Sustainable Agriculture

Green Manure in Rice Farming

International Rice Research Institute

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Green Manure in Rice Farming

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on sustainable agriculture

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Foreword

With the advent of modern crop varieties, more land under irrigation, and greater use of fertilizers and other inputs, Asia has changed within the last 20 yr from a region of food scarcity to a region of food sufficiency. Increased fertilizer use contributed to about one-fourth of the increased rice production. In some countries, fertilizer prices were subsidized, thereby enabling farmers to apply production-maximizing doses. During the same period, use of organic fertilizers—including green manure—declined substantially. But fossil fuel-based inorganic fertilizers are becoming more expensive.

Although today's rice production seems to be sufficient for today's conditions, it may not keep up with future demand. FAO projects demand for unhusked rice of 520 million tons by 1990 and 639 million tons by the year 2000 in the 90 developing countries that account for 98% of the population of the developing world outside China. That represents a projected annual increase in rice supplies of 3% in the 1980s and 2.1% in the 1990s.

Still another issue of great concern is the sustainability of soil productivity as lands are called upon to produce higher yields from a single crop and higher total annual yields under intensive cropping systems. The soil organic matter and nitrogen levels vital to sustained rice production often are limiting in East, South, and Southeast Asia soils, hence the need to identify alternate nitrogen sources to supplement inorganic fertilizers.

The Commission on the Application of Science to Agriculture, Forestry, and Aquaculture (CASAFA) and the International Rice Research lnstitute (IRRI) agreed to convene a series of symposiums on sustainable agriculture. *The role of green manure crops in rice farming systems* was the first.

Sponsors were CASAFA, IRRI, Australian Center for International Agricultural Research (AClAR), Board on Science and Technology for International Development (BOSTID), Centre International de Recherche Agronomique pour le Developpement (CIRAD), Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), International Development Research Centre (IDRC), the Government of the Netherlands, Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), and Winrock International.

Members of the international advisory committee were R.R. Harwood, Winrock, chairman; Yvon Dommergues, ORSTOM-Institut de Recherches

Agronomiques Tropicales et des Cultures Vivrieres (IRAT); Michael Dow, BOSTID-U.S. National Academy of Sciences; M. Jacquot, CIRAD-IRAT; W.G. Sombroek, International Soil Science Society; M.S. Swaminathan, IRRI; Hans Van Enden, Netherlands; K. Wolpers, GTZ; and H. G. Zandstra, IDRC.

The program was planned by Dr. S.K. De Datta, chairman and technical editor; Dr. V.R. Carangal; Dr. J.C. Flinn; Dr. D.J. Greenland; Dr. A.U. Khan; Dr. J.K. Ladha; Dr. C.P. Mamaril; Dr. H.U. Neue; and Dr. I. Watanabe. The proceedings were edited by Dr. M. LaRue Pollard, assisted by Ms. Gloria Argosino.

Klaus Lampe
Director General

Symposium recommendations

The papers and discussion during the symposium reconfirmed that—broadly defined—green manure does increase rice yields. Moreover, empirical evidence and theoretical considerations strongly suggest that green manure can contribute to the sustainability of tropical agricultural systems in which rice is a major crop.

Four working groups identified potentials for green manure, outlined the research needed, and suggested a mechanism for coordinating the research work done by national and international institutions.

Environmental opportunities for increasing use of green manure

In general, opportunities for increasing the use of green manure in different environments should be identified before assessing its relative advantages and disadvantages and before evaluating green manure species. Green manure may well have some distinct advantages in some climates, on some soils, in some socio-economic situations.

Some environmental factors are related to the advantages and disadvantages of green manure use:

In certain climates, green manure could have distinct physicochemical advantages; in other climates, it could face major constraints. In cool climates, low temperature can hinder organic decomposition, which could allow toxicities to build up. In warm, tropical climates, temperature enhances decomposition. Water availability and patterns also are factors in green manure use. Rainfed ricefields may be flood-prone, or suffer drought. Irrigated ricefields have the aerobic/anaerobic cycle to manage. Water availability interacts with temperature in the green manure incorporation-decomposition cycle.

Soil productivity and its sustainability also are important factors. In addition to providing nutrients to rice and other crops, green manure enhances some soil factors. It can be important with low fertility soils; in saline, alkaline, and acid soils; for soils with poor physical properties; and where erosion is or can be a problem.

Socioeconomic considerations appear to be important factors in evaluating organic fertilizer schemes. At a national level, unfavorable balance of payments may

prevent importation of inorganic fertilizers, or the fertilizer-rice price ratio may be unfavorable. Labor availability and costs are important. In areas where subsistence farming means little cash income to farmers, green manure crops may offer opportunities. At the societal level, the enhanced soil biological activity with green manure may alleviate environmental pollution through the detoxification of agrochemical residues.

Advantages and disadvantages of green manure use

Advantages

1. Potentially, green manure species are N sources with relatively high efficiency.
2. Green manure can improve soil properties, as well as conserve and recycle nutrients.
3. Incorporation of organic material increases biological activity in the soil.
4. Organic material and crops help reduce soil erosion.
5. Cropping in normally fallow land can help control pests and weeds.
6. Green manure crops require low cash or purchased inputs.
7. Many green manure species have additional uses, such as food, feed, and fuel.

Disadvantages

1. A green manure crop can compete for time, labor, land, and water; those costs must be balanced against the cost of inorganic fertilizer.
2. Seed of certain green manure species can be costly and scarce.
3. Incorporation of a green manure crop can be costly and difficult.
4. A green manure species may attract pests and diseases that have an adverse effect on a green manure or a rice crop.
5. An intercropped green manure may compete for space, water, and nutrients with the main crop.
6. Control of the quantity and timing of nutrients is more complex than with inorganic fertilizer; currently it is unpredictable.

Characteristics desirable in legume green manure crops

1. Multipurpose
2. Short duration, fast growing, high nutrient accumulation ability
3. Tolerance for shade, flood, drought, and adverse temperatures
4. Wide ecological adaptability
5. Efficiency in use of water
6. Early onset of biological nitrogen fixation
7. High N accumulation rates
8. Timely release of nutrients
9. Photoperiod insensitivity
10. High seed production
11. High seed viability
12. Ease in incorporation
13. Ability to cross-inoculate or responsive to inoculation
14. Pest and disease resistant
15. High N sink in underground plant parts

Research needed

A short-term research strategy should be implemented to identify a limited number of green manure species that show promise. It should include the following steps:

1. Define the target environment in terms of soil, cropping patterns, and climate.
2. Select candidate legumes.
3. Screen in progression for N accumulation patterns: in the laboratory, in the greenhouse, in the experimental field.
4. Test selected species within local cropping patterns in farmers' fields.

Long-term research needs include identifying representative environments and studying the following factors, using standardized research techniques:

1. Long-term effects of green manure on soil productivity.
2. Long-term economic advantages, including sustainability factors.
3. Potential of legumes, with special reference to stem-nodulating legumes and their tolerance for flooding.
4. Legume-rhizobia symbiosis, including the development of simple inoculation methods.
5. Influence of green manure on nitrogen leaching, denitrification, etc.
6. Kinetics of N release by a green manure crop after incorporation in different soils.
7. Effects of nutrients in addition to N in different soils.
8. Relationship between management practices and green manure mineralization rates, relative to rice crop N demands.
9. Nitrogen fixation of different green manure species and N availability to rice.
10. Incorporation techniques and equipment, relative to costs in time, energy, and efficiency.
11. Role of mycorrhiza inoculation in the phosphorus nutrition of green manure crops.
12. Ecophysical characteristics of green manure species (temperature, photoperiod responses).

Discussion leader: J. C. G. Ottow
Rapporteur: J. K. Ladha

Selecting and improving green manure crops

A major deficiency hampering the exchange of information among researchers is inconsistent taxonomic descriptions of green manure plant species. Diverse genera apparently have potential for green manure and associated uses, but experimental materials are poorly characterized; this introduces uncertainty into assessing the data reported. We recommend that consultants be sought to affirm and catalog the poorly defined and identified species and accessions used by international, regional, and national centers for green manure and related purposes in rice-based cropping systems. A primary objective would be to link the catalogs of institutes already engaged in collecting, classifying, and distributing forage, food legume, and woody species with catalogs of institutes that may hold accessions with potential value as green manure.

Given the current state of knowledge and the limited resources available for research, efforts should be directed toward developing technology that is applicable across broad environments. The relevance of much of current knowledge — beyond site, farming system, and species or accession — is unknown. A series of coordinated network trials for broadly defined ecological situations is proposed: a) species elimination trials, b) variety evaluation trials, and c) management trials.

Species elimination trials (SET) would identify species and accessions that perform unacceptably in the target environments; they would be excluded from variety and management trials. Variety evaluation trials and management trials would apply increasing intensities of measurement and performance documentation, including measuring nitrogen fixation, that would enable results to be extrapolated to other locations. Development of a uniform nomenclature for management systems would lead to more efficient and effective data-sharing and information transfer.

Four species groups and five target environments represent broad challenges. The species groups are fodder, food, woody, and leguminous herbs. The environments of rice-based cropping systems are lowland irrigated (LL-I); lowland rainfed, abrupt wet season-dry season transition (LL-RF); lowland rainfed, gradual wet season-dry season transition (LL-R); upland dry season (UL-DS); and upland alley crop perennials (UL-Alley).

Species groups x environment testing should follow this pattern:

	Species group			
Environment	Fodder	Food	Aes/Ses	Woody
LL-I	+ (DS)	+	+	
LL-RF	+ (DS)		+	
LL-R	+ (DS)	+	+	
UL-DS	+	+		+
UL-Alley	+	+		+

Examples of genera in the species groups are

Fodder — *Centrosema, Desmodium, Lablab, Macroptilium, Stylosanthes, Indigofera*

Food — cowpea, soybean, mungbean, pigeonpea, peanut

Aes/Ses — Leguminous herbs that tolerate flooding and that normally bear stem nodules — *Aeschynomene afraspera, A. indica, A. nilotica; Sesbania bispinosa (aculeata, cannabina), S. rostrata, S. sesban*

Woody–Multipurpose trees and shrubs of the genera *Acacia, Aeschynomene, Cajanus, Calliandra, Codariocalyx, Flemingia, Gliricidia, Leucaena, Sesbania, Tephrosia.*

Applications of genetic engineering and biotechnology that can contribute directly to the productivity or adaptation of genetic populations should be encouraged. However, such research should not encroach on resources needed to evaluate the variability currently available.

Discussion leader: D. E. Byth

Rapporteur: R. A. Morris

Integrated use of legumes

Because of economic and labor constraints, it is more likely that legume germplasm that has prospects for multiple use (e.g., grain, fodder, fuel, and residues that can contribute to soil N and general physical and chemical soil fertility) will be more acceptable to farmers.

If they are to be of practical use, multipurpose legumes must be carefully integrated into farming systems. New species and a broader range of cultivars conceivably will open new possibilities for meeting farmers' needs for more cash income, more uniform availability of animal feed, enhanced soil productivity, and greater production sustainability.

Proposed research areas

- *Lowland rice-based cropping systems*
  1. Grain legumes that can be established before, during, or immediately following the rice crop. The principal characteristic of the germplasm should be short duration, so that it can mature before the main rice crop, between rice crops, or on a drying front. Evaluation should consider both grain and short- and long-term green manure value.
  2. Ways to reduce the cost and increase the reliability of establishing grain legume crops.
  3. Multipurpose trees and short-season legumes that can be grown on bunds or waste areas. Legumes that provide both forage and leaf green manure or fuel should be selected. Their genetic lease should be broad to minimize the risk of disease and insect buildup.
- *Upland rice-based cropping systems* (including shifting cultivation)
  1. Grain legumes that can tolerate the adverse soil conditions (low fertility, low moisture-holding capcity) often found in these areas. These crops should have a duration that allows them to be either interplanted with rice (long duration) or grown as a catch-crop following the primary rice crop (short duration).
  2. Perennial legumes, including trees and shrub species, that can be used for soil conservation, fodder, or fuel and as leafy green manure. It should be possible to grow these species without amelioration of adverse soil conditions. Shifting cultivation areas require special attention to shorten the fallow period.

  The studies should cover these areas:
- *Crop management research.* The utility of new genetic materials, especially under adverse soil and water conditions, should be optimized. They need to be carefully integrated into production systems that fulfill the food, feed, and fuel needs of farms. While much of this work will be environment-specific, in several major systems, such as in single-crop lowland rice, planting legume crops to use the residual moisture after rice can have widespread utility. Considerable extrapolation will be possible if research sites are carefully selected and described.
- *Pest and disease management research.* In the foreseeable future, legumes grown in rice-based systems must rely on genetic and biological pest and disease control processes. It is not feasible to use high levels of inputs. Neither is it likely that resources will be available for the large-scale effort needed to breed for plant

resistance in all the species and cultivars involved. Species and genotypes that have high inherent capacity to tolerate or resist pests and disease should be selected. Work should include many species and cultivars, to maintain high genetic diversity across farm, countries, and regions. A small number of the key pests of grain legumes (e.g., pod borers) need to be identified for targeting concerted biocontrol programs.

- *Impact research.* Current quantitative data on the wide range of impacts multipurpose legumes have in rice-based systems are sparse. It is essential to study the major types of systems to quantify effects on the soil, associated crops in the system, and other farm components. Experiments on representative sites should be coordinated with similar work in national programs. These experiments should last at least 5 yr to measure residual and cumulative effects. Environments should be precisely described. State-of-the-art agronomic technologies and accepted analytical techniques, in conjunction with simulation modeling, should be used to maximize extrapolation of results. Economic and social costs and benefits should also be assessed. Wide-scale socioeconomic evaluation of systems as they move in farmers' fields testing is the culminating step.

Discussion leader: R. R. Harwood
Rapporteur: S. Nagarajah

Increasing use of green manures in rice-based farming systems

A major concern of this symposium was to identify ways to increase and sustain the productivity of rice-based farming systems. The research question is: given current knowledge, in what rice environments can that goal be achieved, and by what means? If higher, sustained yields are unlikely to be achieved in a cost-effective manner using inorganic fertilizers alone, a research agenda that includes organic nutrient sources (green manure, fodder, enriched fallows, etc.) is justified.

Current knowledge suggests that a combination of organic and inorganic nutrient sources is a necessary part of any management strategy to sustain riceland productivity, particularly in areas with poor resources. This working group concentrated on three issues:

- What are the factors responsible for the decline in green manure use? Are the factors different in different rice environments?
- What are the current opportunities to expand green manure use in different rice environments?
- What applied research is needed to expand green manure use in areas where the technology is viable?

Factors responsible for the decline in green manure use

The factors responsible for low and declining green manure use vary by situation. Major considerations follow:

- Low cost of inorganic N fertilizers relative to the cost of green manuring.
- Increased availability of inorganic fertilizers to farmers in most countries, and the relative ease in handling inorganic fertilizers.

- More profitable alternate uses for land.
- Low seed viability and high seed costs.
- Difficulties in incorporating green manure biomass.
- Labor shortages at incorporation time.
- Very low emphasis on organic manure by research and extension.
- Often substantial green manure crop establishment costs.

Current opportunities

Available data indicate that the soil fertility maintenance necessary for sustainable rice production is enhanced by a judicious combination of green manure and inorganic fertilizers. This approach is more critical in areas where landholdings are small, the resource base is weak, production and productivity have reached a plateau, and soil nutrient deficiencies or imbalances have emerged. A sizable area in South, Southeast, and East Asia qualifies.

If green manure is to become popular in those areas, it is essential that it be fitted into local cropping patterns without competing with other economic enterprises. The technology will be viable only if unit costs of green manure production, including capital and labor, are low. It is essential to maintain production stability and to minimize risk of green manure crop loss.

Implications for applied research

A grain legume or green manure crop might be grown in the time gaps of current crop sequences. To consider opportunities for expanded green manure use, rice-based farming systems can be divided into three major types: irrigated lowland, rainfed lowland, and upland. Each type has broadly typical crop sequences. Although they vary in detail from country to country, some principles can be identified to help determine the potential for green manure expansion.

Irrigated lowland. The dominant crop sequences are

1. Rice - rice
2. Rice - wheat
3. Rice - rice - upland crop
4. Rice - upland crop

Most irrigated areas produce two cereal crops a year, with a time gap before the wet season crop (sequences 1 and 2). In many years, a short-duration grain legume crop has a strong potential during this period (e.g., mungbean, black gram). Where the gap is very short, or where early season waterlogging occurs, a water-tolerant green manure (e.g., sesbania) would fit between the main crops.

In areas where an upland crop is already grown during the time gap (sequences 3 and 4), intercropping or mix-cropping a green manure or dual-purpose grain legume (e.g., *Indigofera* and *Cajanus*) has the potential to increase biomass and forage production.

Rainfed lowland. Most bunded rainfed ricelands produce a single crop of transplanted rice a year, with a limited proportion planted to an upland crop preceding or following rice:

I. Rice - fallow (finer-textured soils)
2. Rice - upland crop (loamy-textured soils)

The potential for cultivating grain legume crops during the fallow needs to be explored. Where waterlogging obviates grain legume production, a prerice green manure may be feasible. Because very little green manure is currently grown in these areas, work is needed to define the most likely rainfed niches.

Where upland crops are now grown on residual moisture after rice (sequence 2), intercropping a green manure crop or a dual-purpose grain or forage legume with the upland crop has potential. Very little research has explored this possibility.

Uplaland. Most rice-based cropping systems in upland areas are dominated by cereal crop rotations, particularly of rice and maize.

Rice - maize

Rice - fallow

There is potential to enhance sustainability in these systems by cultivating green legumes in the sequence; however, local market demand for legumes is often limited. Green manure legumes intercropped or sequentially cropped with rice could be grown through the dry season for fodder or for incorporation the following wet season. Much more research is needed.

Alley cropping systems on sloping uplands are promising for soil stabilization and green manure crop production. Very little research has been done on these systems in Asia, and little data are available on the effects of green leaf manuring.

