is dominated by Na and those where it is dominated by Al^{+++} and Fe^{++} should not be lumped together.

- Criteria for determining which saline soils have a reasonable potential for paddy rice *and other crops* should be developed.
- Critical levels for salinity tolerance at the appropriate growth stages for important tropical crops and pastures and their main cultivars should be developed.

The constraints of saline soils in nonhumid environments were ignored.

Session III, Subsession 2: P, S, K Microelements
E. J. Kamprath, chairman; Somsri Sinanuwong, reporter.

Phosphorus deficiency in tropical soils as a constraint on agricultural output, by B. Dabin

Highly weathered soils in the tropics such as Ferralsols, Acrisols, and Luvisols are generally deficient in phosphorus. The amount of phosphorus adsorbed by soils is highly correlated with exchangeable aluminum and total iron content. In the highly weathered soils, soil phosphorus is mainly in the organic and occluded forms. Because phosphorus availability in soils is a function of the quantity-intensity relationship, estimates of the phosphorus requirement of soils can be obtained from adsorption isotherms. Most adsorption isotherms, however, are determined at 25°C in the laboratory, whereas soil temperature of many lowland humid tropics approach 40°C.

For optimum plant growth a higher phosphorus concentration in the soil solution is required for sandy soils than for other soils. Various soil test methods can estimate phosphorus availability. The amended Olsen method, 0.5M $NaHCO_3$ + 0.5 N NH_4F, has generally given the highest correlation with plant growth. This undoubtedly reflects the quantities of active Al-P and Fe-P in tropical soils.

Relatively little information is available on the long-term residual effects of various rates and methods of phosphorus application to soils of different mineralogical and chemical properties. Various views exist as to the degree of immobilization of fertilizer phosphorus in iron-oxide *rich* soils and in volcanic soils and soils high in allophane. In acid mineral soil of the savannas used for extensive grazing, the use of rock phosphate may offer some benefit particularly for use with acid-tolerant pasture crop species. Research to determine whether higher utilization of applied fertilizer phosphorus can be obtained by management practices and plant selection is needed.

Sulfur deficiency in soils of the tropics as a constraint to food production, by G. J. Blair, C. P. Mamaril, and M. Ismunadji

Soils in the tropics have relatively low levels of organic sulfur, and adsorbed sulfur is often the major reserve. Sulfur deficiencies have been reported throughout the tropics, but sulfur research is rather limited. Use of lime and phosphate fertilizers will reduce the retention of sulfate in surface soils and may result in less sulfur available for crop growth. Fertilizers manufactured at present are devoid of or are low in sulfur; sulfur deficiencies will increase unless sulfur is

incorporated in the fertilizers. In areas where sulfur is deficient, sulfur fertilization dramatically increases the methionine content of grain.

Priorities for sulfur research are:

- Development of chemical methods to estimate sulfur availability;
- Coordinated investigations of the effect of sulfur fertilization on crop yield and quality;
- Selection of varieties efficient in the use of sulfur;
- Study of sulfur reactions in dryland and wetland soils as regards efficiency of fertilizer sulfur sources, leaching and residual values, and long-term effects;
- Methods of incorporating sulfur into fertilizers that will be used in the tropics.

Potassium deficiency in soils of the tropics as a constraint to food production, by G. Kemmler

Coarse-textured soils and soils with predominantly kaolinitic clays generally have low reserves of potassium, but soils with 2:1 clays generally have good reserves. Indications are that the available-potassium levels of some soils used for rice in Southeast Asia are low. In areas where plant residues are removed and not returned to the soil in the form of compost or manure, the need for fertilizer potassium will increase. Long-term field experiments are needed to assess the potassium needs in tropical areas and to provide data for soil test correlations. Although many soils in the tropics are low in potassium, the use of fertilizer potassium should be based on soil test values rather than follow blanket recommendations.

Additional information is needed on critical levels of potassium for soils containing primarily kaolinitic clays and those containing 2:1 type clays. Research on the effect of potassium fertilization on magnesium uptake and requirement by various crops is needed.

Micronutrients in soils of the tropics as constraints to food production, by A. Lopes

Although micronutrient studies have been conducted in many areas of the tropics, lack of adequate soil characterization seriously limits the extrapolation of the results. Future studies must include adequate soil characterization and classification. In the acid savannas of South America, zinc deficiency severely limits crop production. Ultisols in the Amazon jungle of Peru are deficient in boron, copper, and molybdenum. Volcanic ash soils, particularly the older ones, are deficient in molybdenum. Overliming of Entisols, Oxisols, and Ultisols in Africa has resulted in deficiencies of manganese and zinc. On the other hand, manganese toxicity has been observed in the acid Entisols. Boron deficiencies are extensive in Africa on hydromorphic soils and Alfisols. Molybdenum deficiencies have been a problem in the acid sandy soils in Africa. Zinc deficiency in wetland rice has been observed in calcareous soils in Asia. Iron deficiencies

of wetland rice have been found in calcareous soils where low organic matter contents limited soil reduction.

Soil characterization for soil classification purposes should include micronutrient analyses. Increased attention must be given to field studies or to response of crops to micronutrients and identification of soils deficient in micronutrients. Various forms of micronutrients must be evaluated for efficiency in various farming systems and for their residual effects. Critical micronutrient levels for soil tests and tissue analyses must be determined.

Session III, Subsession 3: N, Bio N
G. Uehara, chairman; E. Craswell, reporter.

Subsession 3 discussion was broken into three areas – nitrogen availability, nitrogen fixation, and integrated nitrogen management.

NITROGEN AVAILABILITY

Nitrogen as a constraint to nonlegume food crop production, by D. Bouldin, R. S. Reid, and P. J. Stangel

The model proposed by the authors provided a framework for discussion:

$$N_P = N_S + N_R + K_F N_F$$

where

N_P = nitrogen uptake by the plant,

N_S = nitrogen supplied from soil nitrogen mineralization,

N_R = nitrogen supplied from mineralization of residue nitrogen,

N_F = nitrogen applied as fertilizer, and

K_F = fraction of fertilizer nitrogen absorbed by the plant.

Plant N (N_P). Samples of genotypic differences in the ability of plants to take up nitrogen from the soil – viz. pasture grasses and millet – were given. Varietal differences not only in the amount of nitrogen taken up but also in the timing of uptake may be related to water use efficiency, especially in arid regions. Research in this area should be conducted in association with plant breeders.

The need to tie research on nitrogen availability to cropping systems research was stressed. Research to develop new concepts related to multiple cropping was suggested because nitrogen absorption by two crops differs from that by one crop.