In areas where crop rotations include a fallow of one or more years, multipurpose uses of legumes—to regenerate soil fertility, provide high quality forage, and reduce labor costs of initiating the following cultivation cycle—need study.

Green manure crops should be seriously examined in countries where inorganic fertilizers are not likely to be available in sufficient quantities in the foreseeable future and where fertilizer-rice price ratios are relatively high.

Additional research needs

1. Survey the green manure species available for different cropping patterns (through international networks, particularly the Asian Rice Farming Systems Network).
2. Classify green manure species into use categories (e.g., grain green manure-nongrain green manure, including forage green manure and leafy green manure).
3. Determine optimum methods for establishing green manure crops at the absolute minimum cost for land preparation (e.g., zero tillage planting, intercropping with a cash crop).
4. Classify the range of potential green manure production environments.
5. Collect and test types of incorporation equipment currently used by farmers; examine their utility in different environments (e.g., the Philippine slicer, the Burmese trampler).
6. Investigate methods to produce and store green manure seed at the farm level; develop national seed programs to protect quantity and quality of seed (e.g., China subsidizes seed producers); determine effective scarification practices to increase field germination.

7. Identify cultivars that are genetically resistant to or tolerant of pests and diseases.
8. Use cellulolytic microbial cultures to accelerate decomposition of green manure.
9. Maintain legume-rhizobia1 germplasm and identify legume species-specific rhizobia for acid, saline, and alkali soils.
10. Identify fast-growing, high leaf-yielding tree species for different agroclimatic environments; study the cropping behavior of tree legumes.
11. Document labor requirements and costs in green manure production; define labor limitations for different areas.
12. Continuously monitor the economics of green manure production in different areas.
13. Provide a linkage from research to extension programs in areas identified as having potential to economically benefit from green manure use; conduct on-farm cropping pattern trials; involve the community social organization in controlling such factors as indiscriminant livestock grazing; forestry programs could popularize green leaf manure-yielding tree species.

Discussion leader: A. Venkataraman
Rapporteur: D. P. Garrity

Conclusion

Participants recognized that coordination of research on the many aspects of green manure that require attention is necessary. Their consensus was that IRRI should be charged with coordinating research being done at collaborating institutes and by collaborating scientists possessing the necessary interest and expertise.

Coordinating the development of a pooled database would allow computer modeling work to be applied to research planning and extrapolation.

IRRI should also continue its own research on green manure species and on green manure use in rice-based farming systems. The focus should be on enhancing understanding of the processes involved—a prerequisite to improving green manure management.

In partnership with institutes that complement IRRI's and each other's expertise, IRRI should seek funding to support green manure germplasm collection and to finance coordination of the research activities outlined.

Coordination responsibilities should include serving as an information clearinghouse. A newsletter containing information of general interest to collaborators, results of management experiments, and highlights of species elimination and variety trials is recommended.

Economic feasibility of green manure in rice-based cropping systems

M. W. Rosegrant and J. A. Roumasset

Analysis of the economic feasibility of azolla employs an azolla growth model linked to a rice paddy water balance model, which permits determination of the expected nitrogen contribution for different qualities of irrigation. The production costs of azolla are estimated from a detailed breakdown of the inputs used in the azolla nursery bed, multiplication bed, and ricefield. The expected nitrogen contribution and production costs together determine the costs per unit of nitrogen supplied by azolla. The results indicate that in most environments, azolla is not a cost-effective substitute for urea fertilizer. High labor costs, high opportunity costs of land, and poor water control are major constraints to the economic feasibility of green manure. Given the current stage of azolla technology and its relatively poor economic feasibility, policy support for widespread investment in technology dissemination is not appropriate. Instead, strong support should be given a research program designed to overcome the constraints to economic feasibility. Improvements in azolla technology that increase nitrogen yield and pest resistance or reduce the opportunity costs of labor and land could make azolla economically feasible in a greater number of environments

Increased use of fertilizer, with development and dissemination of improved varieties and expanded and improved irrigation, has been a key factor in the growth of rice production in Asia and elsewhere. Table 1 shows fertilizer use level and growth rate since 1950 for the major rice-producing countries of Asia. The increase in fertilizer use has been remarkable by any standard. Between the first and second halves of the 1970s, average fertilizer consumption grew by 50% in South Asia, 39% in Southeast Asia, and 53% in East Asia.

The impact of this increase in fertilizer use on rice production has been large. Herdt and Capule (1983) estimated that fertilizer use growth contributed to just under 25% of total production growth in Asia during 1965-80. The other major contributors—modern varieties, irrigation, and factors such as land area, labor, and complementarities among production inputs—each contributed to about a fourth of total rice production growth (Barker and Herdt 1985).

Table 1. Consumption of fertilizer nutrients[a] in Asia (Barker and Herdt 1985).

Country	Consumption (thousand t)				Annual growth rate (%)
	1950/51-1954/55	1960/61-1964/65	1970/71-1974/75	1975/76-1979/80	1960/61 - 1964/65 to 1975/76 - 1979/80
South Asia	125.1	631.4	3,421.7	5,170.8	15.0
India	85.1	469.5	2,707.0	3,974.7	15.3
Pakistan	6.1	60.8	440.0	753.7	18.3
Sri Lanka	31.8	67.4	93.3	113.3	3.5
Bangladesh	2.1	33.2	170.3	312.3	16.1
Nepal	–	0.5	11.1	16.8	26.4
Southeast Asia	66.1	405.8	1,359.7	1,894.0	10.8
Malaysia	5.3[b]	44.4	210.3	334.0	14.4
Thailand	3.2	24.2	163.9	260.5	17.2
Philippines	36.7	89.7	234.5	275.7	7.8
Indonesia	20.4	110.6	426.3	643.2	12.5
Burma	0.5	6.2	46.6	69.3	17.5
Vietnam	–	130.6	277.9	311.2	6.0
Laos	–	0.1	0.2	0.1	0
East Asia	1,308.1	3,334.4	8,543.1	13,063.7	9.5
Japan	1,013.8	1,788.1	2,045.6	2,124.5	1.2
Taiwan	106.8	186.2	300.8	385.2	5.0
North Korea	-	149.2	359.3	622.1	10.0
South Korea	100.5	323.9	743.3	793.4	6.2
China	87.0[c]	887.0	5,094.1	9,138.5	16.8

[a] $N + P_2O_5 + K_2O$. [b] 1952/53 to 1954/55. [c] 1953/54 to 1954/55.

The rapid growth in fertilizer use has been due almost entirely to increased use of chemical fertilizers. Organic fertilizers (green manure crops, animal manure, and compost), traditionally important sources of nutrients, declined in relative importance with the rapid increase in use of chemical fertilizers.

Although data on use of organic fertilizers is scarce, there is at least some evidence that their use has declined in absolute, as well as in relative, terms. In Taiwan, for example, application of farm-produced organic manure and crop residues declined from a high of 17.3 million metric tons in 1962 to 7.1 million metric tons in 1981. The area planted to green manure crops dropped from an average of 200,000 ha in 1948-53 to just 18,000 ha in 1981 (Repetto 1986). In dramatic contrast, chemical fertilizer consumption increased 500% between 1951 and 1981.

Despite (or because of) these trends, interest in the potential for expanded use of green manure has been renewed. The oil price shocks and resulting sharp increases in fertilizer prices in the 1970s raised concerns over the stability of world chemical fertilizer prices, and over the implications of those prices and of heavy imports of chemical fertilizers for balance of payments problems.

Concern also has been rising over possible long-term adverse effects of heavy use of chemical fertilizer on soil structure, crop productivity, and off-farm pollution. Green manure and other organic fertilizers can maintain and improve soil structure. In sandy soils, increased organic matter improves water retention and reduces the

leaching of nutrients. In clay soils, added organic matter can improve soil porosity, reducing water runoff and erosion losses. Organic matter can protect the soil against increases in acidity and alkalinity and can provide a number of micronutrients not available from chemical fertilizers (Repetto 1986). Exclusive reliance on chemical fertilizer precludes those benefits, and may lead to long-term deterioration of soil quality.

Increased use of chemical fertilizers may also incur long-term environmental costs. In areas where chemical fertilizers are heavily used, drainage runoff contributes to eutrophication of rivers and lakes. The extent of this problem in less developed countries has not been carefully analyzed.

Reliance on chemical fertilizer also may tilt income distribution even further toward commercial farmers with large hectarages. Those farmers typically have greater cash flow and better access to credit for purchasing cash inputs.

Green manure and other organic fertilizers have a number of apparent agronomic and environmental advantages. However, the economic feasibility of widespread adoption of green manure in rice-based cropping systems is less clear. There has been relatively little analysis of the economics of green manuring. In this paper, we discuss the key concepts, issues, and methods of determining the economic feasibility of green manure; employ these concepts in a case study of the economics of azolla as a green manure in Philippine rice production; and draw a number of general conclusions regarding the economic feasibility of green manuring in rice-based farming systems.

Farmer decisionmaking and economic policy analysis

We assume, as was argued persuasively by Schultz (1964), that even poor farmers are rational decisionmakers. In economics, rationality is taken to mean that the decisionmaker acts as if he knows the consequences of alternative actions and has consistent preferences regarding those consequences. Even if a farmer recognizes uncertainty, we still assume that he knows the range of consequences of each act and has degrees of belief concerning the likelihood of alternative consequences.

Farmer preferences are typically represented by a utility function or simply by income. The farmer's problem is represented as maximizing utility, subject to resource constraints, or maximizing profits.

The simplest, most widely used model of farmer behavior is expected profit maximization. A general production function can be represented as

$$Y = f(T_i, Z_i, V_i)$$

where Y is yield per hectare; T_i is a vector of inputs (e.g., fertilizer, labor, pesticides); Z_i is a vector of fixed factors and environmental inputs (e.g., soil texture); and V_i are stochastic or random environmental variables (e.g., rainfall, solar radiation, typhoon occurrence).

In the expected profit maximization model, farmers select a vector of inputs, T_i, that will maximize the difference between price of output × yield (i.e., the value of output) and cost as a function of inputs, $C(T_i)$. When farmers are postulated to know

the production relationship, the behavioral model specifies that they will choose inputs in such a way as to maximize expected profits $p = Pf(T_i, Z_i, V_i^*) - C(T_i)$, where V_i^* is the expected value of the stochastic environmental variables.

A broader interpretation of economic rationality is that farmers act as if they were maximizing the expected value of some utility function. Farmers are assumed to act in accordance with preferences ordered over alternative bundles of family consumption. In the utility maximization model, utility is derived from income, but there is not necessarily a direct linear relationship between utility and production income. In most cases, the postulation is that as income increases, utility increases, but at a decreasing rate. If the farmer already has a high income, an additional unit of income will generate less additional utility than if the farmer initially had a low income.

The utility maximization approach allows for differences in preferences toward leisure, risk, and present vs future consumption. The primary difficulty with the utility model lies in specifying for different farmers the exact nature of preferences.

A more pragmatic approach to explaining farmer behavior is to base a decision model on accounting or economic profits. Accounting profits differ from nominal or financial profits in that market prices of outputs and inputs are replaced by opportunity costs to the individual farmer. Opportunity cost can be defined as the value that a resource has in its best alternative use. These private marginal benefits and costs of outputs and inputs are called shadow prices.

A key application of the concept of opportunity cost is in valuing the family labor used in production. The time spent by a farmer and his family in production activities on the farm has an opportunity cost, even if an actual wage is not paid. The time could be spent on other production activities on the farm, in working for other farmers, in performing nonagricultural labor, or even in enjoying leisure. Because of these opportunity costs, farmer labor (and other owned resources) have value; they cannot be assumed to be free.

When family labor is used to produce and apply green manure, the opportunity cost will usually be the market wage of labor. Because these activities are performed during the peak labor season, family labor could be employable off the farm at the full labor wage rate.

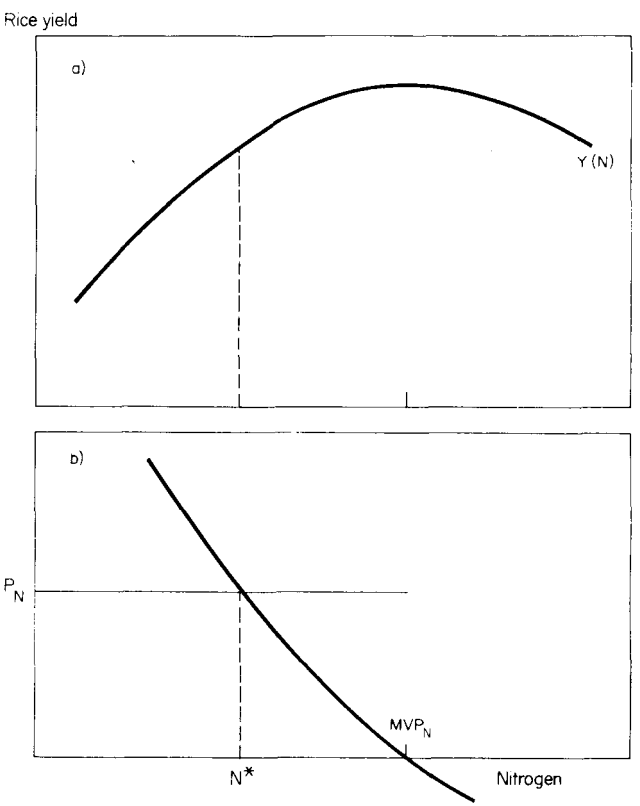
If a farm family consumes its own harvest, then shadow prices must be substituted for market prices of the output. If a farmer is sure of selling part of his harvest, then the relevant shadow price is simply the selling price. Similarly, if he is sure of buying the commodity in question to supplement home production, then the relevant shadow price is the market buying price. In all other situations, the shadow price lies somewhere between market buying and selling prices.

A similar approach can be used for other input markets, including fertilizer, land, and credit. In each case, it is the value of an additional unit of the resource to the farm household enterprise that is relevant. Because borrowing rates are different from lending rates, a household's debt or savings position becomes relevant in determining the shadow price of credit.

For chemical fertilizer, the shadow price to the farmer is the price he pays in the local market (which already includes a margin for costs) plus any additional costs he may face in getting the fertilizer to his farm.

The shadow price of a particular parcel of land planted to one crop is the opportunity cost of not growing something else. Even if the farmer owns the land and does not explicitly pay any rent to himself, there is still an opportunity cost in using the land for one use and not another. That opportunity cost is another key concept in assessing the economic feasibility of green manure. Depending on the type of green manure technology and level of water control, green manuring may displace a second rice crop or a nonrice dry season crop, or delay the planting of rice or other crops, thus reducing yields and profits. These opportunity costs of land must be included when the economic feasibility of green manure is assessed.

The necessary conditions for profit maximization are that the marginal benefits of the last unit of each input (the marginal value product [MVP]) are equal to its shadow price or marginal opportunity cost. Figure 1 depicts a hypothetical solution. Panel a illustrates production (Y) as a function of nitrogenous fertilizer (N). The increase in yield for an increment of N is the slope of the function Y(N) and is called the marginal product of N. Panel b shows the MVP of N as the marginal product evaluated at the shadow price of the output. The profit-maximizing amount of



1. Yield response function of rice: nitrogen (a) and profit-maximizing nitrogen use level (b). P_N = price, marginal value product of nitrogen.

fertilizer (N*) satisfies the condition that the MVP equals the shadow price of fertilizer (P_N).

The analysis is complicated slightly by the recognition of uncertainty. In economic analysis of decisionmaking under uncertainty, explicit consideration of stochastic aspects of the environment (e.g., available moisture and solar radiation) is built in. As we have shown elsewhere, however (Roumasset 1976, 1979; Rosegrant and Roumasset 1985; Rosegrant and Herdt 1981), *ad hoc* incorporation of risk preferences into the farmer's utility function does little to explain farmer behavior and little or nothing to usefully influence policy decisionmaking. A more productive approach is to take into account the ways and the likelihoods that a particular production technique can go wrong and the explicit consequences to the farmer of such unfavorable outcomes. The personal shadow price approach provides an operational vehicle for such analysis.

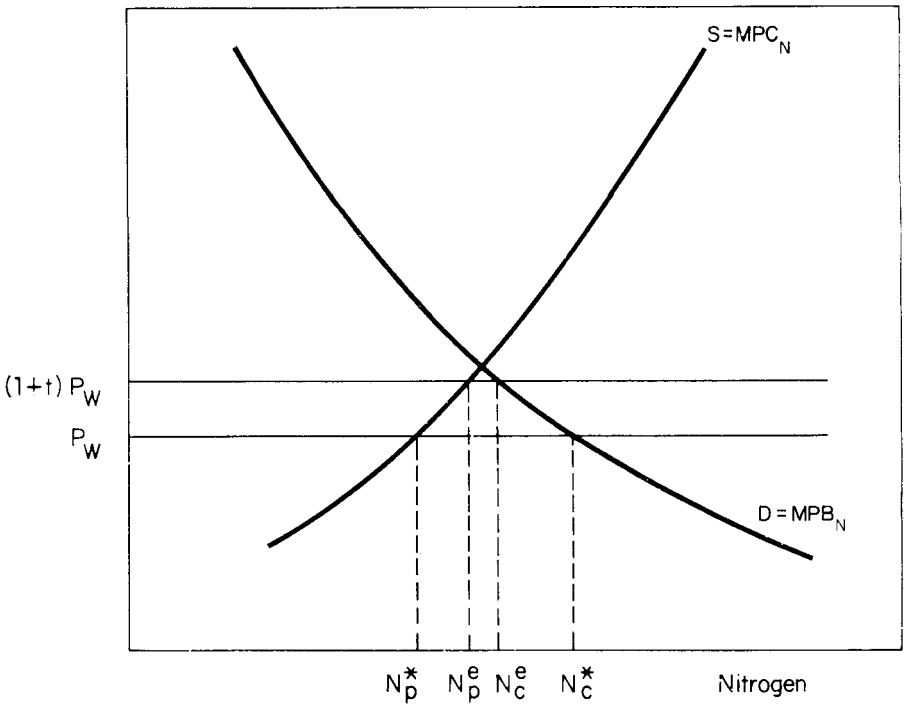
Economic policy analysis

From the point of view of society, economic policy analysis is also based on the principle of equalizing marginal benefits and marginal costs. In this case, costs and benefits are calculated relative to the entire economic society. There are several reasons why marginal social benefits and costs differ from marginal private benefits and costs. For example, if labor and credit markets are distorted, then the private cost to a farmer of credit and labor inputs may differ from the societal opportunity cost.

Fertilizer pricing policies provide a good example of how governments intervene to drive wedges between farmer shadow prices and societal shadow prices. If a country is a net importer of fertilizer, the societal shadow price is the import price of fertilizer plus internal distribution costs. The import price is the shadow price because it represents the opportunity cost to the society of purchasing fertilizer. If the country is a net exporter of fertilizer, the societal shadow price of fertilizer is the cost of efficient domestic production and distribution.

In the absence of externalities, if free import of fertilizer is permitted and if fertilizer is distributed to farmers through an undistorted marketing and delivery system, farmer and societal shadow costs will be equal. However, many countries have introduced differences between societal and private shadow prices through fertilizer subsidies to encourage its use. A country may use tariffs or nontariff barriers, such as import bans or quotas, to discourage use.

Many countries protect their domestic fertilizer industries by restricting fertilizer imports. Figure 2 illustrates how, if tariffs protect domestic fertilizer production, private supply and demand can lead to a socially inefficient solution. In the absence of trade restrictions or subsidies, the domestic fertilizer industry produces at N_P* and farmers consume N_2* fertilizer units. requiring that an amount N_C* - N_P* be imported. An *ad valorem* tariff of t percent increases the domestic price from P_W to $(1 + t)P_W$. Consequently, farmers consume less fertilizer and receive lower net benefits from fertilization. Production also will decline, causing higher commodity prices to consumers or increasing commodity imports.



2. Production, consumption, and imports of nitrogen, with and without import tariffs. P_w = price, marginal production cost, and marginal private benefit of nitrogen.

The distorted equilibrium with tariff occurs at N_c^e and N_p^e, where fertilizer demand (D) or the marginal private benefit (MPB_N) curve and supply ($S = MPC_N$) intercept the price line $(1+t)P_w$.

A second major source of differences between private and societal benefits and costs are external economies or diseconomies arising from the production process. External economies occur when producers confer benefits on other members of society, but are unable to obtain payment for those benefits. External diseconomies occur when farmers impose costs on other members of society without having to fully pay for the production costs. Under those circumstances, the pursuit of private gain does not promote social welfare.

A good example of an external diseconomy occurs with the use of chemical fertilizer. Heavy use of chemical fertilizer may induce drainage runoff, which imparts negative externalities to other farmers and consumers through pollution of rivers and lakes.

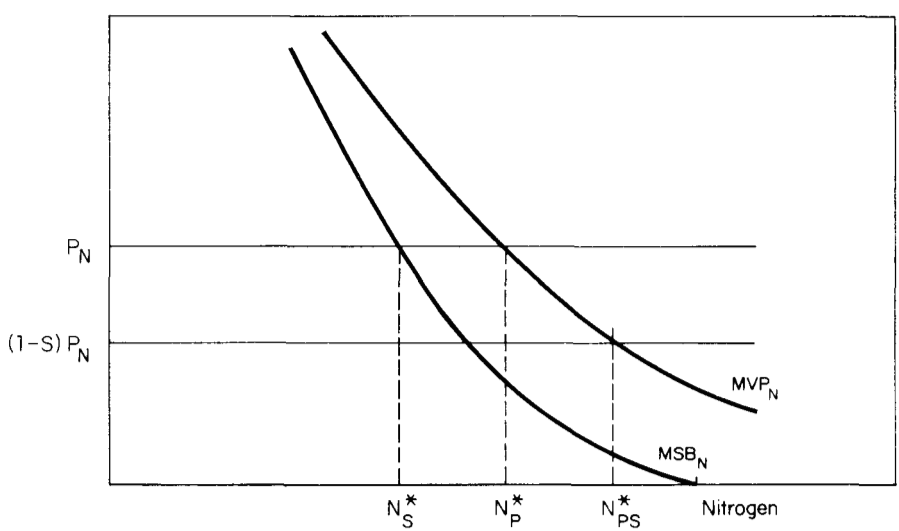
There is an external economy to using organic fertilizers such as green manure because of their long-term positive impact on soil structure and productivity. (This can also be interpreted as an additional diseconomy of chemical fertilizer use.) This external economy is not a pure externality, because part of the benefits of organic fertilizer use (or costs of chemical fertilizer use) accrues to the farmer. However,

because of the long-term nature of those benefits, use of chemical fertilizer instead of organic fertilizer represents a partial trade-off of future benefits for present gain. This trade-off will not be reflected in the private shadow prices of chemical fertilizer.

Figure 3 illustrates the divergence between privately and socially optimum chemical fertilizer use in the presence of external diseconomies arising from chemical fertilizer use. The private MVP of chemical nitrogen (MVP_N) is greater than the marginal social benefits (MSB_N) because the social costs of the pollution externalities, which are not borne by the farmer, must be deducted from MVP_N to arrive at MSB_N. Given the shadow price of fertilizer (P_N), the social-optimum nitrogen use (N_S*) is lower than the private optimum (N_P*) chosen by the farmer. If a government subsidy (S) is provided to support fertilizer use, the private shadow price is reduced to $(1\text{-}S)P_N$ and the private optimum with subsidy (N^*_{PS}) diverges further from the social optimum.

This discussion should not be interpreted as supporting immediate removal of all fertilizer subsidies or implementation of tariffs on chemical fertilizers in order to encourage use of green manure. Fertilizer pricing policies have been instituted to support the achievement of a number of broad-based objectives, including income support for farmers, incentives to increase production. and attempts to balance other taxes against agriculture. In addition, the degree of external costs or diseconomies due to chemical fertilizer use on rice are not known. Research to assess those costs would be very useful.

The discussion, however, highlights the relevance of using broad agricultural policy as well as farm-level cost and production systems to assess the economic feasibility of green manure. Economic policies determined for totally different objectives have a major impact on the feasibility of expanded use of green manure.



3. Private and social optimal nitrogen use with and without rice subsidies on nitrogen. P_N = price, marginal value product, and marginal social benefit of nitrogen.

Economic feasibility of using azolla for rice production in the Philippines

We used the concepts developed in the preceding section to assess the feasibility of using azolla for rice production in the Philippines (Rosegrant et al 1985). The Philippine Government has actively encouraged research on and extension of azolla as a green manure intercrop with rice.

Azolla is an aquatic fern that lives symbiotically with nitrogen-fixing blue-green algae *Anabaena azollae.* It has been used as a source of organic N for rice under flooded conditions in Vietnam. In China and Vietnam, azolla is grown as a green manure or as an intercrop with rice. As a green manure, azolla is grown and incorporated in the soil before rice is transplanted. As an intercrop, it is inoculated after rice transplanting and incorporated after 28 d. In either case, the azolla is first multiplied in a small plot or pond before it is seeded in the ricefield. Normally, 1.5-2.5 t azolla/ ha is required for inoculum or seeding. To produce enough azolla, nursery or multiplication beds usually are starting points.

Relatively few studies of the growth of azolla in the open field or intercropped with rice are available, and there is substantial variation in the recommended amounts of inoculum, reported biomass growth rates, maximum attainable biomass, growth period required to attain maximum biomass, and amount of N fixed per unit of biomass. (Lowendorf [1982] summarizes much of the available information; see also Lumpkin and Pluchknett 1981, 1982; Watanabe et al 1981; Becking 1979.)

The available evidence indicates that the growth process of azolla can be modeled using a logistic curve. The curve is given by

$$A_t = A_m/[1 + e^{-(a+bt)}]$$

where A_t is biomass/ha at time t, A_m is asymptotic maximum attainable biomass ha, and a and b are parameters defining the initial stock of inoculum ha and growth rate. Synthesizing from the available literature and using relatively optimistic assumptions, it is assumed that, for intercropping, the field is seeded with 1.5 t inoculum/ ha and that, under conditions of full water adequacy, the asymptotic maximum biomass is 20 t/ha.

With these parameters, 95% of maximum biomass is achieved in 28 d, which is assumed to be the harvest point, when the field is drained and the azolla incorporated. For use as green manure, higher initial inoculum can be used, with a larger maximum attainable biomass because of lack of competition with rice plants. It is assumed that seeding for green manure is 2.25 t inoculum/ha, with asymptotic maximum biomass of 40 t/ha. Finally, it is assumed that azolla fixes 2 kg N/t biomass. The potential N contribution is 40 kg/ha from intercropping and 80 kg/ha from green manure. Efficiency of N uptake from azolla is comparable to that with inorganic N (Watanabe et al 1981).

Ample water is critical to azolla growth; the recommended water depth is 40-50 mm throughout the growth period. Growth is retarded as water depth

approaches zero, and azolla ordinarily will die if the field is fully drained for 1 to 2 d (Lumpkin and Plucknett 1982).

Water availability conditions in farmers' fields in the Philippines vary widely. To account for the impact of water availability on azolla growth, using the logistic curve model, it is assumed that maximum attainable biomass is depressed by a linear function of water depth when the depth falls below 20 mm and that azolla dies if the field is drained for 2 d. This model of the azolla growth process, together with a water balance model that simulates water depth in the ricefield, permits us to estimate the expected N contribution from azolla under different water regimes.

Costs of azolla production

Estimates of the production costs of azolla as green manure and as an intercrop to provide the biomass assumed in the azolla growth model are shown in Table 2. The chemical inputs required are P and insecticide. P is essential to achieve the biomass growth rates assumed here (Watanabe et al 1980). Recommended rates of P application in the ricefield range from 4 kg/ha to 15 kg/ha; a rate of 8 kg/ha is assumed here (Kikuchi et al 1984). P rates as high as 240 g have been recommended in the nursery and as high as 3.6 kg in multiplication beds (Bunoan 1981). More modest rates are assumed here.

Azolla can absorb as much as 20% of the applied P. P is released when azolla is incorporated into the soil, so this portion of the cost of P is deducted in computing net costs (Watanabe et al 1980, Lumpkin and Plucknett 1982).

Azolla is susceptible to insect attack. The appropriate amount of insecticide will vary considerably, depending on the severity of infestation. Recommendations for maintenance application of insecticides to protect against initial attack when azolla is in the ricefield range from 15 g active ingredient (ai)/ha to 4.0 kg ai carbofuran/ha (Kikuchi et al 1984). A value in the lower part of this range, 150 g ai/ ha, is used here.

Continuous (year-round) cropping of azolla for green manure does not appear feasible in the Philippines because of low humidity, high temperature, and high probability of pest infestation in the dry season (Lumpkin and Plucknett 1982, Watanabe et al 1981). Azolla as an intercrop entails no opportunity cost in terms of alternative land use forgone because the azolla nursery and multiplication beds can be grown simultaneously with the rice seedbed. However, when azolla is used as a green manure, rice transplanting will be delayed by a minimum of 1 mo/season to grow the azolla. Delays of this length eliminate the potential for a dry season nonrice crop after harvest of the wet season rice crop in rainfed or poorly irrigated areas or after the dry season irrigated crop in better irrigated areas. The opportunity cost of land because of the change in the cropping calendar so as to grow azolla for green manure may vary widely, depending on irrigation status and agroclimatic conditions.

In areas with good irrigation, the delays in planting will, in many cases, displace a second rice crop, imposing a considerably higher opportunity cost than is assumed here. Where no second or third crops are normally grown, the direct opportunity cost of land may be lower. In these areas, however, moisture is likely to be so limiting that the delays in planting could shift first season crop growth to a low-moisture and

Table 2. Estimated costs of azolla production in the Philippines (Rosegrant et al 1985).

	cost[a] ($)
A. Nursery bed (40 m^2)	
Azolla starter inoculum (8 kg, $0.05/kg)	0.45
Land preparation (0.25 man-animal day, MAD)	0.28
Superphosphate fertilizer (93 g P_2O_5)	0.03
Fertilizer application (0.25 man-day, MD)	0.14
Seeding and tapping azolla (0.25 MD)	0.14
Insecticide (20 g active ingredient [ai])	0.28
Subtotal	1.30
B. Multiplication bed (600 m^2)	
Land preparation (0.33 MAD)	0.37
Superphosphate fertilizer (1.3 kg P_2O_5)	0.42
Fertilizer application (0.33 MD)	0.18
Seeding and tapping azolla (0.5 MD)	0.28
Insecticide (30 g ai)	0.42
Subtotal	1.67
C. Azolla in ricefield (1 ha)	
1. As green manure	
Land preparation and rototilling (8 MAD)	8.94
Superphosphate fertilizer (8 kg P_2O_5)	2.49
Fertilizer application (1.5 MD)	0.84
Seeding and tapping azolla (2 MD)	1.12
Insecticide (150 g ai)	2.10
Opportunity cost of land[b]	30.73
Subtotal	46.20
2. As intercrop	
Seeding and tapping azolla (2 MD)	1.12
Superphosphate fertilizer (8 kg P_2O_5)	2.48
Fertilizer application (1.5 MD)	0.84
Insecticide (150 g ai)	2.10
Incorporating azolla in soil (5 MD)	2.79
Subtotal	9.33
Total cost per hectare[c]	
With azolla as green manure	49.20 (48.45)
With azolla as intercrop	12.30 (11.58)

[a]Converted at the rate of $1 = ₱17.90. [b]Farmer's profit forgone on use of land because of change in cropping pattern for azolla cultivation before rice transplanting. [c]Figures in parentheses are net costs of P fertilizer, assuming 20% recovery of P for rice production, released by azolla upon incorporation in the soil.

high-stress period. imposing a high opportunity cost from yield reductions. The estimate provided here is a medium estimate from the possible range of costs.

The opportunity cost of land for the use of azolla as green manure is estimated as the average net returns on dry season nonrice crops in Central Luzon (Special

Studies Division, Ministry of Agriculture, Philippines, 1980). To estimate the effective cost of N from azolla, its expected N contribution must be estimated.

Nitrogen contribution from azolla under different water regimes

To assess the N contribution from azolla as a green manure or intercrop with rice under different water regimes, we utilize the azolla growth model together with a rice paddy water balance model, which permits determination of the daily water depth and expected N contribution for different qualities of irrigation.

Water balance model. The stochastic water balance model simulates weekly irrigation flow, rainfall, crop and soil water use, and resulting water depth in the ricefield throughout the growing season (Rosegrant and Herdt 1981. Wickham et al 1978). Irrigation qualities are defined in terms of weekly probability distributions of irrigation flows, estimated from sample sites in Central Luzon and Laguna. Average quality irrigation is represented by a weekly mean flow of 79 mm and a standard deviation of 70 mm. Poor irrigation distribution has a weekly mean flow of 53 mm and a standard deviation of 42 mm; high quality probability distribution has a weekly mean flow of 119 mm and a standard deviation of 85 mm.

Weekly rainfall distributions were computed from rainfall data recorded at Cabanatuan, Nueva Ecija, 1949-74. Evapotranspiration (loss of water through plant transpiration and evaporation from the ricefield surface) was estimated from field data at 40 mm/wk in the dry season and 28 mm/wk in the wet season. Seepage and percolation (lateral and downward loss of water through dikes and soil) was set at 14 mm/wk in the wet season and 32 mm/wk in the dry season.

Integration of the azolla growth model with the water balance model permits the estimation of expected biomass and N contribution under any water regime. Draining water stored in the ricefield so as to incorporate azolla may increase the probability of moisture stress on rice from inadequate water later in the season. Using the water balance model to estimate stress with and without azolla indicates that drainage causes small increases in expected stress days (days without standing water in excess of three) for average and poor irrigation during the critical reproductive stage. Expected stress is unchanged for good irrigation. Substituting expected stress into production functions incorporating N and stress (Rosegrant and Herdt 1981) shows that, at optimal N levels, field drainage for azolla incorporation could reduce dry season yields by 2-4% for average-to-poor irrigation.

A number of seasons of rice + azolla intercrop and azolla as a green manure were simulated, with an estimate of the N contribution of azolla computed for each season. A stable estimate of the expected N production that results after 1,000 iterations of this simulation is shown in Table 3. N contribution across water regimes varies substantially in the dry season, with smaller differences in the wet season. Only good irrigation approaches the contribution attainable under full water adequacy. The estimated cost of N from azolla is computed by dividing the costs of azolla production (Table 2) by its expected N yield. The resulting costs of biological production of N for various moisture-stress regimes are presented in Table 3.

Table 3. Expected N contribution and effective cost of N from azolla as a green manure intercrop, by quality of irrigation[a] (Rosegrant et al 1985).

Quality of irrigation	Wet season				Dry season			
	Intercrop		Green manure		Intercrop		Green manure	
	Contribution (kg N/ha)	Cost ($/ha)	Contribution (kg N/ha)	Cost ($/ha)	Contribution (kg N/ha)	Cost ($/ha)	Contribution (kg N/ha)	Cost ($/ha)
Good	38	0.30	65	0.75	37	0.30	64	0.75
Average	33	0.35	57	0.85	27	0.43	46	1.05
Poor	32	0.35	55	0.88	10	1.14	17	2.85
Rainfed	29	0.40	50	0.97				

[a] For comparison, the costs of chemical fertilizer (including the costs of transportation, application, and credit) are $0.35/kg N as urea and $0.55/kg N as ammonium sulfate. Conversion rate: $1 = ₱17.90.

Economic feasibility of azolla in rice production

The Philippine Government's fertilizer policy has created a two-tiered price for N, depending on the source: urea or ammonium sulfate. Historically, this has resulted from a trade-off between the conflicting objectives of providing low fertilizer prices to farmers and protecting inefficient domestic fertilizer producers. The government, through the Fertilizer and Pesticide Authority (FPA), has provided tax exemptions and subsidies to domestic producers, while controlling imports and setting the price of fertilizer to farmers (David and Balisacan 1981, Te and Herdt 1982).