The importance of rainfall in determining N availability and uptake was discussed. For wetland rice systems, the effect of wetting and drying cycles on nitrogen availability in the field was thought to be a major research topic. In semiarid areas, the effect of seasonal variation in rainfall on crop growth, nitrogen availability, and nitrogen recovery by plants was also considered important.

The effect of other nutrients, e.g. sulfur, on plant growth and hence plant nitrogen uptake should also be considered.

Soil N (N_S). The importance of understanding the time course of nitrogen mineralization in relation to the rate of plant nitrogen uptake was stressed. Cover

crops were suggested to absorb nitrogen mineralization at a rapid rate after land clearing.

Residue N (N_R). Long-term studies in the field with different residue management practices are needed. For nitrogen availability incorporation of residues is less efficient than surface mulching.

Fertilizer N (N_F). Measurement of the efficiency factor (K_F) in different environments with different fertilizer sources, timing and placement, and in different cropping systems are needed. Research should aim to increase K_F from the present values of 0.3–0.5 to 0.7 or higher. K_F should be measured at the time of maximum nitrogen uptake, which is not necessarily at crop maturity.

Some speakers stressed the need to better understand the loss mechanisms operating in the tropics, viz. nitrification-denitrification, leaching, ammonia volatilization. Soil type and environment as well as fertilizer management are important variables.

Acidity due to excessive use of ammonium sulfate and other nitrogen fertilizers was cited as an important research topic.

Research methodology. Benchmark-type field experiments to study the efficiency of different nitrogen management systems are needed. They are best conducted in farmers' fields over a long period in the cropping systems and environment of the site. Improved technology may be compared with traditional practices, where possible. Measurements of plant nitrogen uptake, soil nitrogen and residue, and organic waste nitrogen are needed. Each site's soil and environment should be fully characterized.

NITROGEN FIXATION

Constraints to biological nitrogen fixation in soils of the tropics, by A. A. App, D. R. Bouldin, P. J. Dart, and I. Watanabe

Nonsymbiotic fixation

Autotrophs. Research on the effect of soil constraints such as pH, water, phosphorus, and molybdenum on the ecology and on nitrogen fixation by blue-green algae is needed. Research on the effects of nitrogen fertilizer management on nitrogen fixation by algae was given high priority.

Heterotrophs. The importance of nitrogen fixation associated with the roots of tropical grasses and nonleguminous crops was a controversial research topic. Some participants suggested that this source of nitrogen was not important agronomically, but others cited evidence to the contrary. Further research might resolve this issue.

Symbiotic fixation

Rhizobium competition and survival in soils were cited as an important research area. Identification and characterization of situations responsive to inoculation are also necessary. Research on forms of inoculum used and the selection of strains of Rhizobium resistant to heat, anaerobiosis, salinity, low pH, and high soil nitrogen should be given high priority. Host cultivars with high nitrogen fixation rates and resistance to soil toxicities and deficiencies without the need for starter nitrogen fertilizer applications should be developed. Research on the effects of soil physical factors (e.g. moisture and porosity) as well as of chemical

factors (e.g. fertilization with phosphorus, potassium, molybdenum, boron, calcium, cobalt, and zinc) is needed. The extent of nitrogen transfer from legume to nonlegume in mixed cropping was another area of research mentioned.

Techniques for measuring nitrogen fixation

Development of methods for quantifying nitrogen input from fixation was cited as a major research priority. The use of ^{15}N, especially indirectly through labeling of soil organic matter, was thought to be a useful technique for studying symbiotic nitrogen fixation.

INTEGRATED NITROGEN MANAGEMENT

Research should be designed to develop and evaluate management practices that increase the efficiency of nitrogen fertilizers and organic residues, and at the same time maximize the inputs from biological nitrogen fixation.

Research should match biological nitrogen fixation with ecological zones and land types.

Session III, Subsession 4: Drought, impedance, erosion

N. Ahmad, chairman; C. Valverde, reporter.

Water stress as a constraint to crop production in the tropics, by T. C. Hsiao, J. C. O'Toole, and V. S. Tomar

The paper discussed a model of the soil-plant system with respect to water uptake by roots and loss from leaves. Drought stress, which causes stomatal closure to conserve water, also reduces carbon dioxide assimilation and hence photosynthesis. Water deficiency affects the growth pattern of crop plants much more basically than carbon dioxide assimilation does, and is more critical to cereal crop yields when it occurs at the ear elongation stage.

More research on the growth characteristics-water deficiency relationships of tropical crop plants is needed to determine the time when irrigation would be most beneficial. The same is true for moisture retention-supplying capacities. More emphasis should be placed on these factors when tropical soils are being mapped. Various techniques of assessing the factors were discussed. It was agreed that soil properties, rather than geographical location, should determine the methods used. The case of very fine-textured soils on the one hand and coarse-textured layers on the other was cited as problems in the use of instruments for meaningfully characterizing soil moisture relationship.

In areas where there is moisture deficiency, various cultural techniques such as planting dates and duration of the particular crop in relation to the wet seasons have been traditionally used by farmers and should be considered when selecting crops for water-deficient areas.

Because of soil limitations such as the presence of high-impedance layers, soil acidity, and associated problems, water stress in crops is not necessarily confined to semiarid areas. Essentially humid areas with a marked seasonal rainfall distribution could suffer from drought effects for several months of any year and irrigation would be essential for all-year crop production.

Mechanical impedance related to land preparation as a constraint to food production in the tropics (with special reference to fine sandy soils in West Africa), by R. Nicou and C. Charreau

Soil tillage is done for many reasons: to increase soil porosity and infiltration, control weeds, and facilitate seedling emergence. In the case of soil porosity, both pore size distribution and total porosity are affected. These factors influence root development distribution. Tillage could reduce evaporation and maintain water in the soil during dry periods, thus increasing water supply to the roots. It incorporates crop residues into the soil, thereby influencing microbial activity in the soil. It could facilitate seedling emergence, especially if done with provisions for facilitating drainage. One of the more significant advantages is weed control in the early stages of crop establishment. This is significant because the use of weed killers is not universally accepted because of their cost and uncertain effectiveness for all soil conditions.

The effect of soil tillage on soil erosion should be carefully considered. It should not be assumed that tillage would directly lead to erosion. In some cases, if a stubble is worked into the soil, tillage could lead to a decrease in soil loss by erosion.

The tillage requirements of each soil and crop should be individually considered so as to reduce overtillage and to prevent its undesirable effects on soil physical properties and soil crust development. This is also important from the point of view of power requirements. For many tropical soils where the soil surface hardens as the soil dries, tillage seems indispensable if a crop is to be established.