FPA price policy has tended to further protect domestic producers. While urea usually has been priced at about the world price, prices of other types of fertilizer have been set much higher. The resulting large wedge between the prices of N from urea and from ammonium sulfate has been maintained by limiting urea imports, implying a rationing of urea to farmers. This causes many farmers to use high-cost ammonium sulfate.

The domestic price of N from ammonium sulfate is almost 60% higher than that of N from urea. The retail market price in 1981 was $6.65/50 kg urea and $4.93/50 kg ammonium sulfate. Because urea is 45% N and ammonium sulfate 21% N, this implies an effective N price of $0.30/kg from urea and $0.47/kg from ammonium sulfate. Adding into the figures credit cost, which we generally assume to be l0%/ season (in real terms) of the market price of N, an average marketing cost of $0.01/kg N from urea and $0.02/kg N from ammonium sulfate and an estimated application cost $0.01/kg N (based on wages and man-days utilized) gives us these effective costs: $0.35/kg N from urea and $0.55/kg N from ammonium sulfate.

Low-resource farmers are rarely in the position to buy their fertilizer requirement without access to credit, which if obtained from a government production credit program may be as low as 4% (in real terms) or as high as 50% for 6 mo (one crop season) if funds are obtained from traders or private moneylenders. Fertilizer application cost is estimated to be $0.02/kg N for the first 25 kg and

$0.01/kg N thereafter. Because the expected optimal N computed using the first figure exceeds 25 kg N for all water regimes considered, marginal application cost is taken to be $0.01/kg N both with and without azolla intercrop.

The economic feasibility of substituting azolla for chemical fertilizer can be determined by comparing the price of N from chemical fertilizer to the cost of producing N through azolla.

Azolla as green manure is cost inefficient under all types of irrigation, with an effective N cost considerably higher than even the high cost of N from ammonium sulfate. The effective cost of N from azolla as an intercrop is lower than the cost of N from ammonium sulfate for all water regimes in the wet season and for average and good irrigation in the dry season. Only with good irrigation is the effective cost of N from the azolla intercrop less than the cost of N from urea.

These results indicate that, where urea is available, adoption of azolla intercropping is unlikely and, if adopted by farmers with good irrigation, the net income benefits will be small. That modest reduction in N price makes adoption of azolla intercropping by farmers with good irrigation unlikely. Using azolla requires altering farm-level water management practices; the field-to-field irrigation practice in common use is not appropriate for azolla intercropping, as it allows loss of azolla to neighboring fields. Investments in supplementary farm ditches to replace field-to-field irrigation would probably more than offset the expected gains from azolla intercropping. Moreover, if farmers with good irrigation also have good access to market centers and low-cost credit, then their effective price of urea will be substantially lower than the $0.35/kg estimate used for the average farmer.

Summary

The case study results (based on data and policy environment prior to fertilizer trade liberalization) suggest that azolla usually is not a cost-effective substitute for urea fertilizer. Green manuring is uneconomic, largely because of the opportunity cost of land used to grow azolla. Use of land for azolla incurs a substantial cost of alternative cropping opportunities forgone. Compared to using N from urea, using azolla as an intercrop is profitable only with good irrigation.

However, it was possible in 1984 to justify public policies supporting production and distribution of azolla planting materials and techniques on second-best grounds. With a policy instrument, the second-best action is the appropriate action if the distortions resulting from all other policies are taken as given. Since importation of urea was formerly controlled and urea was rationed to individual farmers, the shadow price of nitrogenous fertilizer for many farmers was the price of ammonium sulfate ($0.55/kg N). At this price, intercropping with azolla in the wet season becomes relatively attractive. Now that import controls on urea have been removed, and the world price of N is relatively low, urea is no longer rationed and N is available at a lower price. This renders the second-best defense of azolla irrelevant and suggests that urea is typically more profitable than azolla.

Implications for policy and research

With the reform of the fertilizer import policy, the second-best justification for supporting azolla research, production, and distribution no longer holds. However, there are still strong grounds for continuing to support research in azolla and other green manure crops.

Improvements in azolla technology, which increase its nitrogen yield and pest resistance or reduce the opportunity costs of labor and land could make azolla as fertilizer economically feasible in a greater number of environments. In addition, the marginal social benefits of green manure are higher than the private, marginal value of production. Substituting green manure for chemical fertilizer provides increased social benefits: reduced pollution from fertilizer runoff and long-term improvements in soil quality and productivity. These benefits may not be fully valued by farmers. but are of substantial long-term benefit to society.

Given the current stage of azolla technology and its relatively poor economic feasibility, policy support in terms of widespread investment in technology dissemination is not appropriate. Instead, strong support should be given a research program designed to overcome the constraints to economic feasibility described here.

High labor costs and high opportunity costs of land use are two of the major constraints to the economic feasibility of green manure. However, it should be noted that the case study does not represent all rice-based farming systems. Economic feasibility may be much higher under alternative environments where opportunity costs of land and labor are lower.

Kikuchi et al (1984) identify some areas where azolla can be grown in small catchments, tanks, or canals of irrigation systems. In such areas, the azolla can be floated into the ricefield for incorporation into the soil. This system for growing and incorporating azolla provides large savings in both opportunity costs of land and labor costs. Cropping systems research on green manuring should focus more strongly on identifying areas where even current technology is economically feasible. In such areas, additional subsidies for production and distribution of inoculum and provision of increased extension services may be appropriate. Research and extension efforts should be aimed at providing a menu of green manure cropping systems for alternative environments, rather than at developing broad recommendations.

Breeding and agronomic research also should focus on the constraints identified. Nearly one-fourth of the cost of azolla as an intercrop is for insecticide. Development of increased insect resistance in azolla would substantially reduce the costs of azolla N. Development and use of integrated pest management techniques also could reduce insecticide costs.

The sensitivity of azolla to moisture stress, so that good irrigation is required to gain the full N contribution from azolla, is another major constraint. Development of azolla varieties or production systems that are less sensitive to moisture stress would lower expected costs per kilogram of N.

Considerably more research on the economic costs and benefits of green manure under different environments is needed. Better estimates of the differences between the private and social costs and benefits of both green manure and chemical fertilizer are particularly important. A better understanding of the order of magnitude of private vs social costs and benefits is required to determine whether greater support should be extended to production and distribution of green manure.

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Woody species as green manure crops in rice-based cropping systems

J. L. Brewbaker and N. Glover

Characteristics of 28 woody species or groups of species that are used or that deserve consideration for use as green manure in rice-based cropping systems are reviewed. All are legumes, only one is an annual. Three species are of special importance: *Gliricidia sepium, Leucaena leucocephala* and its hybrids, and *Sesbania bispinosa.* The value of N_2-fixing woody species as green manure has not been widely studied. At least 10 plant families, including 650 known and perhaps 5,000 additional species, are N_2 fixing. They are usually perennials, commonly high in leaf N and usually easy to coppice or lop for fodder Earlier studies focused primarily on species with fodder value. The vast majority of woody legumes carry tannins or toxins that may render them poor in digestibility but do not affect their utility as green manure.

The woody species that can serve as green manure crops are largely the N_2-fixing ones. They are commonly perennial shrubs or trees; there are no vines of importance and relatively few annuals. The legume family is by far the most significant, with 3 subfamilies of papilionoids (12,000 species, including a few trees), caesalpinioids (2,500 mostly woody species, but with few N_2-fixers), and mimosoids (2,800 mostly woody species, N_2-fixing). N_2 fixation occurs in nine other plant families, normally through the action of actinomycetes, but few species are tropical and fewer still are effective as green manure.

Herbivore animals have played a major role in the evolution of important green manure woody plants. Because the high-protein legumes are unusually attractive to herbivores, selection pressures have favored mechanisms that deter predation (e.g., spines, toxins, tannins, fibrous leaves). Many otherwise attractive green manure shrubs are too thorny to deserve consideration. One, *Mimosa invisa,* was unwisely disseminated and has become a serious thorny weed.

Also pertinent to evaluating a species for green manure is the phyllody, a condition in which leaflets are replaced by a sclerified, coriaceous phyllode (expanded petiole). Phyllodes are not digestible by animals and offer an ineffective vehicle for N recycling. Phyllodes characterize many *Acacia* species and often associated *Eucalyptus* species. They are retained on the plant for a long period and

create a litter that degrades slowly. In contrast, many of the best green manure species have bipinnate leaves with fragile leaflets (e.g., *Leucaena esculenta* averages over 10,000 leaflets, each 30 cm long).

The largely bipinnate species of the Mimosoideae representing genera such as *Acacia, Calliandra, Inga, Leucaena, Prosopis,* and *Samanea* are thus important green manure species. Other bipinnate leaf legumes of importance include the papilionoid genera *Codariocalyx, Erythrina, Flemingia, Gliricidia, Sesbania,* and *Tephrosia.*

N_2 fixation is known in more than 650 trees and shrubs, and is suspected to occur in as many as 5,000 species (Brewbaker 1987b). Many of these species are fast-growing, secondary-forest species that coppice or hedge readily. With the relatively low emphasis on green manure in the tropics among both scientists and rice growers, only a few of these species have been assessed seriously as an integral part of rice-based cropping systems. The tolerance for waterlogging desirable for irrigated rice systems is not common among the tropical leguminous shrubs; the exceptions are *Aeschynomene* and *Sesbania* species.

Woody perennials necessarily occupy specific niches in rice-based cropping systems. Historically, they have been part of a high natural forest or of a farm agroforestry system where trees are pruned for addition to compost or for direct use. The natural forest species do not serve agroforestry systems well. Smaller shrubs or trees are preferred because they can be coppiced regularly to maximize foliage yields while minimizing the interception of light for the food crop. The best known species of this type are fodder trees, often historically used as animal feed. On most small farms, the real or perceived value of fodder is high compared to the value of green manure. Inevitably, the two uses can become competitive.

This paper considers the botany and improvement of such woody plants and seeks to identify promising species for further research.

Best-known green manure species

Three woody species of the genera *Gliricidia, Leucaena,* and *Sesbania* are widely used for green manure in tropical food crop systems.

Gliricidia sepium (Jacq.) Steud.

Botany andecology. Farmers throughout the tropics are familiar with the many uses of *Gliricidia sepium,* one of about 10 species in a poorly studied American tree genus. It is cross-pollinating with 2n = 20 chromosomes. In its native Mexico and Central America, it is traditionally used as plantation shade for coffee and cacao and is referred to as “mother of cacao.” It was introduced into Asia in the 1600s as a nurse or shade tree for tea and coffee. Its name in Jamaica. “quick stick,” refers to the ease of propagation, with cuttings. Field boundaries and roads are often lined with gliricidia. Its forage value is not widely recognized, since animal acceptance is high only for wilted foliage, but it has high feed value (55% dry matter digestibility and palatability). Gliricidia’s wood is durable, resistant to weathering, and is a preferred firewood. Gliricidia produces high foliage yields in areas receiving 1,500 mm or more

rainfall per year at elevations from sea level to about 700 m. Temperatures below 22 °C can reduce growth. Growth rates on low fertility soils are satisfactory, but yields are highest on well-drained, fertile sites.

Use as green manure and yield. Extensive research on green manuring with gliricidia was undertaken in India and Sri Lanka in the 1920s (Anonymous 1928). Studies were reported on the effect of gliricidia mulch on soil moisture, C-to-N ratios, and yields under different lopping regimes (Joachim and Kandiah 1934). The Indian Government recommended that farmers plant gliricidia around rice plantations to help reduce the requirements for manure.

Research at Coimbatore in the 1950s showed that gliricidia planted 2 m apart along the bunds can produce 4.0 t leaf dry matter/ha (equivalent to 120 kg N). Rice grain and straw yields were increased 15-45% by 5 t gliricidia mulch/ha applied 3 wk before planting. In experiments in Sri Lanka, green leaf manuring with gliricidia in addition to inorganic fertilizers increased rice yields by 60%.

Gliricidia has provided green manure for rice, cassava, cowpea, maize, taro, sugarcane, and yam (Agboola et al 1982, FAO 1981, Kidd and Taogaga 1985).

Particularly extensive studies on maize production with gliricidia mulch have been conducted at the International Institute of Tropical Agriculture (IITA) in Nigeria (Kang et al 1985).

Gliricidia coppices vigorously and tolerates regular lopping. Green leaf yield data show that it produces about 1-3 t dry leaf material/ mo from 10,000 trees/ha (Table 1).

Foliage quality. Nodulation in species in many countries contributes to the production of N-rich (2.9-4.3%) green manure. One ton gliricidia leaf meal (dry matter) provides the following nutrients (Kang et al 1985):

Nitrogen	29-43 kg
Phosphorus	2.9 kg
Potassium	16-26kg
Calcium	14.0 kg
Magnesium	5.4 kg

Gliricidia leaves are pinnate, about 20 cm long, with 7-9 pairs of 4- to 8-cm-long leaflets. Organic matter decomposition and nutrient release vary, depending on climatic and edaphic conditions. In the Ivory Coast, with 2,100 mm annual rainfall.

Table 1. Leaf yield of *Gliricidia sepium.*

Spacing (trees/ha)	Cutting interval (mo)	Leaf yield (t dry matter/ha)	Reference
—	3	3.6	Catchpoole et al 1985
10,000	1	2.3	Ella and Jacobsen 1985
10,000	3	2.0-3.5	Budelman 1985
10,000	3	3.3-6.9	Sriskandarajah 1987
10,000	2	1.3	Kidd and Taogaga 1985
—	3	0.4-3.7	Panjaitan et al 1985
10,000	4	0.5-2.0	Oakes and Skov 1962

26 °C mean temperature, and low fertility-sandy soils. half the nutrients were released in 22 d (Budelman 1985). K was released much faster (9 d half-life).

***Leucaena leucocephala* (Lam.) de Wit**

Botany and ecologi. Leucaena comprises at least 12 species, with several additional but doubtful taxa among the 50 or more designations made in the genus. The extensive literature on this group (more than 3,000 references) are summarized well in books by Pound and Martinez (1983) and the US National Research Council (NAS 1984), bibliographies by Oakes (1984), and the reviews by Brewbaker (1987a) and Brewbaker and Hutton (1979). Leucaena grows from sea level to 2,500 m, from Peru to Texas, in areas with <500 mm annual rainfall to areas with more than 2,000 mm. It favors calcareous and well-drained soils. All species can hybridize with pantropically distributed *L. leucocephala,* the only common commercial species. More than 50 hybrids have been produced, most of them seed-fertile. Many have commercial potential (Sorensson and Brewbaker 1987). The genus has a potentially large gene pool.

Leucaena is of interest primarily as animal fodder (Brewbaker 1985a, 1987b). It is planted widely for fuel and post wood, increasingly is being studied as a source of pulpwood and timber, is used as nurse trees with plantation crops, and is planted for shade or soil amelioration.

Leucaena has low tolerance for acidity. *L. diversifolia* is among the best in acidity tolerance. Strains now disseminated internationally are psyllid-tolerant, arboreal, tetraploid (2n = 104), and self-fertile. The hybrid with *L. leucocephala* (designated KX3) works well as a hedge and shows excellent foliage yields in midlands and highlands where *L. leucocephala* does not thrive.

Use as green manure and yield. Leucaena has historically been used in alley farming with upland crops, but not with irrigated rice. At IITA, it has been intensively studied (Kang et a1 1985) as green manure for upland crops in Africa. Its use is primarily with maize in Southeast Asia and Africa and, to a lesser extent, with other crops (Brewbaker 1987a, Pound and Martinez 1983). Leucaena's potential with rice is limited because it does not tolerate waterlogging and must be lopped aggressively to avoid shading. It may be more attractive for on-farm use as animal fodder.

Some early studies of leucaena as green manure for rice-based cropping systems were devised at IRRI by R. Bradfield and J. L. Brewbaker in the late 1960s. Leucaena foliage was incorporated before rice and before maize in rotations of rice, mungbean, sweet maize, and sweet potato. A primary constraint in any such system is the level of organic matter, which cannot be maintained in the tropics without manuring, at least through incorporating weeds. A student of Bradfield's continued studies in Hawaii to refine spacing and cutting regimes for optimal leucaena yields (Guevarra et a1 1978). He reported yields of 459-551 kg N/ ha for normal harvest cycles.

Leucaena herbage yields generally exceed those of other shrubby tropical legumes and are comparable to those of the best herbaceous legumes. They range from 40 to 80 t fresh weight/ha when moisture is not limiting (Brewbaker 1987a).

Yields are reduced to 20-50 t/ ha in the seasonally dry tropics. Yields are optimized with a harvest cycle of 2-4 mo. Other variables affecting yield include variety, cutting height, and plant densities.

Favored systems involve varieties of the Salvador or hybrid types, cut to 75 cm hedge height in fields with 75,000 or more shrubs/ha. As cutting intervals increase. the percentage of wood increases but total biomass per day remains relatively the same.

Maize grain yields responded linearly to leucaena green manuring, with 24.1 kg grain/kg N from incorporated leaves and 14.8 kg maize/kg N from leaves provided as mulch (Brewbaker 1985b, based on data of Evensen). Similar data have been obtained at IITA (Kang et al 1985).

Foliage quality. The nutrient levels of leucaena leaves are summarized by Brewbaker and Hutton (1979). They found 1 t (dry matter) leucaena foliage contains these nutrients:

Nitrogen	30-35 kg
Phosphorus	2.7 kg
Potassium	14.0 kg
Calcium	8.0 kg
Sulfur	1.4 kg

The leaves are bipinnate, 20-35 cm long, with 4-9 pairs of pinnae bearing 11-22 pairs of leaflets 8-16 mm long. N release from incorporated foliage occurs rapidly, with a 7 d half-life (Guevarra et al 1978).