The question of deep tillage was also considered. In some areas of pedologically indurated subsoil layers, deep tillage may increase the rooting soil volume. This is possible if lime and fertilizer materials could be incorporated into the soil at the time deep tillage is done, to encourage roots to grow deeper into the soil.

Soil tillage in tropical soils must be viewed in a broad sense and should not be automatically interpreted as the use of mechanical implements; chemical tillage may be appropriate where erosion hazard and the cropping system warrant it.

Mechanical impedance to root growth, by H. M. Taylor

The effects of mechanical impedance on the growth of roots were discussed. Mechanical impedance results in restricted root development, particularly in limited elongation. Root growth pressure, defined as the difference between turgor pressure and cell wall constraint, must be greater than the impedance acting upon the cross section of the root for the root to elongate. Roots grow partly through existing voids in the soil and partly by pushing soil particles aside.

It is important to characterize what constitutes mechanical impedance in any soil layer. Obvious indurated layers such as duripans, fragipans, densipans, ortstein layers, and petrocalcic layers require little further characterization and these are mappable features. A simple bulk density measurement is often enough to characterize the impedance of a soil layer in other cases. Values associated with lack of root development vary with texture, and range from 1.55 for clay loam to 1.85 for loamy sand.

Soil strength, conceived as the resistance of the soil to the penetrating root bulk density and soil water content, is an important soil property. It can be measured simply by a penetrometer. Root elongation is known to decrease as penetrometer resistance increases. Penetrometer resistance is not directly related to root growth because the penetrometer measures soil strength in soil volumes substantially larger than the plant root and also because small flexible roots can penetrate soil layers through cracks, worm channels, and root channels. Other factors, such as soil acidity, moisture, and nutrient deficiencies, affect root growth. There is, however, a positive correlation between soil strength and penetrometer resistance and root growth.

Soil layers of high impedance can be mechanically shattered by deep-tillage practices such as growing certain crops with root systems that have the ability to penetrate such layers.

Information on the effects of mechanical impedance to the development of root systems in the tropics is needed. The ease with which high impedance layers can be developed in tropical soils by machines should be known. Such information should be incorporated into detailed soil surveys to assist national planners. The ability of the roots of crop plants to penetrate high-strength soil layers should be studied. Also, the effects of root growth – whether constrained by mechanical impedance or some other soil factors – on water and nutrient uptake should be investigated. Such information would assist planners in forecasting with some accuracy the consequences of any proposed land development scheme.

Erosion as a constraint to crop production, by R. Lal

Under some cropping conditions in the tropics, soil loss by erosion can be very considerable and there are experimental results to show that where this occurs, crop yields are greatly diminished. More work on water as an agent in soil erosion has been done. Much more attention should be given to wind in soil erosion either per se or in its role of increasing the erosivity of water on rainfall. Soil erosion via surface wash or rill erosion has been most studied. Other forms of erosion such as gullying and land slipping could be very serious and difficult to control or reduce.

The best form of erosion control is good soil and crop management that minimizes water runoff through improved soil structure and water infiltration. Continuous ground cover through cropping sequences or crop combinations would substantially control erosion by keeping the soil protected most of the time. Mulching with crop residues and tillage practices are also important factors affecting soil erosion. Land development and land use in new developments in the tropics should be planned on a watershed protection basis where land use on various slope categories should be carefully regulated to minimize the soil erosion problem.

The methods of clearing forest land for agricultural development could greatly influence soil loss. The indiscriminate use of the bulldozer should be controlled. Factors such as cost, speed of clearing, and consequences for soil erosion must be carefully considered before embarking on machine clearing as opposed to hand clearing which is to be preferred for erosion control.

The erodibility of the major soil groups should be assessed as a guide to land development. Overgrazing as a factor in soil erosion, the effect of termites consuming crop residues, and other components of the vegetative cover should also be assessed. The associated loss of plant nutrients and organic matter from the soil are also important consequences of soil erosion that should not be ignored.

Session III, Subsession 5: Soil fertility, evaluation, extrapolation
A. Islam, chairman; H. Obeng, reporter.

Constraints to soil fertility evaluation and extrapolation of research results, by S. W. Buol and J. J. Nicholaides, III

The need of soil researchers for a quantitative grouping of surface-soil properties that define the boundary conditions of the uncontrolled variables within which field research is conducted for extrapolation of results is the most critical constraint to soil fertility evaluation and extrapolation of research results today. All other user groups of soil fertility evaluation, land use planners, extension workers, and both small and large farmers rely on information developed first by soil researchers.

Soil properties considered for taxonomic purposes are not necessarily relevant for soil fertility purposes. Dudal has stated that the upper 20 cm, which soil classifiers discard because it is highly variable, is the key zone for soil management and crop production. Data from Sopher and McCracken showed that 70% of the crop yield variability in 441 field trials was explained by a combination of all topsoil properties, whereas the subsoil properties explained markedly less.

The Fertility Capability Classification System (FCC) as proposed by Buol, Sanchez, Cate, and Granger, and which builds on soil classification information is presented as one means to overcome the primary constraint to soil fertility evaluation and extrapolation of research results. The FCC consists of three levels: type – the texture of the surface 20 cm; substrata type – the texture of the subsoil if there is a change within 50 cm; condition modifiers – specific properties noted if a specific range of conditions is encountered.

The worldwide soils were grouped into 117 fertility capability classes with the use of published profile descriptions and analytical data for 244 soil profiles representing a broad geographic and morphological range. Four textural types – loamy, clayey, loamy over clay, and sandy – represented 92% of the soils. Ten condition modifiers represented 51% of the population.

When the FCC was used to group soils from McCollum and Valverde's potato fertilization trials in the Sierra of Peru, the 73 sites were grouped into 5 categories. Economic analysis of the response curves showed that fertilizer recommendations based on a combination of the FCC and soil test analyses gave the highest gross returns to fertilizer of any system tested.

When properly used by building on *Soil taxonomy* information and combined with soil testing, the FCC could enable soil researchers to help the farmer – no matter how small or remotely located – reduce risks and increase his probability of producing economical crop yields.

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Discussion summary

REPORT ON SESSION IV: RESEARCH PROGRAM PRIORITIES

Three discussion groups, formed during Session IV, were asked to identify research program priorities of particular interest to different ecological zones. Group A addressed priorities for the humid tropics savanna and rain forest conditions; group B, tropical wetland conditions; and group C, the semiarid tropics.

The chairman and the reporters of Session III circulated their drafts on research priorities to each group. Group reports were presented in a plenary meeting at the end of Session IV and were modified to include comments and observations made at that time.

Group A: Humid tropics savanna rain forest
K. Kyuma, chairman; A. Smyth, reporter.

For purposes of discussion the humid tropics was defined as areas under savanna and rain forest with a growing period of more than 150 days. Their soil problems are principally those related to low-activity clays of high acidity, low nutrient status, and low capacity to retain moisture and nutrients.

In many contexts a need for systematic land resource evaluation of these regions – which leads to some sort of land classification in terms of climate, physiography, and soil – was recognized as a basis for technology transfer. The land classes thus established will serve as the frame of reference for the researches to be conducted under the following headings.

Acidity

In the context of acidity, a liming formula based on N KCl extractable aluminum was recognized as the most practical criterion for determining lime rates. The most appropriate formula for specific soil-farming systems needs to be determined.

The major research needs include

- long-term liming trials to evaluate residual effects and balance of cations,
- development and evaluation of cultivars tolerant of high levels of aluminum saturation,
- development of cropping and management systems not dependent on lime for areas where lime is not available,
- practical methods of liming into subsoils, and
- nutrient toxicities and deficiencies in acid soils.

Phosphorus

More information on residual effects of phosphorus fertilizers through long-term experiments is needed. There is also need for standardized methods of measuring phosphorus absorption and fixation capacity of soils, which is particularly serious in Oxisols and Ultisols of high clay content. The method must be standardized in relation to crop response. Other issues include lack of information on desirable maintenance dressing of phosphorus, on the significance of mycorrhiza, and on the best use of locally available rock phosphate.

Sulfur
Some evidence of sulfur deficiency has been reported in these regions and it is possible that this problem will increase. Information on the extent of the problem is needed so that fertilizer manufacturers can plan accordingly.

Potassium
Additional information on critical levels of potassium in kaolinitic soils is needed. Interaction between potassium, magnesium, and calcium needs further attention.

Micronutrients
In Africa, deficiencies of zinc, molybdenum, and boron are most significant. Zinc deficiencies may be important elsewhere. Overliming may induce zinc and manganese deficiencies especially in Oxisols and Ultisols. Micronutrient analysis in support of soil classification is desirable but will necessitate the use of equipment.

Nitrogen
Particular stress is placed on the management of organic matter in this context, including the residues of relay cropping, green manures, and organic refuse. Quantification of leaching losses from mineral fertilizers is especially necessary in these humid regions.

Deleterious and side effects of nitrogen fertilizer, notably acidification, are not well understood and require study. Methods and time of application, and forms of nitrogen fertilizers need further evaluation particularly in the coarse-textured low cation exchange capacity Udults and Orthox soils in the high rainfall regions.

In general there is need to raise the efficiency of fertilizer to obtain better economic returns. This applies not only to nitrogen fertilizer but also to other fertilizer elements.

These are the short-term research needs. Studies on the potentials of biological nitrogen fixation are the long-term needs.

Drought
Despite humidity in these regions periodic drought stress can be important. Poor root development in acid soils aggravates drought hazards. Crop management studies are required to maximize use of available water. Interdisciplinary research is called for to establish specific soil-crop-water relationships.

Strongly interacting with soil moisture stress, high soil temperature regime can be a serious limiting factor and needs to be investigated in terms of crop and soil management.

Mechanical impedance
More attention to physical soil properties in the topsoil is advocated both in the context of seed emergence and root growth and in land preparation. Overtillage must be avoided and this requires consideration of the tillage requirements of individual soils and crops.

Erosion
In parts of the humid tropics, notably in Latin America, erosion is the most serious constraint to agricultural development, although less serious in udic than

in ustic zones. The need for extension based on research relevant to the farm level was stressed. Keeping the soils covered at all times is seen as the most effective control measure presently available; nevertheless more knowledge on crops adapted to dry season conditions is needed. Mixed cropping of perennials and annuals will often be appropriate.

Investigation of alternative methods of forest clearing is a research priority and there is need for widespread evaluation of parameters that affect erosivity and erodibility. Quantification of yield loss in relation to soil erosion for a range of soils and crops is needed for planning for land development, bearing in mind that erosion may lead to loss of the land resource itself. Methods of restoring eroded land also need study.

Soil fertility evaluation

A three-phase approach to evaluation was envisaged. A macro investigation of climate, physiography, and soil is followed by fertility capability classification and finally by a soil fertility evaluation phase which includes soil testing, foliar analysis, and field trials.

Systems of interpretation should provide flexibility to adapt to local environmental conditions and to specific uses of the land.

Group B: Tropical wetlands

B. Balankura, chairman; F. Dent, reporter.

Tropical wetlands are lands that are water saturated to such shallow depth and for such durations that they require, for their agricultural use, either critical drainage or the growing of adapted crops – mainly rice – for at least the period when there is lack of oxygen in the rooting zone.

Research aims for each of the five subsessions and their divisions are listed in order of priority. They are restricted to areas where few studies presently exist.

In all studies of wetland soils a complete taxonomical, chemical, and physical characterization should be made before and during the experiments. In addition field experiments should record relevant climatic data.

Wetland acid soils and Histosols

Chemical and physical criteria to separate definitely unsuitable Histosols and acid wetland soils from those that have potential such as Aquults,[1] shallow Histosols, Sulfic Tropaquepts, and Sulfic Haplaquepts must be developed.

Where other options to increase food production are available, deep ombrogenous Histosols[2] Sulfaquents and Sulfaquepts should receive low priority. Where no other options to increase food production exist or commitments have been made, priorities should be given to them.

[1] Wet Ultisols (Aquults), shallow Histosols, and moderately to slightly acid sulfate soils (Sulfic Tropaquepts, Sulfic Haplaquepts).

[2] Strongly acid sulfate soils (Sulfaquents and Sulfaquepts).

Management strategies for all taxa and acid sulfate soils (dressing of lime, rock phosphate; preflooding, dry season irrigation, shallow water table; growing of adapted cultivars), Histosols (minimize waterlogging, trace and major nutrient application, weed control), and Fe-toxic inland valley swamps (growing of adapted cultivars; interception of interflow; application of organic matter, potassium, and phosphorus; minimal N application) should be tested and refined.

The effects of temporary drainage and oxidation on the chemistry of acid soils and on crops (mainly rice) grown under such conditions must be studied.

Saline soils in the humid tropics

The different kinds of salt-affected soils must be recognized and demarcated. Their dynamics and the variability of their chemical, physical, hydrological, and climatic properties should be characterized.

Critical levels for salinity tolerance for important tropical food crops must be developed and the breeding of cultivars with tolerance for salinity should receive further attention.