Sesbania bispinosa (Jacq.) W. F. Wight

Botany and ecology. The genus *Sesbania* comprises about 50 species, with several doubtful taxa and the customary problems of synonyms for tropical legumes. The literature on important cultivated species was reviewed by Duke (1981) and Evans and Rotar (1987). Sesbania favors the moist tropics; many species show exceptional tolerance for waterlogged soils, which appears in part through their ability to nodulate. Stem nodulation is known for the annual *Sesbania rostrata,* an important potential green manure plant preceding rice. Three woody species of the genus have been grown widely: *S. bispinosa, S. grandiflora,* and *S. sesban.*

S. bispinosa (Jacq.) W. F. Wight is a shrubby annual or short-lived perennial that can grow to 6-7 m tall. It is also known as *S. aculeata* (Willd.) Poir. and as *S. cannabina* (Retz.) Poir., and by the common name dhaincha. Dhaincha has thick glabrous stems, large (35 cm) pinnate leaves, yellow flowers, and long (25 cm) curved pods. It is self-fertile and seeds freely. It is a multipurpose shrub; the wood and leaves are used for poles, fiber, fodder, and green manure. It is adapted to wet areas and heavy soils. It is viewed as a marsh plant able to produce floating roots with a spongy aerenchyma, and is also said to withstand drought, with rainfall as low as 500 mm in the growing season.

Use as green manure and yield. S. bispinosa is grown widely in India as a green manure crop. Seeds are sown at the onset of the monsoon; 2- to 3-mo-old plants are incorporated before rice is transplanted. Its rapid growth resulted in N accumulation of 80 kg/ ha in 30 d and 230 kg in 60 d at IRRI. Evans and Rotar (1987) surveyed an

array of published data and reported yield averages of 26 t fresh foliage/ha from growth periods averaging 75 d. Yields greatly exceed those of other green manure crops, such as crotalaria, mungbean, and pigeonpea, but evidently are exceeded in summer by yields of the herbaceous *S. rostrata.*

Leaves are pinnate, averaging about 38 cm long, with 20-50 leaflets, 1.2-2.5 cm long, per leaf. The leaflets degrade rapidly in moist soil and release 50% of their N within 4 wk of incorporation (IRRI 1985).

Other woody green manure species

Many shrubs and trees contribute high-N leaf litter as nurse trees or are lopped to provide foliage for green manure, for addition to compost, or for fodder (Burley and Von Carlowitz 1984). Only a few have become significant as green manure for upland crops, notably maize; still fewer are used in rice-based cropping systems. Responses to such green manure crops are most impressive on low organic-matter soils; responses are less obvious on rich organic irrigated soils, despite evidence that linear responses to added N are parallel (Tanaka 1978). We discuss here woody species known as green manure or nurse trees in tropical farming systems and known or suggested to have potential for rice-based farming systems. Useful reference works dealing with fodder and related uses include Brewbaker et al (1982), Burley and Von Carlowitz (1984), Duke (1981), NAS (1979), Okigbo (1984), Robinson (1985), Singh (1982), and Skerman (1977).

All species listed in Table 2 are N_2-fixing legumes and tend to have similar leaf N levels (2.5-4.5% dry matter) under widely varying soil and growth conditions. Green manure N values were 2.6% for fodder legumes vs 1.4% for grasses in studies cited by Brewbaker (1985a). Tanaka (1978) reported foliage values of 3.8% for legumes vs 2.3% for nonlegumes used as green manure, with averages of 0.4% for compost and 0.6% for rice straw.

Several tree and shrub species that fail to fix N_2 have been used as green manure crops, but are generally recommended only where N levels are already likely to be high. Among them are *Acioa barterii* (Chrysobalanaceae), *Alchornea cordifolia* (Euphorbiaceae), and *Gmelina arborea* (Verbenaceae).

Discussion

Great genetic variability in total biomass yield per unit time and area exists for any plant species. Natural evolution has not necessarily favored the heavy foliage desired in a green manure species, nor the maximum rates of C or N fixation sought. Dramatic increases in biomass productivity that have occurred as first increments of plant breeding in several fast-growing trees (e.g., leucaena) have encouraged the prediction of an initial doubling of foliage yields through provenance trials in any new species, and additional increases through refinements in management and harvest regimes. Few national or international institutions are likely to mount such improvement programs if green manure is the sole product. Despite this conservative view, a wealth of woody species deserves attention as possible green manure plants.

Table 2. Species of N_2-fixing leguminous plants that are used as green manure crops.

Species epithet	Common names	Subfamily: family[a]	Center of origin, distribution, uses	Description, botany, ecology	Green manure use and problems
Acacia albida Del.	Winterthorn	Mimosoideae: Leguminosae	Africa; widespread, now to India, Israel; fodder, ornamental, shade, green manure	Tree to 20 m; = *A. leucophloea;* often leafless in rainy season; bipinnate; thorny; drought tolerant (to 300 mm); frost-sensitive	Not commonly lopped, N levels low (2.4%)
Acacia angustissima Miller			Central America, now to SE Asia; green manure, fodder	Shrub to 5 m; rapid growth; not thorny	Limited evidence of its utility as green manure
Acacia nilotica (L.) Del	Babul (India) Munga (Africa) Prickly acacia (Australia)		India, Africa; now widespread; firewood, charcoal, timber, tannin, and gum source, fodder	Tree 6-12 m; very thorny; bipinnate; tropics, midlands, frost-susceptible; drought tolerant, deciduous	Good leaf and pod fodder yields and quality under drought stress, but little used as green manure
Acacia villosa Willd.			Caribbean, introduced to Indonesia; green manure, fodder (poor, high tannins, low DMD)	Shrub to 3 m; non-thorny; highly branched; bipinnate, compact leaves; low elevation tropics	Little used in the Americas, but grown in Indonesia as hedge; growth rate slow
Aeschynomene americana L.	Thornless mimosa	Papilionoideae: Leguminosae	Tropical America; now widespread; fodder, hay	Subshrub to 2 m; lowland mesic tropics; tolerant of waterlogged soils, stem nodules	Soil cover for teak in marshy areas
Aeschynomene elaphroxylon (Guill and Perr) Taub	Ambatch Pith tree Balsawood tree		Tropical Africa, now widespread; ornamental, corky wood (0.15 sp. gr.), fodder	Shrub or small tree to 9 m; mesic and swampy tropics to 2000 m, adventitious roots profuse in marshes, conspicuous orange flowers, nodules on stems, branches with small thorns and sticky hairs	Little used as green manure

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Table 2 continued.

Species epithet	Common names	Subfamily: family[a]	Center of origin, distribution, uses	Description, botany, ecology	Green manure use and problems
Albizia falcataria (L.) Fosberg		Mimosoideae: Leguminosae	Indonesia, New Guinea; widespread in humid tropics; timber (low sp. gr. 0.33), pulp wood, soil improvement	Tree to 40 m; humid tropics to 1000 mm min.; thrives in moist midlands = *Paraserianthes* sp.	This and related species *A. odoratissima* and *A. stipulata* are commonly lopped fodders, with low DMD; less used in compost
Baphia nitida Lodd.	Camwood	Papilionoideae: Leguminosae	W. Africa; dyewood, turnery, fencerows, medicinal, green manure, fodder (low quality)	Shrub to 3 m; simple leaves; moist tropics	Slow growth, high-protein leaves
Cajanus cajan (L.) Millsp.	Pigeonpea Catjang	Papilionoideae: Leguminosae	India and Africa (cult. <2000 BC); now world-wide; food, medicinal, green manure, fodder (DMD 50%). windbreak, honey	Variably perennial shrub to 4 m; annual types for food, arid tropics, low to midland; not frost or fire tolerant	Tall perennial varieties and the related *Atylosia* spp. can be lopped for fodder or green manure 12.6% N)
Calliandra calothyrsus Meissn.	Kaliandra	Mimosoideae: Leguminosae	C. and S. America; to Indonesia; fuel wood, green manure, fodder (low DMD <40%), ornamental, honey	Shrub to 8 m; moist tropics, cold tolerant, poor on alkaline soils	Lopped fodder yields 3.7-4.3 t (DM)/km of hedge
Chamaecytisus ,palmensis (Christ) Bisby et Nicholls	Tagasaste Tree lucerne	Papilionoideae: Leguminosae	Canary Islands, to N. Z. and Australia; hedges, good fodder (DMD 70%), bee pasture, soil restoration	Shrub to 6 m; temperate, frost tolerant to -10C; drought tolerant, not tolerant of acid soils	Deserves consideration for green manure in frost-prone areas; high yields lopped (15 t dry matter/ha per yr)
Codariocalyx gyrans (L.) Hassk.	Telegraph plant	Papilionoideae: Leguminosae	Indo-Malaysia, Philippines; green manure, fodder	Shrubs and subshrubs; related to *Desmodium*	Little research experience

Codariocalyx gyroides (Roxb.) Hassk.			Indo-Malaysia and Philippines; green manure, coffee shade	Vigorous tropical shrub to 2.5 m; = *Desmodium gyroides* DC; wet tropics; tolerant of poor drainage	Little research experience
Desmanthus virguatus (L.) Willd.	Donkey bean	Mimosoideae: Leguminosae	S. and C. America, now widespread worldwide; browse fodder (2.3% N)	Subshrub to 3 m; short-lived perennial; aggressive,coppices and reseeds well; unarmed; mesic tropics but drought tolerant; not acid tolerant	Yields low relative to leucaena
Desmodium discolor Vog.	Horse marmalade (S. Africa)	Papilionoideae: Leguminosae	S. America, now widely distributed; fodder	Subshrub to 3 m; woody when mature; subtropical, but frost-hardy	Little used as green manure
Desmodiurn distorturn (Aubl.) Macbride			Venezuela; now in Africa; fodder	Subshrub to 2 m; woody at base; moist tropics	Little used as green manure
Erythrina spp.	Coral tree Phaledo (Nepal)	Papilionoideae: Leguminosae	Americas, Africa, Asia; green manure, ornamentals, fencerows, windbreaks, shade trees	Trees to 20 m; thorny; mesic to cool tropics; large leaves	Reports of occasional green manure use include *E. abyssinica Lam., E. arborescens, E. bertoeroana, E. hookeriana, E. stricta, E. suberosa, E. variegata*
Flemingia macrophylla (Willd.) Merrill		Papilionoideae: Leguminosae	S. E. Asia; dyes, fodder (low DMD = 40%), green manure	Shrub to 2 m; = *F. congesta* Roxb., = *F. latifolia* Benth; mesic-wet tropics, moderately shade tolerant	Rapid regrowth from coppice, large fragile leaves

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Table 2 continued.

Species epithet	Common names	Subfamily: family[a]	Center of origin, distribution, uses	Description, botany, ecology	Green manure use and problems
Gliricidia sepium (Jacq.) Walp.	Madre de cacao Quick stick	Papilionoideae: Leguminosae	C. America/Mexico; now worldwide; green manure, firewood, timber, shade, ornamental, fodder (good DMD = 55%. 3.7% N)	Tree to 15 m; easily propagated by cuttings; rapid growth, dry to mesic tropics to 1000 m; = *G. maculata*	Green manure use detailed in preceding section
Leucaena leucocephala (Lam.) de Wit	Leucaena Ipil-ipil Lamtoro	Mimosoideae: Leguminosae	C. America, Mexico, worldwide; fodder with high DMD = 65%, 3.4% N; fuel wood, shade, pulpwood, post wood, lumber, food	Tree to 20 m; dry to mesic tropics; not acid tolerant, growth slow in highlands; widely studied and planted, fast growth	Green manure use detailed in preceding section
Leocaena spp.			N. and S. America; 11 species; uncommon internationally; food, fodder, green manure, fuel wood, post wood	Shrubs and trees to 20 m; dry to mesic, lowland to highland	Green manure production fair to good on *L. collinsii, L. diversifolia, L. lanceolata* and *L. pallida*
Prosopis cineraria (L.) Druce	Khejri	Mimosoideae: Leguminosae	India; used before 1000 BC; firewood, charcoal, green manure, post wood, fodder (DMD low = 40%, 2.2% N, high tannins)	Tree to 9 m; thorny; hot dry tropics to 100 mm, normally 500-800 mm; light demanding	Highly valued in desert areas as the only available green manure or as browse, despite low quality. Many other Prosopis spp. are drought- and saline-tolerant, with some use as lopped fodder, but little valued for green manure due to low foliage yields

Samanea saman (Jacq.) Merrill	Raintree Cow tamarind	Mimosoideae: Leguminosae	C. and S. America; now pantropical; ornamental, timber, craftwood, fuel wood, food, feed (pods)	Tree to 40 m, spreading; mesic to wet tropics; fast growth; widely adapted	Not normally considered for foliage harvest, yet vigorous in coppice regrowth and with good green manure yields and quality (2.6% N)
Sesbania bispinosa (Jacq.) W. F. Wight	Dhaincha Daincha	Papilionoideae: Leguminosae	India; now widespread especially in Africa and N. India; green manure, fodder, fiber crop, fences, medicinal, small poles	Short-lived shrub to 6 m; spiny; adapted to waterlogged and saline soils; forms spongy aerenchyma; weedy; = *S. aculeata,* = *S. cannabina*	Green manure use is described in preceding section
Sesbania grandiflora (L.) Poir	W. Indian pea tree Katurai Agati Gallito Baculo		Indonesia; now worldwide, food (flowers, pods, leaves); fodder; pulp wood, ornamental, medicinal	Tree to 10 m; = *S. formosa* F. Muell.; short-lived; large flowers and pods; fast early growth; slow foliage regeneration; mesic tropics (>1000 mm); tolerant of waterlogging, shallow rooted	High N (>5%) foliage, rapid young growth (to 20 t DM/ha per yr), but in limited use as green manure, many pests
Sesbania sesban (L.) Merrill	Sesban		Tropical Africa (very widespread), Asia; green manure, fodder of variable value to 70% DMD (probable genetic diversity), fiber, medicinal (seeds)	Shrub to 5 m; = *S. aegyptiaca* (Poir.) fast growth; moist tropics to midlands; saline and flooding tolerant, weedy	Little planted, but often left in fields for green manure

continued on next page

Table 2 continued.

Species epithet	Common names	Subfamily: family [a]	Center of origin, distribution, uses	Description, botany, ecology	Green manure use and problems
Tephrosia candida (Roxb.) DC	White tephrosia	Papilionoideae: Leguminosae	S. E. Asia; green manure, soil improvement, nurse tree, ornamental	Shrub to 3 m; tolerant of drought, acidity, water-logging, shade, not frost tolerant	High green manure yield to 15 t DM/ha per yr in Africa
Tephrosia vogelii Hook.	Fishbean		W. Africa, introduction in Asia; fish poison, insecticide (rotenone); cover crop, hedge, ornamental	Short-lived dense shrub to 4 m; tolerant of drought, fire, acidity	High N (4.5%) foliage; rare as green manure; several other spp. or hybrids in this large (400 spp.) tropical genus serve as hedges, windbreaks, and plantation tree shade or nurse trees

[a]The family name is provided only for the first species in each genus cited.

Mimosoid legumes are predominantly woody and tropical, with only 3 herbaceous genera among a total of 66. About 2,300 species are perennial shrublets, shrubs, or trees.

In contrast, some woody papilionoids (e.g., *S. bispinosa)* are annual or short-lived perennials. Among the 388 mimosoids surveyed for N fixation, only 37 failed to nodulate (Allen and Allen 1981). Applying this expectation of 90% nodulation, there are at least 1,900 other woody mimosoids that can fix N, but that have not yet been identified.

The genera discussed here include *Acacia, Albizia, Calliandra, Desmanthus, Leucaena, Prosopis,* and *Samanea.* Several large mimosoid genera that have great potential as green manure are *Albizia* (150 spp.), *Calliandra* (150-200 spp.), and *Inga* (200-300 spp.). Research is needed on these and related mimosoid genera; many of them are also interesting as high-protein fodder and soil restoration species (Brewbaker 1987b).

Papilionoids constitute the largest group of legumes (12,000-14,000 spp.). They are overwhelmingly herbaceous. Many perennial herbs that lignify and approach woodiness are well known as green manure (e.g., species of *Crotalaria, Desmodium, Medicago, Melilotus,* and *Pueraria).* Woody papilionaceous genera include *Aeschynomene, Baphia, Cajanus, Chamaecytisus, Codariocalyx, Erythrina, Flemingia, Gliricidia, Sesbania,* and *Tephrosia.* Several of these are short-term perennials. Most have larger leaflets than the mimosoids and tend to have a wider spectrum of pest and disease problems. Since more than 95% of the 2,416 papilionoids reported by Allen and Allen (1981) were able to fix N_2, untested woody papilionoids can safely be expected to fix N_2.

Among the caesalpinioids, the proportion of N_2-fixing species is much lower, 28% of the 258 reported species. None appear in the list given here. Many of the caesalpinioids are woody; a few have a good reputation as fodder (e.g., species of *Bauhinia, Ceratonia,* and *Gleditsia)* although they fail to fix N_2. The large genus *Cassia* (600 spp.) includes many tropical trees and shrubs; the few that fix N_2 are largely in the American subgenus *Chamaecrista.* None are significant as green manure, but adaptability and foliage production of species like *Cassia siamea* make it a favored tree in Asia.

Nonleguminous plant families that have been found to nodulate include the Betulaceae, Casuarinaceae, Coriariaceae, Cycadaceae, Elaeagnaceae, Myricaceae, Rhamnaceae, Rosaceae, and Ulmaceae. Many important additions may be expected in the future. None appear to have been used directly as green manure, although some probably have use in composting. Several important tree species in these families provide lopped fodder or serve as nurse trees for high-N litter, including the *Alnus* spp. (alders), *Coriaria* spp., *Elaeagnus* spp. (Russian olive), and *Shepherdia* spp. (buffalo berry). Others can be nasty weeds (e.g., *Myrica faya* Ait., the firetree, introduced from Azores to Hawaii for reforestation and now a pest).

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Notes

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Green manure in rice: the Japan experience

M. Ishikawa

The area planted to green manure crops in Japan increased under government recommendation between 1868 and 1934, then gradually declined to today's low levels. The primary green manure crops were milk vetch and green soybean. Milk vetch fresh weight reaches about 45 t/ha, with about 0.4% N and 2% carbohydrate. N efficiency of milk vetch nearly equals that of ammonium sulfate. Annual application of milk vetch overtime increases soil organic matter and rice yields, but excessive application causes rice root injury and soil mineral leaching. Moderate application is proposed to increase N efficiency and to prevent rice crop damage.