Criteria for determining which saline tracts have a potential for rice and other food crops with high benefit-cost ratios should be developed.

Phosphorus, sulfur, potassium, and microelements

A common feature of this group of nutrients is the need for coordinated long-term studies among a network of sites.

Particular emphasis should be placed on the effects of continuous flooding on phosphorus transformations. Screening and understanding mechanisms responsible for increased phosphorus efficiency in rice and other flood-tolerant plants should be encouraged.

There is a need to conduct multilocation experiments to supply planners of fertilizer facilities with information on where sulfur deficiency is now a problem and where, because of changes in technology of multiple and double-cropping, it is likely to occur.

There is a lack of understanding of fertilizer sulfur transformations in wetland soils and the effects of different sulfur sources on soil properties, particularly pH.

Characterization of soil properties to predict potassium responses under low to medium technology appears adequate. Studies on low activity clay soils to assess potassium requirements under high output technology are needed. Direct yield effects and those attributable to disease resistance should be noted.

The major priority of micronutrient research should be delineation of zinc-deficient areas.

Nitrogen, bionitrogen

It is essential that the major components of the nitrogen program for tropical wetlands be carried out under the philosophy of integrated management where the important nitrogen sources (soil, crop residues, organic wastes, nonsymbiotic and symbiotic N, and fertilizer) are so used as to result in a high benefit-cost ratio. Specific attention should be given to evaluating the systems applicable to areas with different population densities and cost of labor.

The proposed model $N_p = N_S + N_R + K_F N_F$ was accepted in principle as a useful means of carrying out this research. Some components need refinement and will be identified further.

Specific attention should be given to the development of techniques used to measure nitrogen losses and nitrogen fixation. This may take the form of short-term studies where ^{15}N is used to measure nitrogen transformations as well as long-term studies at carefully selected sites at or at least related to the benchmark sites.

Within the framework described in section A the following items were assessed as needing high priority:

Soil N (N_S). The importance of understanding the factors that affect mineralization of soil nitrogen was stressed. Specific reference was made to the influence of soil properties and temperature.

Plant N (N_p). Nitrogen uptake relative to time of need and nitrogen influence on yield components such as those affected by variety need to be studied for the various crops used within a given cropping system. Specific attention should also be given to the importance of water management and plant nutrient interactions because these affect yields.

Residue N (N_R). Specific attention should be given to characterizing the various organic residues, i.e. plant, animal, and human manures, as to their actual nitrogen content and benefit.

Fertilizer N (N_F). The efficiency of fertilizer (K_F) nitrogen should be determined by identifying nitrogen losses (K_F) through ammonia volatilization, denitrification, and leaching, and identifying periods of maximum uptake. Where possible, information on nitrogen losses should be related to other environmental issues, including the effects on the ozone layer.

Nitrogen fixation. Emphasis should be placed on nitrogen fixation systems that are likely to have a high benefit-cost ratio. Specific attention should be given to the contributions of symbiotic nitrogen in mixed cropping and the effects of nutrients on nonsymbiotic fixation.

Drought, impedance, and erosion in relation to tropical wetlands

Within this group of constraints moisture stress was recognized as the most important during certain growth stages of the rice crop. Constraints relating to impedance and erosion were considered of lesser importance. The following research priorities were, therefore, considered:

Soil hydrologic studies, inclusive of the total landscape where necessary, with a view to characterizing the seasonal sequential properties of the hydrology;

Search for specific morphochemical characteristics of the profile that would significantly reflect the seasonality of the soil hydrology;

Better characterization of wetland soils with respect to their soil physical properties inclusive of the influence of plow pans because they influence tillage and workability under different moisture regimes.

Soil fertility evaluation, extrapolation

1. For the use of fertilizer capability classification in wetland rice, a modifier indicating the degree and duration of reduction must be included. This modifier must be linked to a resetting of critical levels of plant nutrients.

2. The reliability of fertilizer capability classification must consider soil variability due to fragmented small holdings under individual management.

Group C: Semiarid tropics
R. Murthy, chairman; R. Fauck and P. Dart, reporters.

The semiarid tropics (SAT) are characterized by a pronounced dry season and a rainy season in which average monthly precipitation exceeds potential evapotranspiration for 2–7 months during which 95% of the rainfall occurs. The outstanding constraints to agricultural production derive from the undependable rainfall.

There is a need to analyze and describe the present status of SAT soils to follow the long-term effects of their utilization particularly in relation to fertility and erosion and in certain geographical areas, on the development of salinity and acidity. Soil surveys should be conducted with a view to matching crop and environmental requirements so that recommendations of appropriate land utilization can be made.

Because several constraints usually operate simultaneously, it is imperative that any research be done within the framework of the farming system in current use or being developed to better utilize existing and potentially available soil, climate, biological, and socioeconomic resources.

Soil-plant-water relationships. The constant risk of drought means that the highest priority should be given to research on the dynamics of soil-plant-water relationships and to identifying and developing appropriate crops which match better the probabilities of supply of water (both its deficiencies and brief seasonal excesses) and nutrients during critical stages in the growing season.

Nitrogen. Nitrogen deficiency severely limits potential SAT yields. Because most of the nitrogen for present and immediate future agricultural production in the SAT zone derives from biological N_2 fixation, both symbiotic and nonsymbiotic, research on ways to increase and more efficiently use biologically fixed nitrogen is of high priority.

A better understanding of the dynamics of nitrogen transformations and movement in semiarid tropical soils is essential for more efficient use of expensive nitrogen fertilizers.

Much of the land is presently intercropped; therefore, research is needed to understand the effect it has on plant nitrogen nutrition, and the effect of management on the interaction between the crops.

Long-term field experiments to study the efficiency of different nitrogen management systems to see if the nitrogen status of these soils, and hence their productivity, can improve under cropping are required. International agencies should be involved in planning, locating, and executing long-term experiments, and for work using isotopic ^{15}N, because of the expenditure and analytical support required.

Efficient methods are required for recycling residues much of which are currently used for fodder, fuel, or structures. Use of trees as a substitute source of fuel seems a desirable way of increasing crop residue availability for recycling. Composting may become economic as fertilizer costs increase.

Soil impedance. In many semiarid regions severe problems of crusting, sealing, and mechanical impedance affect seedling emergence, water infiltration, soil erosion, root elongation, and mineral uptake. High mechanical impedance limits the use of minimum tillage as a means of water conservation and erosion control. Ways to alleviate these constraints should be sought through management practices, and plant selection and breeding.

Erodibility. There is a need to assess the erodibility of the major soils as a guide to land development. The best form of erosion control is good soil and crop management, which increases water infiltration, and minimizes and controls runoff. Research on appropriate management systems is needed.

Soil testing. Soil fertility evaluation is required on a regional basis for total nitrogen, phosphorus, sulfur, potassium, and the micronutrients zinc, molybdenum, and boron, which are known to be deficient in semiarid tropical soils. Because of the small holding size in the semiarid tropics, the potential for soil testing and fertility capability classification on an individual holding basis is limited. Research to determine the critical levels of micronutrients for both soils and tissue analyses to determine the extent of deficient soils is needed.

Sulfur. Sulfur deficiency is rapidly becoming more widely recognized in SAT soils, and there is a need to develop effective testing methods to identify deficient areas.

Sulfur deficiency may be especially important where nitrogen fertilizer is used, because the increased grain yields associated with it require more plant sulfur uptake. The use of high analysis fertilizers will aggravate sulfur problems. National economic planners should be alerted to include the capability to add sulfur to the design for new fertilizer plants.

Phosphorus. SAT soils are often deficient in phosphorus. It is, therefore, important to determine the efficiency of use (including residual uptake) of P fertilizers. There is a need for research on sources of P fertilizers and their proper placement; selection and development of cultivars that require low amounts of P for good yields; and response to mycorrhizal inoculation.

Potassium. Long-term studies are needed to determine the rate of depletion of soil potassium reserves with improved crop yields, and the maintenance fertilizer applications needed.

Soil acidity. Fertilization with ammonium sulfate or urea may lead to development of acidity on sandy soils or soils with low-activity clays. Research on ways to prevent development of this acidity is needed.

Soil salinity. Salinity developing on irrigated lands also merits attention.

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RESEARCH COORDINATION AND INTERNATIONAL COLLABORATION

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- to strengthen national research programs by coordinating research efforts, establishing collaborative research projects, and supporting the application of basic research to the use and management of soils.
- to draw attention to present and future needs in soils research and mobilize resources for the realization of such research.

The objectives of the coordinating bodies should not be confined to food production; it should include a variety of crops, particularly when considering preservation of land resources.

Question 3. Composition and structure. The plenary session approved the recommendation of the discussion groups that the organization would have a small headquarters staff with administration and technical coordination capabilities. It was agreed that research and training programs be implemented through collaboration with appropriate existing international agencies, international research centers, and national institutes.

The organization would have a Board of Trustees composed of members of soils research institutions, representatives of donor organizations, and subject matter coordinators.

Question 4. Steering Committee. The plenary session agreed that a steering committee would be appointed to develop the necessary proposals for the establishment of the coordinating body. The organizers of this meeting, Cornell University and the International Rice Research Institute, were authorized to circulate a report on the session to knowledgeable individuals in various national and international programs. This way, a larger group of people representing a broad spectrum of soils research could be contacted to establish a broader-based steering committee. The plenary session encharged organizers of this meeting with finding appropriate ways to form such an enlarged committee.

Discussion summary

REPORT ON SESSION V: RESEARCH COORDINATION AND INTERNATIONAL COLLABORATION

L. D. Swindale, chairman; H. G. Zandstra, reporter.

Three discussion groups formed during Session V considered the institutional aspects of international collaboration for research on soil-related constraints with the final objective of strengthening soil research capabilities at the national level. This session discussed ways in which this coordination could be structured.

Discussions took place in three groups, each with a chairman and a reporter. The conference organizers asked each group to discuss the following questions:

- Does the group believe that an international coordinating body for solving soil-related constraints is needed?
- What should be the objective of such a body?
- What should be the composition and structure of such an organization?
- Does the group authorize the organizers of this meeting to circulate a report on the session to knowledgeable individuals in various national and international programs?

Plenary session group reports and discussion

The chairman and the reporter of each group summarized the group discussion. The following is a description of the items agreed on during the plenary session. Where required, differences in opinion or emphasis expressed by the groups are mentioned.

Question 1 Need for coordinating body. The plenary session agreed on the need for an international coordinating body. Group A called it an international board. Group C agreed that an independent body should be created, but suggested that it should reinforce the existing national programs and take full advantage of basic and applied research programs already under way.

Question 2. Objectives. The overall objective of the body should be to help feed the additional 2 billion people over the next 20 years by providing coordination and encouragement of research on the properties, management, and utilization of land resources for crop production.

The following specific recommendations for objectives were agreed upon during the plenary session:

- to compile, collate, and disseminate soil research data from various priority areas. This may involve the development of a data bank and a documentation center and facilities for some service functions such as reference laboratories.
- to inventory problems and set priorities for research on soil-related constraints.
- to develop broadly applicable research methods for the solution of soil constraints and for the extrapolation of research results. The session felt that standardization of research methods was not a practical objective. The body would rather provide a framework in which methods can fit and that allows comparisons between them.
- to strengthen national research capabilities by encouraging appropriate training programs and conferences.

a period of time. Even if the 500 tests were to continue, the data from them would be more useful if placed in a data bank and if the soils on which they were performed were classified in international terms.

With regard to the development of common methods for classifying soils, I note some resistance to the standardization of taxonomical units. Standardization may not be desirable, but I believe it is desirable to have some agreement in terms of methodologies so that what is learned in one section of the world can be interpreted properly in another. This is valid, not only from the standpoint of soil classification but from the standpoint of the types of soil performance tests that are being run.

I am pleased that there seems to be a unanimity, or near unanimity, of opinion that we are not talking about more bricks and mortar – about building a large physical facility. Needed facilities already exist in organizations throughout the world. If we need additional facilities, they ought to be associated with facilities of organizations already in existence.

With regard to a governing body or board of trustees, I was pleased you did not specify exactly how many individuals would serve on that board and from where they might be chosen. I believe the experience of the CGIAR-initiated organizations suggests that this ought to be left flexible until a decision is made as to the exact nature of the governing board, and its objectives and duties. Certainly membership in this body should include individuals that are acceptable to the donors. But if there should be differences of opinion as to whether donor representatives should serve on the board, we should be certain that the donors respect the members. National programs too should be properly represented in such an organization.

A small secretariat attached to an existing institution has been suggested. The organizational approach could be partly on the basis of geographic regions and partly on the basis of subject matter.

With regard to the setting up of a steering committee, those chosen will have a lot of work to do; they must write a proposal and then seek support for it from one or more donors. They will serve on only a temporary capacity until a more permanent Board can be set up. I am hoping that the steering committee can do its job and can move toward the setting up of a more permanent structure within a year. I may be a bit optimistic in that regard, but we must be positive.