In ancient times, Japanese farmers used natural plants— wild grasses, tree leaves, and branches—as green manure. During the Edo era 1603-1867, Chinese milk vetch, green soybean, radish, rape, and other crops were grown.

Milk vetch *Astragalus sinicus* L. was the primary green manure crop. Milk vetch, thought to have originated in China, was brought to Japan before the 8th century. When the Japanese-Russian War began in 1904, the Japanese Government policy recommending green manure crops (such as milk vetch, green soybean, green broad bean, green pea, and yellow trefoil) was important in increasing food production.

Research on green manure started in 1919. The Ministry of Agriculture and Commerce entrusted the research to the following university and prefectural agricultural experiment stations: Tokyo Imperial University, leguminous crop utilization of nitrogen gas from air; Toyama Prefecture Agricultural Experiment Station, study on milk vetch manuring; Fukuoka Prefecture Agricultural Experiment Station, study on green soybean manuring; and Mie Prefecture Agricultural Experiment Station, study on green manure crops not native to Japan.

To counter the agricultural depression in 1931, the government recommended green manure, established green manure crop seed production farms, and subsidized the supply of seed and root nodule bacteria. These activities continued to 1945 as countermeasures to fertilizer insufficiency during the Pacific War.

Fertilizer insufficiency continued after the war. From 1950 to 1953, the government subsidized the establishment of seed production farms, original seed

farms, and breeder's stock farms for milk vetch, green soybean, and green broad bean. In 1967, milk vetch seed stock facilities were established and subsidies for green manure ceased because of decreasing use.

Table 1 shows the green manure crops that have been used in Japan. At the peak period of green manure use, milk vetch and soybean occupied some 95% of the cropped area, mainly in the southern and western districts (Table 2). The area planted to green manure crops reached a maximum 505,000 ha in 1934, then decreased rapidly. In 1980, milk vetch was produced on only 4,540 ha, mainly for fodder.

Table 1. Green manure crops used in Japan (Matsuki 1944).

Common name	Scientific name
Leguminous type	
Chinese milk vetch	*Astragalus sinicus* L.
Green soybean	*Glycine max* Merr.
Alfalfa	*Medicago sativa* L.
Bur clover	*Medicago hispida* Gaertn.
Serradella	*Ornithopus sativus* Brot.
Pea	*Pisum sativum* L.
White clover	*Trifolium repens* L.
Broad bean	*Vicia faba* L.
Common vetch	*Vicia sativa* L.
Hairy vetch	*Vicia villosa* Roth.
Lespedeza	*Lespedeza thunbergii* Nakai
Pseudo acacia	*Robinia pseudo* Acacia L.
Nonleguminous type	
Rape	*Brassica napus* L.
Buckwheat	*Fagopyrum esculenturn* Maench
Green maize	*Zea mays* L.
Green rye	*Secale cereale* L.
Green oats	*Avena sativa* L.

Table 2. Area planted to green manure crops (Kurokawa 1983).

Year	Area (thousand ha)			
	Milk vetch	Green soybean	Others	Total
1909	206	131	23	360
1914	238	140	26	404
1919	256	145	22	423
1924	281	133	19	433
1929	280	126	22	428
1934	304	153	48	505
1939	260	146	65	471
1944	197	198	39	434
1949	178	41	18	237
1954	177	24	16	217
1960	143	-	4	147
1969	91	-	1	92
1985	4.5	-	-	4.5

Growing milk vetch

Toyama Prefecture had the largest cultivated area of milk vetch in Japan. The 48,000 ha of milk vetch covered 60% of all irrigated ricefields. Here, I report mainly research on milk vetch green manure conducted at the Toyama Agricultural Experiment Station from 1919 to 1966. Yamazaki and Miyamoto (1967) described the method of growing milk vetch.

Of the many varieties of milk vetch in Japan, Funosen No. 24 was chosen by the Toyama Agricultural Experiment Station for its high resistance to snow rot disease and higher yields.

Sowing

Milk vetch cultivation is suitable for well-drained ricefields. In poorly drained fields, it is necessary to make a drainage ditch before sowing milk vetch with rice.

Sowing time for milk vetch is mid-August to early September in the snowy districts of northern Japan and early September to early October in the warmer districts. Seeds at 20 liters/ha are sown by hand between standing rice plants 30 d before harvest.

Fertilizer

Normally, no fertilizer is needed for producing milk vetch green manure. However, K, Ca, and, particularly, P do have significant effects. Optimum fertilizer application times are after rice harvest and in the spring. Optimum level is 380 kg calcium hydroxide/ha and 100 to 200 kg superphosphate/ha.

Disease control

Because milk vetch seeds sometimes are contaminated with *Sclerotinia* rot, it is important to select seed by specific gravity or to sterilize seed in 47 °C water for 7 h. To control *Sclerorinia,* irrigating several times during the apothecial formation stage is effective.

Growth process

Ishikawa (1963) investigated the growth process and chemical components of milk vetch (Table 3). Milk vetch was sown without fertilizer between standing rice plants in the Toyama Agricultural Experiment Station field on 7 Sep. That year, snowfall was minimal and so was *Sclerotinia* rot disease. The following April, plants elongated rapidly. Blooming began the end of April and continued through early May, with full bloom the middle of May. Pod formation began in mid-May. Fresh weight at bloom commencement was 23 t/ha. It was 40 t during blooming and reached 47 t at full bloom.

Chemical components of milk vetch

Water content of fresh matter was about 90% throughout growth (Table 4). N content before blooming was 4.5% of dry matter, decreasing gradually to 3.5%

Table 3. Growth and yield of milk vetch. Toyama Agricultural Experiment Station, 1963 (Ishikawa 1963).

Date	Growth stage	Length (cm)	Fresh weight (t/ha)	Dry matter weight (t/ha)
11 Apr		21	12.0	1.3
18 Apr		27	15.5	1.9
25 Apr	Blooming begins	38	23.0	2.5
2 May		51	36.3	3.3
9 May	Blooming season	63	40.9	4.5
16 May	Full bloom	76	47.0	4.3
23 May	Pod formation	84	34.4	4.7

Table 4. Content and quantity of milk vetch components. Toyama Agricultural Experiment Station, 1963 (Ishikawa 1963).

Date	Water content (% of fresh matter)	Component content (% of dry matter)						Quantity (kg/ha) of component			
		N	C	C:N	Crude protein	Soluble carbo-hydrate	Crude cellulose	N	Crude protein	Soluble carbo-hydrate	Crude cellulose
11 Apr	88.4	4.60	41.0	8.9	28.7	13.2	8.2	64	400	183	124
18 Apr	87.9	4.80	43.0	9.0	30.0	12.3	10.7	90	564	231	200
25 Apr	89.0	4.28	40.5	9.5	26.8	17.0	9.6	108	687	430	243
2 May	91.0	3.73	39.8	10.7	23.3	16.9	13.1	122	760	667	394
9 May	89.0	3.45	40.2	11.6	21.6	22.5	12.6	156	970	837	523
16 May	90.8	3.20	41.8	13.1	20.6	19.0	20.1	138	890	922	912
23 May	86.4	2.63	40.0	15.4	16.4	21.3	20.1	123	756	996	931

during blooming and to 3.2% at full bloom. It was 0.33-0.47% from bloom commencement to full bloom.

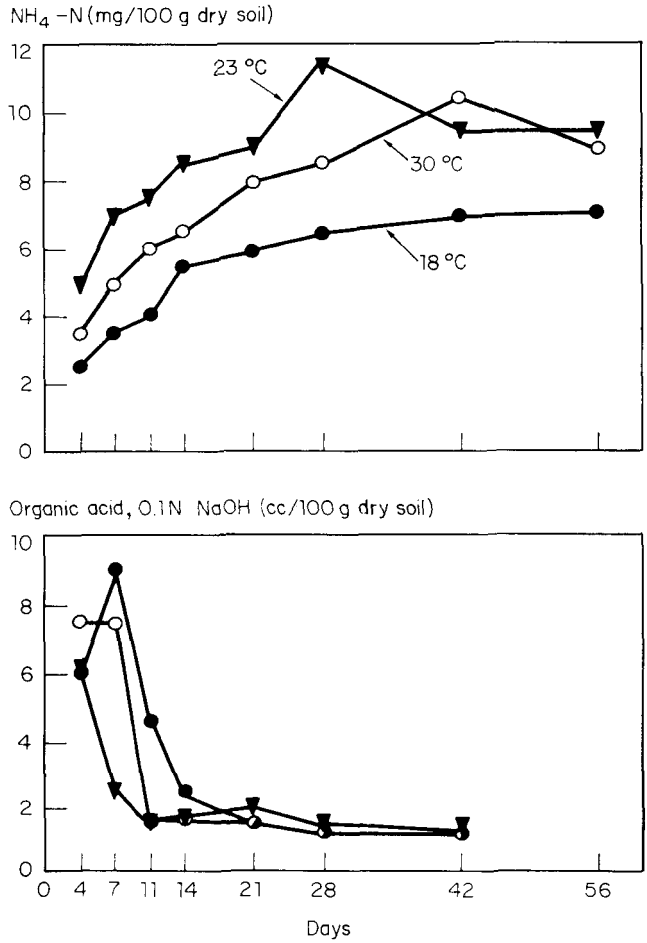
As milk vetch grows, protein content decreases and soluble carbohydrates, cellulose, and the carbon-to-nitrogen ratio (C:N) increase. During blooming, protein was 23%, soluble carbohydrates was 17%, and cellulose content was 13% of dry matter. C:N during blooming was 10, increasing to 15 at full bloom. N during blooming was 108 kg/ha; at full bloom it increased to 156 kg/ha.

Maximum protein was about 1 t/ha at full bloom. Maximum soluble carbohydrates and cellulose quantities during pod formation were about 1 t/ha.

Dry matter yield, N, soluble carbohydrates, and cellulose increase rapidly after blooming begins. If green manure incorporation is delayed, the excess N will have a negative effect on the rice crop. Excess carbohydrate will adversely affect rice growth through the formation of excessive levels of harmful substances such as organic acids and through soil reduction.

The root-to-top ratio of milk vetch is about 0.05 and N content in the root is 0.35% fresh weight during blooming. If 20 t milk vetch/ha is incorporated, the roots will supply only 3.5 kg N/ha, a negligible quantity for rice production.

For these reasons, incorporation time and the quantity of milk vetch applied are important factors. The blooming season seems to be the safest and most suitable time for milk vetch green manure application.



1. Ammonium N and organic acid in milk vetch-manured soils under different temperatures. Toyama Agricultural Experiment Station, 1963 (Ishikawa 1963). Air-dried milk vetch (0.8 g) was applied to 250 g fresh soil.

Green manuring rice with milk vetch

The efficiency of milk vetch as fertilizer is influenced by many factors, such as climate, quantity and quality of green manure, incorporation time, plowing method, and water management.

Influence of temperature on decomposition

Milk vetch was incorporated early to mid-May, when the temperature was about 18 °C. In summer, the temperature was about 30 °C. To study the influence of temperature on milk vetch decomposition, soil samples were mixed with milk vetch and incubated at 18, 23, and 30 °C. Figure 1 shows ammonium N and organic acid formation during incubation. Milk vetch decomposed even at 18 °C; the

decomposition rate increased with higher temperatures. At 30 °C, N mineralization reached its maximum—70% of the N contained in the green manure 30 d after incubation. Organic acids were greater at low temperatures than at higher temperatures, and organic acid formation continued longer.

We concluded that milk vetch decomposition begins at low temperatures, with increasing N mineralization as temperatures increase.

Fertilizer efficiency

Field experiments comparing milk vetch and ammonium sulfate were carried out under different soil conditions (Table 5). In well-drained lowland ricefields, yields from plots fertilized with milk vetch were almost the same as from plots fertilized with ammonium sulfate. In medium or poorly drained soils. yields from milk vetch-fertilized plots were less than yields from ammonium sulfate-fertilized plots, for the following reasons:

1. Leaching of milk vetch N from well-drained soils is less than leaching of ammonium sulfate N.
2. Harmful substances, such as organic acids formed from the decomposition of milk vetch, are leached out by water percolation in well-drained soils. Poorly drained soils retain the harmful substances.

Optimum application rate

If incorporation of the milk vetch crop is delayed, the milk vetch matures and the amount of N applied increases. N level is an important factor in rice production; if it is too little or too much, rice yields suffer.

Table 6 shows the results of experiments applying different amounts of milk vetch to rice. Maximum rice yield was obtained with 33.8 t milk vetch/ ha (135 kg N/ ha). At that level, however, rice plant growth showed symptoms of excess N and grain quality was low. We concluded that the optimum amount of milk vetch is less than 33.8 t ha.

Root injury. Problems arising from the amount of milk vetch applied are not limited to the amount of N introduced. The amount of carbohydrate applied is also important. Through anaerobic decomposition of carbohydrates, the soil redox potential drops, harmful substances are formed. and rice plant roots suffer injury.

Table 5. Milk vetch and chemical fertilizer as sources of nitrogen (Yamazaki 1959).

Field type	Experimental fields (no.)	Grain yield (t/ha)		(A/B) × 100 (%)
		Milk vetch (A)	Chemical fertilizer (B)	
Well-drained soil	4	4.82	4.76	101
Fairly well-drained soil	8	4.54	4.72	96
Poorly drained soil	4	4.86	4.54	93

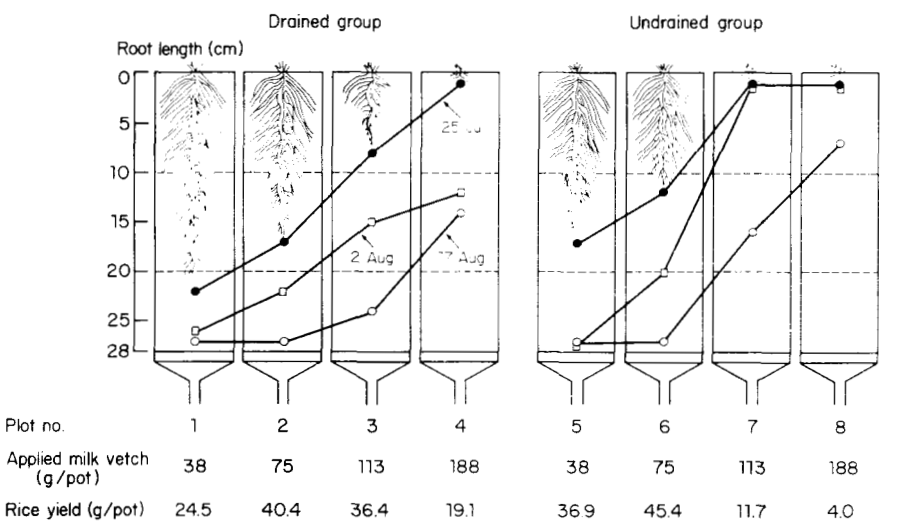
Table 6. Grain yield with different levels of milk vetch. Toyama Agricultural Experiment Station, 1930-44 (Yamazaki 1959).

Milk vetch applied (t/ha)	Nitrogen (kg/ha)	Grain yield (t/ha)	Ratio
0	0	2.3	100
22.50	90	4.2	145
33.75	135	4.4	151
45.00	180	4.2	147

Yamazaki (1959) investigated the influence of milk vetch on rice plant root growth in a glass pot experiment (Fig. 2). As the amount of milk vetch applied increased, rice plant root elongation and plant growth decreased. However, root growth recovered after drainage and increased rapidly because of the leaching out of harmful substances. When excess milk vetch was applied to drained and undrained plots, the rice yield from the drained plots was greater than that from the undrained plots. When less than optimum quantities of milk vetch were applied to drained and undrained plots, the rice yield from the drained plots was less than from undrained plots due to the loss of N through leaching.

The conclusion is that, with excess milk vetch application, drainage is important for plant growth and rice production in spite of the loss of N it causes.

Recommended amounts. To counter the problems of excess application of milk vetch, each prefecture published standards for milk vetch manure application (Suetsugu 1954). The optimum amounts recommended ranged from 7.5 to 17 t/ha, with upper limits from 11 to 30 t/ha. The amounts were less in the northern, cooler districts than in the southern, warmer districts.



2. Effect of milk vetch application on rice root elongation (Yamazaki 1959). Pots were drained 15 d after transplanting.

Supplementing with chemical fertilizers. To avoid injury caused by excess milk vetch application, farmers decrease the amount of milk vetch applied. Consequently, the amount of N applied decreases, as do rice yields. Chemical fertilizers can supplement milk vetch N. Table 7 shows the results of experiments combining ammonium sulfate with milk vetch. The rice yields from plots fertilized only with milk vetch was less than yields from plots fertilized only with ammonium sulfate. However, yields from plots combining milk vetch and ammonium sulfate were greater than yields from plots fertilized with ammonium sulfate alone.

The combination of the early effect of ammonium sulfate with the comparatively late effect of milk vetch was beneficial to rice yields.

Influence of water management

Before 1955, milk vetches were incorporated during the blooming season, from early May to full bloom in mid-May. Rice was transplanted early June to mid-June. The period between milk vetch incorporation and rice transplanting was 20-30 d.

During that period, farmers flooded and puddled the fields. The period between milk vetch incorporation and field flooding differed from farmer to farmer because of different irrigation customs and the farmers' work schedules.