I have shown in general terms my understanding of the general concept that has been developed at this conference and others that have preceded it (Fig. 1). The concept is similar to that on which the International Board on Plant Genetic Resources is based. A governing board or coordinating body would be supplemented by a small planning and coordinating staff, some of whom should help set up and operate one or more data banks for storing soil characterization and soil performance data. The field work would be concerned with soil characterization and classification or with soil performance. Research would be planned and implemented by groups of soil scientists concerned with regional or geo-

Concluding remarks

N. C. BRADY

THE GENERAL ATTITUDES HEARD at this conference differ somewhat from those expressed at a similar conference held in IITA in 1972, a conference which many of us attended. But I believe there is unanimity on two points. First, soils should be very high on the priority list of those concerned with international agricultural development, which means that soil scientists have a significant contribution to make to help the world increase its capacity to feed itself. Second, we must organize and present our proposed inputs in such a way as to make them attractive to others.

Soil constraints are a major factor in holding down the production of food. We recognize this, and believe we can bring this fact to the attention of others. We believe there are ways we can alleviate those constraints as we work in cooperation with crop scientists. We can show through crop production – or lack of production – on different soils how important the soil is to helping people produce more food.

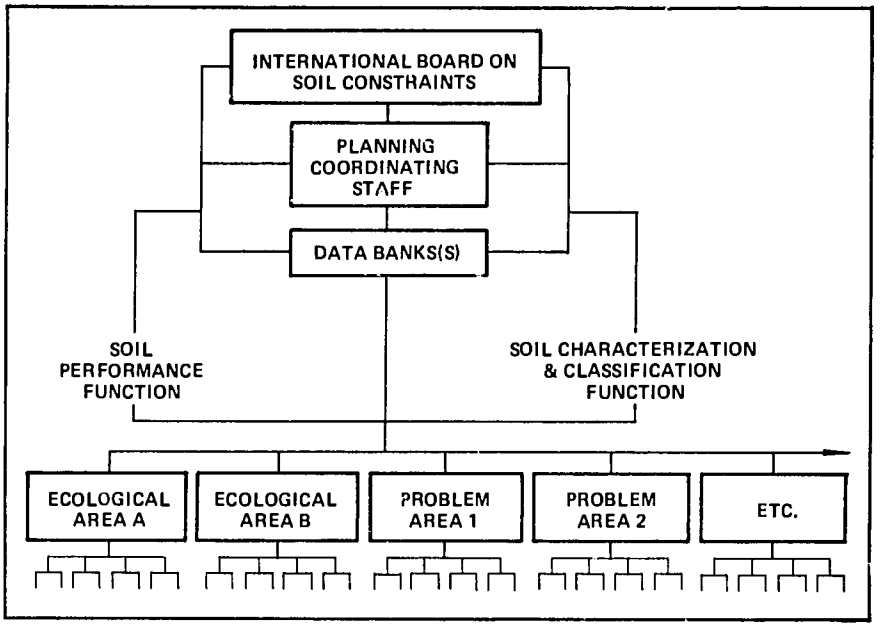
I am pleased that this conference had suggested a mechanism for coordination of soils research and for support for that research. I am convinced that with modest financial resources, we can accomplish much more than we have accomplished in the past. Over a period o time, success will help us attract support. It will help us mobilize the human resources as well as the economic and other resources needed to get a job done.

Your discussions indicate an almost unanimous opinion that some kind of a coordinating mechanism or entity would be worthwhile. We are thinking of an organization similar to the International Board on Plant Genetic Resources, which is primarily a body coordinating what others do and a provider of some resources to get the job done.

I noted among the objectives discussed the words "catalyze," "communication," and "coordination." These words indicate what this coordinating body might do. Activities you mentioned include the inventory of the soil-related constraints, development of one or more data banks, establishment of a documentation center for communication, and finally the mobilizing of resources to get the job done.

It is likely that on a given continent as many as 500 fertilizer experiments may be initiated in a year. I suspect that with proper coordination, so as to make valid comparisons from one test to another on a rational basis in terms of soil characteristics, 75 or 100 experiments might provide much more meaningful information than the 500. Such a change will take place, not immediately but over

Director general, International Rice Research Institute, P.O. Box 933, Manila, Philippines.



1. General concept for organization and function of an international board on soil-related constraints to world food production.

graphic problems, or with specific problems based on subject matter (e.g. nitrogen fixation, or soil-water-plant relations). The organizing unit for group planning might be a national or international research center, a consortium of universities, or other such groups with a common interest.

It is likely that the funds needed to support this effort would not be excessive. Travel for the coordinating board, salaries and travel for the planning and coordinating staff, and funds for the data bank would be the major initial expenses. Funds would also be needed for workshops and planning conferences in the field, but in many cases these activities could be combined or dovetailed with existing conferences.

I am optimistic as to the possibilities of our developing a mechanism to better coordinate research on soil constraints. You have contributed much during the past week to make this possible. I thank each one of you for the contributions you have made. I also thank those who took the immediate responsibility for the implementation of this conference. Dr. Zandstra and Dr. Van Wambeke were the two that did most of the organizational work and we ought to recognize their efforts. We should also thank USAID and the German government for their generous support of this conference. Lastly, we should wish every success to the steering committee that will be asked to develop the ideas presented by this body.