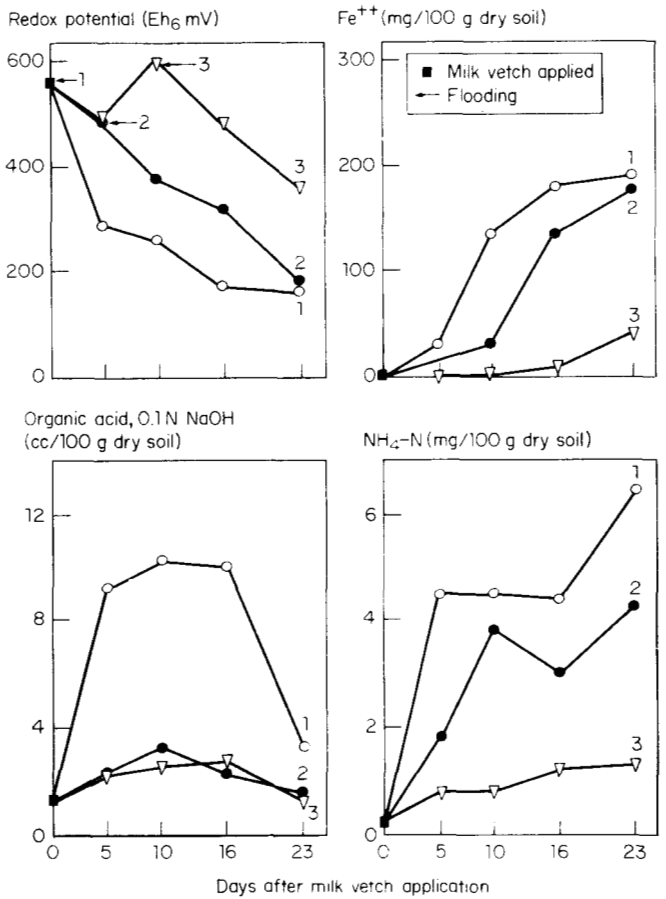
At the time of horse-powered cultivation, some farmers incorporated milk vetch under flooded conditions because of the ease in plowing. Others plowed dry fields, then flooded before transplanting rice. The decomposition of the milk vetch in soils seemed to be influenced by cultivation practices.

To study the influence of flooding time, especially in dry fields, Ishikawa (1963) conducted experiments on the decomposition of milk vetch (Fig. 3). Three cases were studied.

1. With incorporation in flooded fields, milk vetch decomposed under anaerobic conditions and the soil redox potential dropped significantly. A lot of organic acids and Fe^{+2} were formed; loss of N through apparent denitrification was small.
2. When flooding began 10 d after application, it seemed that most of the soluble carbohydrates in the applied milk vetch decomposed rapidly under the aerobic conditions of those 10 d. Consequently, soil redox potential did not drop very rapidly after flooding and the formation of organic acids and Fe^{+2} was less.

Table 7. Grain yield with N applied as ammonium sulfate and as milk vetch. Toyama Agricultural Experiment Station, 1930-44.

Amount applied				Yield	
Milk vetch (t/ha)	Nitrogen (kg/ha)	Ammonium sulfate (kg/ha)	Nitrogen (kg/ha)	t/ha	Index
23.44	93.8	0	0	3.9	100
18.75	75.0	94	18.8	4.2	107
14.06	56.3	188	37.5	4.2	108
9.38	37.5	281	56.3	4.1	105
4.69	18.8	375	75.0	4.2	108
0	0	469	93.8	4.0	103



3. Changes in soil characteristics and time of flooding after milk vetch incorporation (Ishikawa 1963). 1 = simultaneous flooding and milk vetch incorporation, 2 = flooding 5 d after milk vetch incorporation, and 3 = flooding 10 d after milk vetch incorporation.

However, ammonium N was converted to nitrate N under the 10-d aerobic conditions and a lot of nitrate N was lost after flooding, possibly through denitrification.

3. When flooding began 5 d after milk vetch application, the formation of organic acids and the loss of N was less.

To investigate the influence of flooding time on the efficiency of milk vetch in rice, field experiments were performed under different soil conditions (Table 8).

The Toyama and Wakaguri fields were well-drained fields where nitrification seemed to be active. The Mizuhashi field was poorly drained, with seemingly inactive nitrification. In the Toyama and Wakaguri fields, rice yields of late-flooded plots were less than yields of early-flooded plots. Yield in the Mizuhashi field was not influenced by flooding time.

Table 8. Effect on yield of time between milk vetch incorporation and flooding. Toyama Agricultural Experiment Station, 1954 (Yamazaki 1959).

Flooding (days from milk vetch incorporation to flooding)[a]	Toyama field		Wakaguri field		Mizuhashi field	
	Yield (t/ha)	Ratio	Yield (t/ha)	Ratio	Yield (t/ha)	Ratio
Early flooding (0 d)	4.1	100	4.0	100	3.7	100
Late flooding (at 20 d)	3.7	89	3.4	85	3.6	99

[a]Milk vetch incorporated 25 d before transplanting.

The reason for these results could be the N loss that occurred through denitrification and leaching after flooding of well-drained ricefields. It was concluded that in cases of optimum milk vetch application, later flooding time would cause N loss and reduction of rice yields in well-drained fields. In cases of excess milk vetch application, rice growth injuries caused by organic acids and excess N would be reduced by delayed flooding.

Effect on soil fertility

Green manure crops historically were used for plant nutrition and as organic matter for increasing soil fertility, especially soil organic matter and inorganic soil components.

Long-term application

Table 9 shows the variations in rice yield and soil organic matter in experimental plots due to long-term, annual application of milk vetch compared with other manures. At the Toyama Agricultural Experiment Station, rice yields of unmanured plots decreased gradually over the years; yields of milk vetch-manured plots increased gradually. At the Agricultural Research lnstitute of the Ministry of Agriculture and Foresty in Konosu, rice yields increased gradually in all plots. Yields in milk vetch-manured plots did not differ from yields in plots treated with organic and inorganic fertilizers. Yields in all treated plots were greater than yields in unmanured plots.

Total C and N content of the soil and the amount of ammonium N formed by incubation were greater in milk vetch-treated plots than in unmanured plots and plots where inorganic fertilizer was applied. The conclusion is that long-term, annual application of milk vetch increases rice yields and soil organic matter.

Leaching of soil mineral nutrients

In 1955, Konishi and Yamazaki (1955) studied the influence of milk vetch application on leaching of soil mineral nutrients in lysimeter experiments. They used three types of soil, with a milk vetch-fertilized plot and an ammonium sulfate-fertilized plot for each soil.

Table 9. Rice yield and soil organic matter with long-term, annual green manure application in Toyama (Toyama Agricultural Experiment Station, 1959) and Konosu (Agricultural Research Institute of the Ministry of Agriculture and Forestry, 1980).

Material applied	Brown rice			Soil[a]				
	Yield (t/ha)	Linear equation for yield $Y = a + bx$, Y = rice yield, x = year	r	Total carbon (%)	Total nitrogen (%)	C:N	Mineralized NH_4-N (mg/100 g soil incubated)	
							Air-dried soil	Wet soil
Toyama, 1952-64 (13 yr)								
No manure control	2.9	$Y = 2.926 - 0.00445X$	−0.363	1.36	0.161	8.5	17.3	2.14
Compost	3.2	$Y = 3.139 + 0.00156X$	+0.126	1.69	0.172	9.8	17.7	2.71
Ammonium sulfate	4.1	$Y = 3.296 + 0.01317X$	+0.685	1.53	0.162	9.4	18.7	2.14
Milk vetch	4.2	$Y = 3.560 + 0.01041X$	+0.574	1.87	0.184	10.2	23.4	3.86
Konosu, 1926-79 (54 yr)								
Inorganic fertilizer	3.3	$Y = 2.623 + 0.00263X$	+0.601	2.76	0.255	10.8	11.7	10.6
Organic fertilizer	3.4	$Y = 2.469 + 0.00328X$	+0.660	3.63	0.347	10.5	18.4	13.9
Milk vetch	3.4	$Y = 2.649 + 0.00277X$	+0.670	2.89	0.298	9.7	16.9	11.4
No manure control	2.0	$Y = 1.364 + 0.00237X$	+0.629	2.17	0.207	10.5	10.9	7.2

[a]Analyses conducted in 1961 (Toyama) and 1982 (Konosu).

Soil redox potentials on the milk vetch plots were lower than on the ammonium sulfate plots. The amounts of mineral nutrients lost, except N, were greater on milk vetch plots than on ammonium sulfate plots. The N loss was less on the milk vetch plots than on the ammonium sulfate plots. Half the applied N was lost from one ammonium sulfate plot.

Fe, Mn, and P levels increased greatly in milk vetch-treated plots. Milk vetch application promoted leaching of K, Mg, and silicates. However, Ca loss was greater from the amount of water percolation than from milk vetch application.

Konishi and Yamazaki concluded that because mineral nutrients, especially Fe and Mn, leached out of soils, degradation of lowland soils would be promoted by milk vetch application.

The degradation of lowland soils was an important farm problem. Ishikawa (1963) studied methods to reduce mineral nutrient leaching on plots manured with milk vetch.

In the Konishi and Yamazaki experiment, milk vetch was applied after flooding. Under this condition, it is thought that milk vetch decomposes anaerobically and that some of the soil mineral nutrients are reduced or form chelating compounds. This increases the solubility of the soil mineral nutrients and, consequently, increases leaching.

Ishikawa suggested that, if milk vetch is applied about 1 wk before flooding, most of the milk vetch carbohydrates would be decomposed under aerobic conditions. The soil redox potential would not drop greatly and leaching of mineral nutrients would be reduced. Ishikawa's experimental results are shown in Table 10.

On the plot where milk vetch was incorporated during flooding, loss of Fe and Mn was much greater than on the ammonium sulfate plot. Other nutrients also showed much greater loss. On the plot where milk vetch was applied 7 d before flooding, loss of Fe and Mn was only a little more than on the ammonium sulfate plot, and the amount of N leached was less. The conclusion is that the leaching of

Table 10. Leakage of soil components from milk vetch and ammonium sulfate applied to soil (Ishikawa 1963).

Component	Component leaked (mg/pot)			Ratio		
	Ammonium sulfate	Milk vetch applied at flooding	Milk vetch applied 7 d before flooding	Ammonium sulfate	Milk vetch applied at flooding	Milk vetch applied 7 d before flooding
Fe	23	309	43	100	1,428	190
Mn	30	120	40	100	395	131
Ca	864	1,222	781	100	142	90
K	225	313	212	100	140	94
Mg	103	104	76	100	102	74
P	5	8	4	100	167	87
Si	169	189	129	100	112	76
NH_4-N	168	127	36	100	76	21
NO_3-N	1	1	10	100	31	678
NH_4-N + NO_3-N	169	128	46	100	76	27

mineral nutrients due to milk vetch application can be prevented by improving the method of application.

Milk vetch manuring standards

Manuring standards were proposed for Toyama Prefecture, on the basis of research results. The principles were considered adaptable to other districts, with minor adjustments.

Suitable soil condition

Milk vetch production and manuring are suitable for well-drained irrigated ricefields in districts with minimal snowfall. In snowy districts, yields from milk vetch manure will be reduced by *Sclerotinia* rot. On poorly drained fields that have high groundwater levels, milk vetch will be injured by excess moisture. Milk vetch manure will accelerate the formation of harmful substances in the soil and decrease the soil redox potential, and the rice roots will suffer damage.

Suitable quantity

Although the optimum quantity of milk vetch to be applied differs with the rice variety to be planted, a suitable quantity usually is in the range of 20 t fresh matter/ ha, containing about 80 kg N/ha. Under normal growth conditions, milk vetch fresh weight reaches about 20 t/ha during blooming. Milk vetch application of more than 20 t/ha will cause root injury and symptoms of excess N.

Suitable incorporation

Milk vetch is suitable for incorporation at the blooming stage. Because N content is higher and carbohydrate content is lower at this stage than at later stages, the milk vetch will decompose easily. Suitable flooding time is 1 wk after milk vetch incorporation. This reduces the formation of organic acids and the loss of N.

Supplementing with chemical fertilizer

At rice transplanting, the amount of ammonium N in fields treated with milk vetch is minimal and insufficient for rice growth. To promote rice growth in the early stages, a small basal application of a nitrogenous chemical fertilizer with the milk vetch is effective.

With late-maturing rice varieties, the N efficiency of milk vetch does not last to heading. In those cases, topdressing with a nitrogenous chemical fertilizer is very effective for increasing rice yield.

Irrigation management

To reduce rice root injuries caused by the harmful substances formed by excess application of milk vetch, intermittent drainage is very effective.

Factors in green manure introduction

The area planted to milk vetch in Japan has varied across time because of changes in the evaluation of the crop as fertilizer. Socioeconomic changes and advances in agricultural and industrial technology have influenced the variation.

Socioeconomic factors

Kurokawa (1983) divided the history of milk vetch production into four periods to consider the variation in the area planted to milk vetch from a socioeconomic point of view.

During 1867-1915, farmers supplied their own manure. Milk vetch was readily available and its area of production increased.

During 1916-38, chemical fertilizer production increased and prices decreased. But because of the agricultural depression, chemical fertilizers were expensive compared to the price of rice (Table 11, 12). The ratio of fertilizer cost to total cash cost of rice production was about 50%. Farmers produced green manure to reduce cash expenditures. Green manure production increased, reaching its maximum extent in 1933.

During 1939-50, the supply of chemical fertilizers was controlled by the government. Production of ammonium sulfate decreased. The government recommended green manure and compost. In spite of these recommendations, the area planted to green manure crops decreased because of insufficient farm labor and because grains such as barley and wheat were produced instead of green manure crops.

Table 11. Price variations of brown rice, ammonium sulfate-N, and milk vetch seed (Kurokawa 1983).

Year	Price			Ratio		
	A Brown rice (yen/ton)	B Ammonium sulfate N (yen/ton)	C Milk vetch seed (yen/ton)	B:A	C:A	C:B
1913	138	765		5.54		
1918	217	1,891		8.71		
1923	216	1,885		8.73		
1928	205	677	400	3.30	1.95	0.54
1932	138	357	333	2.59	2.41	0.93
1938	228	515		2.29		
1941	327	504		1.54		
1946	2,000	5,171		2.59		
1950	36,134	68,533		1.90		
1955	65,035	108,267		1.67		
1960	69,368	95,200		1.37		
1965	108,969	92,267		0.85		
1970	137,869	83,200		0.60		
1975	259,505	117,381		0.45		
1985	311,130	158,571	1,200,000	0.51	3.90	7.57

Table 12. Nitrogen consumption in Japan (Kurokawa 1983).

	Nitrogen consumed (1,000 ton units)			
	Organic fertilizer [a]		Chemical fertilizer	
Year	Nitrogen from soybean meal	Nitrogen from all organic fertilizers	Nitrogen from ammonium sulfate	Nitrogen from all chemical nitrogen fertilizers
1904	12	22	0.6	0.8
1909	38	53	9	10
1915	51	56	11	14
1921	85	111	35	37
1927	91	117	79	96
1929	71	102	107	143
1935	47	98	167	208
1941	32	76	265	323
1945	19	X	58	74
1949	20	X	298	406
1955	X	X	342	586
1960	20	71	349	798
1965	13	62	250	834
1970			196	1,001
1975			163	910
1980			204	1,027
1984			209	995

[a] X = uncertain data.

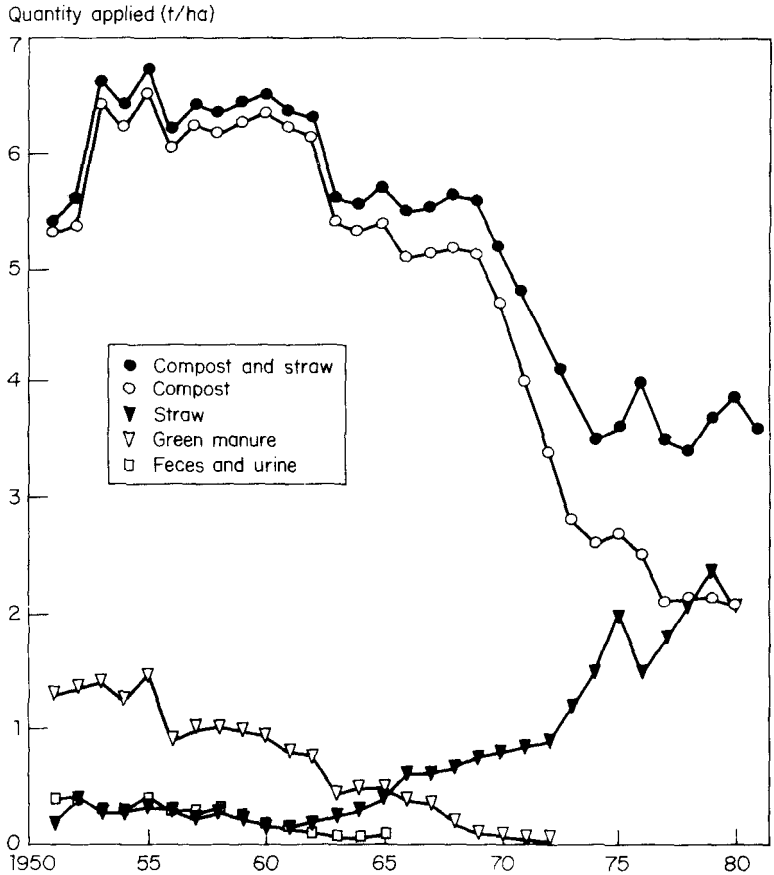
After 1950, ammonium sulfate production expanded rapidly and its price became cheap relative to the price of rice. In 1970, chemical fertilizer costs dropped to 14% of total cash expenses for agricultural materials for rice production. In addition, milk vetch seeds became very expensive compared to the cost of ammonium sulfate and the sale price of rice. As a result, farmers selected chemical N rather than green manure N for rice production and the area planted to milk vetch decreased very rapidly. The area planted in 1980 covered only 4,500 ha, 1.5% of the area planted in 1934, and most of the milk vetch cultivated was used as fodder, not as green manure.

Agricultural factors

Yearly variation in green manure yield. Growth and yield of green manure crops are influenced by climatic conditions. The crops sometimes suffer snow rot disease, especially in snowy districts, and yields decrease. The coefficient between milk vetch yield and the length of snow cover is -0.874 in Toyama Prefecture.

Advanced rice transplanting time. The rice transplanting season in Japan has been advanced by as much as 1 mo, from June to May. Consequently, the time of applying green manure has also been advanced. The result is reduced yield of green manure crops (the quantity of N they add to the soil as they mature), decreasing their value as fertilizer.