Participants

AHMAD, N., University of West Indies, St. Augustine, Trinidad, West Indies
ALCASID, G.N., JR., Bureau of Soils, Manila, Philippines
ALI, MOHAMED A., Soil Survey Administration, Soil Survey Dep., Wad Medani, Sudan
ALWIS, K. DE, Land Use Division, Irrigation Dep., Colombo 7, Sri Lanka
BALANKURA, B., Land Development Dep., Bangkhen, Bangkok, Thailand
BANDY, D., North Carolina State University, Raleigh, N.C. 27650, USA
BANDYOPADHYAY, A.K., Central Soils Salinity Institute, West Bengal, India
BENTLEY, C.F., Governing Board, International Crops Research Institute for the Semi-Arid Tropics, c/o Dep. Soil Science, University of Alberta, Edmonton, Alberta, Canada T6G2E3
BLAIR, G.J., Dep. Agronomy and Soil Science, University of New England, Armidale, New South Wales 2351, Australia
BOULDIN, D., Dep. Agronomy, Cornell University, Ithaca, N.Y. 14850, USA
BRADY, N.C., International Rice Research Institute, Manila, Philippines
BRAMMER, H., Food and Agriculture Organization, c/o UNDP, Dacca-2, Bangladesh
BREEMEN, N. VAN, Dep. Soil Science and Geology, Agriculture University, Wageningen, The Netherlands
BUOL, S., Soil Genesis and Classification, North Carolina State University, Raleigh, N.C. 27650, USA
BURFORD, J.R., International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, A.P., India
CHAN, H.Y., Rubber Research Institute of Malaysia, Kuala Lumpur, Malaysia
CHARREAU, C., Institut de Recherches Agronomiques Tropicales et des Cultures Vivrières, Paris, France
COCHRANE, T., Centro Internacional de Agricultura Tropical, Cali, Colombia
CRASWELL, E., International Rice Research Institute, Manila, Philippines
DABIN, B., Office de la Recherche Scientifique et Technique Outre-Mer, Paris, France
THE TUAN DAO, National Agricultural Sciences Institute, Hanoi, Socialist Republic of Vietnam
DART, P., International Crops Research Institute for the Semi-Arid Tropics, 1-11-256 Begumpet, Hyderabad 500016, A.P., India
DENT, F.J., FAO, Land Resources Evaluation with Emphasis on Outer Islands, Soils Research Institute, Bogor, Indonesia
DROSDOFF, M., Cornell University, Ithaca, N.Y. 14853, USA
DUDAL, R., Land and Water Development Division, FAO, United Nations, Rome, Italy
FAUCK, R., Office de la Recherche Scientifique et Technique Outre-Mer, Paris, France
GILL, T., Agency for International Development, Washington, D.C., 20523, USA
GRANGER, M., Upper Mazurini Development Authority, Georgetown, Guyana
GREENLAND, D.J., International Rice Research Institute, Manila, Philippines
HSEUNG YI, Nanking Institute of Soil Science, People's Republic of China

HSIAO, T.C., International Rice Research Institute, Manila, Philippines
HSU-CHI, Nanking Institute of Soil Science, People's Republic of China
ISLAM, M. AMIRUL, Bangladesh Agricultural Research Council, Dacca-5, Bangladesh
JOHNSON, W.M., Soil Conservation Service, U.S. Dep. Agriculture, Washington, D.C. 20013, USA
JONES, R.A.D., Rice Research Station, Rokupr, Sierra Leone
JUO, A.R.S., International Institute of Tropical Agriculture, Ibadan, Nigeria
KAMPEN, J., Farming Systems Research Program, International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, A.P., India
KAMPRATH, E.J., Dep. Soil Science, North Carolina State University at Raleigh, Raleigh, N.C. 27650, USA
KANG, B.T., International Institute of Tropical Agriculture, Ibadan, Nigeria
KATYAL, J.C., Dep. Soils, Punjab Agricultural University, Ludhiana, India
KEMMLER, G., Buntehof Agricultural Research Station, Federal Republic of Germany
KYUMA, K., Faculty of Agriculture, Kyoto University, Kyoto 606, Japan
LAL, R., International Institute of Tropical Agriculture, Ibadan, Nigeria
LOPES, A., Departamento de Ciencias do Solo, Escola Superior de Agricultura de Lavras, Minas Gerais, Brazil
MALCOLM, J.L., Tropical Soil & Water Management Division, Office of Agriculture, Bureau for Development Support, Agency for International Development, Washington, D.C. 20523, USA
MENYONGA, J.H., National Agriculture Research Center, Ekona P.M.B. 25, Buea, United Republic of Cameroons
METZ, J.F., JR., International Agriculture, Cornell University, Ithaca, New York 14853, USA
MOKWUNYE, U., Fertilizer Technology Division, International Fertilizer Development Center, Muscle Shoals, Alabama 35660, USA
MOORMANN, F.R., Soils Dep. State University of Utrecht, Utrecht, The Netherlands
MORRIS, R.A., International Rice Research Institute, Manila, Philippines
MURTHY, R.S., National Bureau of Soil Survey and Land Use Planning, Indian Agricultural Research Institute, New Delhi, India
NICHOLAIDES, J., III, Tropical Soils Research Program, Dep. Soil Science, North Carolina State University, North Carolina 27650, USA
NICOU, R., Institut de Recherches Agronomiques Tropicales et des Cultures Vivrières, IRAT/GERDAT, BP 5035, 34.032 Montpellier, Cedex, France
NYANDAT, N., Kenya Soil Survey, National Agricultural Laboratories, Nairobi, Kenya
OBENG, H., Soils Research Institute, Kwadaso-Kumasi, Ghana
OTOWA, MICHIZO, Soil Survey and Classification Laboratories, Hokkaido National Agriculture Experiment Station, Hitsujigaoka, Sapporo, Japan
PANABOKKE, C.R., Dep. Agriculture, Peradeniya, Sri Lanka
PANICHAPONG, SAMARN, Soil Survey Division, Land Development Department, Bangkhen, Bangkok, Thailand
PARAMANTHAN, S., Soil Survey Station, Soils & Analytical Services Branch, Dep. Agriculture, Swettenham Rd., Kuala Lumpur, Malaysia

PONNAMPERUMA, F., International Rice Research Institute, Manila, Philippines
RASHEED, M.A., Inter African Bureau of Soils, BP 1352, Bangui, Central African Empire
REYES, E.D., University of the Philippines at Los Baños, College, Laguna, Philippines
SANCHEZ, P.A., International Tropical Soils Program, North Carolina State University, Soil Science Dep., Raleigh, North Carolina 27650, USA
SATYAPAL, K.N., Division for Global and Interregional Project, UNDP, New York 100017, USA
SCHARPENSEEL, H.W., Ordinariat fur Bodenkunde, Federal Republic of Germany
SMYTH, A., Ministry of Overseas Development, Surrey KT6 7DY, England
SOMBROEK, W., International Society of Soil Science, Wageningen 6140, The Netherlands
STANGEL, P.J., International Fertilizer Development Center, Muscle Shoals, Alabama 35660, USA
SUNANUWONG, SOMSRI, Land Development Department, Dep. Agriculture, Phaphalyotin Road, Bangkhen, Bangkok, Thailand
SWINDALE, L.D., ICRISAT, Hyderabad, A.P., India
TAYLOR, H.N., Agricultural Research, North Central Region, Ames, Iowa 50011, USA
UEHARA, G., College of Tropical Agriculture, Dep. Agronomy and Soil Science, University of Hawaii at Manoa, 3190 Maile Way, Honolulu, Hawaii 96822, USA
VALVERDE, C.V., Programa Nacional de Suelos, Ministerio de Agricultura, Lima, Peru
WAMBEKE, A. VAN, Dep. Agronomy, Cornell University, Ithaca, New York 14853, USA
ZANDSTRA, H.G., Cropping Systems Program, International Rice Research Institute, Manila, Philippines