It can be concluded that the area planted to green manure crops increases when the fertilizer expense portion of total production costs is large. In selecting green



4. Quantities of organic material applied to rice. 1950-80 (Kodama et al 1984).

manure crops, it is important to consider the natural environment, the cropping calendar for rice and the green manure crops, and socioeconomic factors.

Movement for soil improvement in Japan

The quantity of organic matter, especially compost, applied as fertilizer has decreased while chemical fertilizer use has greatly increased (Fig. 4). As a result, soil organic matter and soil productivity may be reduced.

To prevent that, the government and agricultural cooperatives have recommended applying organic matter to farm fields. Cereal crop straw is more effective than leguminous green manure crops because of the higher lignin content of the straw.

Irrigation water pollution is increasing because of excessive use of chemical fertilizers, increased cattle waste products from intensive breeding, and increased water pollution from urban areas.

To solve the developing problems of declining soil fertility and environment, soil improvement is being promoted in many districts in Japan. The main focus of these soil improvement movements is compost application and recycling of cattle waste and sewage slags. Compost banks have been established in many areas.

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Notes

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Green manure cultivation and use for rice in China

Chen Lizhi

This paper consists of three parts. Part 1 illustrates the yield-increasing effect of green manure and its role in maintaining and increasing soil organic matter and improving soil structure and physical characteristics. Part 2 deals with the place of green manure crops in rice-based cropping systems and four ways of growing green manure crops. Part 3 discusses the effects of crop choice, fertilizer application, and inoculation on green manure production.

China has a 3,000-yr history of using green manure to increase yields of cereal crops and to maintain and increase soil fertility.

In 1949, the area in which GM crops were cultivated, chiefly along the Yangtze River Valley, totaled 1.33 million ha. By the end of the 1970s, the area was nearly 10 million ha, 90% of it ricefields. During the early 1980s, the area decreased because of increased use of inorganic fertilizer.

However, increasing the amount of applied fertilizer somewhat reduces its effect and increases costs. The area planted to green manure crops is therefore growing again, and has reached 6 million ha. Green manure crops are particularly popular in South China, with 1 million ha planted in Jiangxi and 1.3 million ha in Hunan (Xiao 1981).

Yield increase and soil improvement

The green manure crops cultivated in China are mostly legumes that have high amounts of nutrients and lower C-to-N ratios (range 10-20); 1,000 kg of fresh matter contains about 5 kg N, 0.44 kg P, and 3.3 kg K. Decomposition after incorporation appears to be rapid and available N is released quickly. Because some irrigated ricefields have low soil fertility, the effect of green manure on yield is significant.

In 588 experiments in South China, 1,000 kg fresh matter green manure increased rice yields 38-80 kg/ ha (Jiao 1983). Unpublished National Experimental Network of Green Manure (NENGM) data from 1981 to 1986 showed that winter crop green manure applied to ricefields for 4 consecutive years gave an average yield increase of 0.3-1.9 t/ha (Table 1). In 1,500 experiments in South China, 15-20 t fresh azolla/ha incorporated into ricefields increased yields 0.6-0.8 t/ha (Chen S. 1986). Experiments in Zhejiang showed that incorporating 15-22.5 t fresh azolla/ha

Table 1. Effect of green manure on rice yields and organic matter in soil, 1981-86.

Region	Crop	Amount (t dry weight/ha)	Yield (t/ha)		Organic matter (%)	
			Fallow	With green manure	Fallow	With green manure
Jiangsu[a]	Vetch + ryegrass	3.7	5.7	6.8	1.5	1.6
Fujian	Milk vetch	2.9	10.7	12.3	2.4	2.7
Hunan	Milk vetch	2.7	10.1	11.9	2.6	2.7
Yunnan[a]	Vetch	4.5	6.7	7.1	1.9	1.9
Jiangxi	Milk vetch	3.0	5.1	5.5	2.2	3.1
Zhejiang	Milk vetch	4.5	5.2	6.1	3.5	3.7

[a] Single cropping rice.

increased yields 0.7-0.8t/ha. In Guangdong, sesbania interplanted and incorporated increased late rice yields 8-13%. The annual increase in yield of 2 rice crops totaled 0.2-0.6 t/ha, although early rice yields decreased by 2-4% (Chen L. 1986).

Green manure can also raise soil fertility. In experiments of NENGM, organic matter accumulated in different soils. After 4-5 consecutive years of green manure incorporation, organic matter increased 0.1-0.2%, soil bulk density was reduced, and porosity was enhanced (Chen S. 1986).

The effect of green manure is greater on soils with lower fertility (Table 2) (Chen S. 1986). Hunan, Jiangxi, Fujian, and Zhejiang have red soils which usually have lower fertility. Green manure crops are one of the effective measures for soil Improvement.

Green manure cropping sequences

Because farmland in South China is limited, green manure crops and agricultural crops compete for space and time—a competition between land utilization and land upkeep. Coordinating these conflicting needs is the reason for arranging a place for green manure in a cropping system.

Winter green manure and double-cropped rice

Green manure is primarily sequenced with rice in South China. From the 1960s to the 1970s, the areas planted to a winter green manure crop, winter oil rape, and

Table 2. Effect of green manure on organic matter accumulation in soils with different fertility levelr

Treatment	Organic matter (%)		
	High fertility	Moderate fertility	Low fertility
Fallow	3.07	1.71	0.89
Urea (110 kg/ha)	2.86	1.69	0.88
Milk vetch (3.9 t dry matter/ha)	2.95	1.78	0.97

Table 3. Effect of green manure on rice yield and soil organic matter using different planting methods. Hunan, China.

Method	Green manure (t fresh matter/ha)	Rice yield (t/ha)	Organic matter (%)
Fallow	-	9.6	1.70
Interplanted milk vetch with late rice	22.5	10.4	2.15
Milk vetch planted after plowing	16.0	10.2	1.93
Common vetch planted after plowing	8.5	10.3	1.89
Milk vetch + rape + oat planted after plowing	16.5	10.7	1.95
Common vetch + rape + oat planted after plowing	17.6	10.8	2.03

winter wheat were the same, with each accounting for about one-third of the total. However, the area for green manure recently dropped to about one-fourth or one-fifth of the total.

Milk vetch *Astragalus sinicus* L. is the chief green manure crop in this system. Seeds are broadcast in the field before late rice is harvested in mid-November. Part of the vetch is cut for forage or waterlogged compost during the second 10 d of April or earlier. The rest is incorporated as basal manure. If the green manure crop is poor. all the grass will be incorporated.

Production averages 30-45 t fresh matter/ha, with 75 t/ha possible. Usually, it is better to apply 30-40 t fresh matter/ha to moderately fertile soils. Very high amounts of green manure can be unfavorable, even harmful, to plant growth because the nutrients are released faster and are more concentrated. The result is ineffective tillering and lodging.

Recently, milk vetch interplanted with higher rice plant densities has not performed as well. Moreover, the soil becomes harder and has limited permeability that is unfavorable to rice growth. In experimental studies in Hunan, milk vetch or common vetch *Vicia sativa* L. mixed with mustard *Brassica juncea* (L.) Coss. and barley *Hordeum vulgare* L. or oats *Avena sativa* L. were sown after rice with shallow plowing. The mixed cultivation gave better effects than single cropping or intercropping milk vetch with rice (Table 3) (Chen S. 1986).

Intercropping sesbania with early rice

In Guangdong, Guangxi, Jiangsu, Anhui, and other provinces, 30- to 40-d-old *Sesbania cannabina* Pers. seedlings are interplanted about 30 d after transplanting rice. After the early rice harvest, the sesbania plants are incorporated as basal manure for late rice. Although early rice may yield less in such a cropping system, late rice yields increase by 10-13% and the total yield increase of the double crop exceeds 0.4-0.8 t ha.

It is important to choose suitable row spacing for interplanting sesbania. According to experimental results from Guangdong and Jiangsu, the best row spacing for sesbania is 400-600 cm in the south and 200-250 cm in the north (Chen L. 1986).

Azolla cultivated as green manure for rice

Azolla grows fast and has a high N fixation rate. It is cultivated in the ricefields of South China as green manure or fodder.

In winter-flooded fields. A large area of ricefields in Sichuan, Zhejiang, and other provinces is flooded over the winter. Azolla is cultivated in late autumn, winter, or spring. Before transplanting rice in April, part of the azolla may be dredged up for fodder or to make waterlogged compost; the rest is incorporated as basal manure. The azolla cultivated in the winter can produce about 75 t fresh matter/ha; that in the spring, 30-45 t/ha. Because temperatures during azolla growth are low, a cold-tolerant variety should be chosen.

In early ricefields in the spring. Azolla cultivated before or alter transplanting early rice can grow with rice for 20-30 d. Then it is incorporated as topdressing. This azolla crop produces 15-25 t fresh matter/ha.

In early ricefields in the summer. After harvesting early rice, a heat-tolerant azolla variety is incorporated as basal manure for late rice. Insects and diseases must be controlled to produce 20-30 t fresh matter/ha.

In seedbeds for late rice. Azolla cultivated for 20 d is incorporated as basal manure before sowing late rice. It can produce 20-30 t fresh matter ha.

Rice - azolla - fish system. A new system of azolla cultivation has recently been recommended. Ditches 20-25 cm deep and 25-40 cm wide are dug in the ricefields. Along both sides of the ditches, 24-cm-wide ridges are made. Fish are bred and azolla cultivated in the ditches, with two rows of rice planted on each ridge. In this system, part of the azolla is eaten by the fish; the rest is incorporated as topdressing for rice or dredged up to make compost or to feed animals. Fresh matter production is about 100-150 t/ha in April-November. Rice yields are as high as with conventional cultivation; total output value may be raised more than 25% (Gu 1986).

Single rice crop with green manure

This planting system is found in both South and North China. In South China, green manure crops may be cultivated in late autumn. The species include milk vetch, hairy vetch *Vicia villosa* Roth., and cow vetch *Vicia cracca* L. On acid red soils, radish *Raphanus sativus* L. or radish mixed with legume may be cultivated. The following year, they are incorporated as basal manure for a single rice crop.

In North China, the green manure crop may be drilled or broadcast in early spring. The best species are pakchoi *Brassica chinensis* L. or bird rape *B. campestris* L., hairy vetch, and common vetch. In mid-May or early June, before rice is planted or transplanted, the green manure crop is incorporated as basal manure.

About 15-30 t fresh matter/ha may be produced in the South; about 48-72 kg N/ha is supplied in the North.

Double-cropped rice and oil rape with green manure

In Anhui, Jiangsu, and Zhejiang where rice is double-cropped, oil rape is usually planted in the winter. In fertile soils, oil rape is planted after late rice, with common vetch or bur clover *Medicago hispida* Gaertn. as an intercrop. About 1,500 kg oil rape seeds/ha may be produced and 15 t fresh matter/ha incorporated as basal manure for early rice.

Wheat, rice, and green manure

In Sichuan, Hubei, Anhui, and Jiangsu, and the southern part of Honan, there are about 30-50 d between rice harvest and wheat planting. During this time. a catch crop may be planted. Sunn hemp *Crotalaria juncea* L. is the fastest growing green manure crop and is often sown after rice is harvested in the autumn, or it may be interplanted in late summer before the rice harvest. About 15 t fresh matter is incorporated at the end of October as basal manure for wheat.

In another method, green manure is interplanted with wheat. After wheat harvest, green manure is grown for 20-30 d, then incorporated as basal manure for rice.

The green manure crops are primarily hairy vetch, cow vetch, bur clover, sweet clover *Melilotus albus* Desr., common vetch, and broad bean *Vicia faba* L. or garden pea *Pisum sativum* L. Broad bean or pea is either harvested for seeds or picked as fresh pods for vegetable. Fresh matter is incorporated.

Rice and dryland crop with green manure

In some irrigated fields in North China, where water is lacking and rice has been planted for a long time, the groundwater level will be raised and secondary salinization in soils may arise. In this case, rice in rotation with dryland crops is the best measure.

There are three methods of planting green manure:

lnterplanting with single crop maize. In mid-August or later, hairy, vetch is interplanted with maize. The next May, 25-30 t fresh matter/ ha is incorporated for rice.

With wheat. Before or after wheat harvest in mid-May or early June, common vetch, hairy vetch, or sweet clover is planted and grown 60-90 d. Before winter, it is incorporated for rice or maize planting the next spring.

With double-cropped wheat - maize. In mid-May, maize is interplanted with wheat. After the wheat harvest, from late June to early July, sesbania, sunn hemp or mungbean is planted in the wheat stubble. When the maize has been harvested, green manure and maize are incorporated. Rice is planted the following year.

If the green manure crop is hairy vetch or oil rape, it is interplanted with maize in August or planted the next spring. It is incorporated before rice is transplanted.

Planting in saline soils

The coastal areas of Jiangsu and Zhejiang have large areas of saline soil. In these regions, azolla is cultivated in the spring and sesbania planted in the summer and incorporated for soil improvement. After planting green manure for 1-2 yr, rice can be grown.

Cultivation techniques for green manure crops

The effectiveness of green manure is somewhat related to its biomass production. Biomass, on the other hand, is affected by management. Usually, 15-30 t green manure/ ha may be produced, with 75 t/ha the highest. Good management is important in increasing yields.

Choice of green manure crops

The characteristics and management of green manure crops differ. For example, milk vetch requires a cooler climate and well-drained soil. Its seeds germinate at 4-5 °C; optimum growth temperature is 15-20 ºC. It cannot grow well on waterlogged land. The optimum soil water content for this crop is 60-75% of field capacity in sandy or clay loam soils. If water content is lower than 40% of field capacity, the plant will stop growing or die.

Radish can grow well on acidic and poor soils and can be cultivated on low-yielding fields with acid red soil. Sesbania needs warm and moist conditions; its seeds germinate at 15 °C, with 25-30 °C the optimum growth temperature. It will grow normally on flooded soil if the top of the plants is above the water surface.

Azolla filiculoides Lamk. can resist lower temperatures. *Azolla imbricata* (Roxb.) Nakai. and *Azolla caroliniana* Willd. can grow at higher temperatures.

Some characteristics of green manure crops are given in Table 4 (Gu 1986).

Fertilizer application

The ability of leguminous plants to utilize P is rather strong. However, available P is deficient in some regions. Applying phosphate can give significant results. K gives similar effects as phosphate (Table 5).

Phosphate application increases green manure production and the N and P contents of plants. Phosphate applied to green manure crops increases rice yields more than applying phosphate directly to the rice crop. Experiments in Jiangsu indicate that rice absorbed 66.2% of the phosphate applied to green manure crops; 1 kg superphosphate might increase rice yield 5 kg/ha. Rice absorbed only 14.7% of the phosphate added just before planting, and 1 kg phosphate increased rice yield only 1.5 kg/ha. In Jiangxi, when fused calcium magnesium phosphate was applied before planting milk vetch, 1 kg phosphate increased rice yield 3.2 kg. Applied directly, 1 kg phosphate increased rice yield only 2.6 kg/ha (Gu 1986).

Inoculation

Most leguminous crops can form nodules and fix N without inoculation. But some species have difficulty forming nodules without inoculation, especially in regions

Table 4. Characteristics of green manure crops.

Species	Resistance [a] to						Temperature (°C)			PH	Seeding rates (kg/ha) when broad-cast or close drilled
	Moist-ure	Drought	Adverse soils	Frost	Heat	Shade	Germi-nation	Frost-bite	Killing frost		
Asrragalus sinicus	H	L	M	H	L	H	5-8	−7	−17	5.58.0	30-37.5
Vicia villosa	M	H	H	H	M	M	3-5	−12	−20	4.5-9.0	60-90
Vicia sativa	L	H	M	M	M	M	3-5	−5	-8	5.0-8.5	90-120
Vicia cracca	M	M	M	L	M	L	3-5	−3	-8	5.0-8.0	45-75
Sesbania cannabina	H	M	H	L	H	M	12			5.5-9.0	75-90
Raphanus sativus	M	M	H	M	M	L	3-4	-5		4.8-7.5	15-22.5
Brassica chinensis	M	M	M	M	M	L	2-3	−8		5.08.5	15-22.5
Azolla imbricata	H	L	H	L	M	H	5[b]	0	−2	4.5-7.5	4500-600[c]

[a] H = high, M = moderate, L = low. [b] Lowest temperature for growth. [c] Fresh azolla.

Table 5. Effect of applied fertilizer on green manure production.

Region	Trials (no.)	Crop	Fertilizer	Amount of fertilizer (kg/ha)	Production increase (kg/kg P or K)
			Phosphorus		
Zhejiang	188	Milk vetch	Superphosphate	170-280	335
Jiangsu	123	Milk vetch, vetch	Superphosphate	170-280	365
Zhejiang	100	Milk vetch, vetch	Fused calcium, Magnesium phosphate	240-340	250-438
Sichuan	56	Milk vetch, vetch	Ground phosphate, Rock phosphate	450-1080	74
			Potassium		
Zhejiang	46	Milk vetch	Potassium sulfate	150	47-56
Jiangsu	17	Vetch	Potassium chloride	115	131
Hunan	70	Milk vetch	Cement kiln dust	750	172

Table 6. Effect of inoculation on milk vetch production.

Region	Period of cultivation	Production (t/ha)		Increase(%)
		With inoculation	No inoculation	
Yancheng, Jiangsu	First year	32.9	7.0	370.0
Yangzhou, Jiangsu	First year	75.4	18.0	318.9
Quxian, Zhejiang	First year	20.1	3.0	570.0
Zhoushan, Zhejiang	Many years	52.2	42.5	22.8
Hangzhou, Zhejiang	Many years	42.4	32.2	31.7
Changsha, Hunan	Many years	41.4	17.1	142.0

where no such crop had been planted before. Milk vetch is responsive to inoculation. Before 1960, it did not grow normally in the southern part of Guangdong and Guangxi. When inoculation and drainage were introduced, milk vetch grew successfully in ricefields and the area of cultivation increased quickly. A number of experiments indicated that milk vetch inoculated with rhizobia before sowing had 2-3 times the production without inoculation (Table 6) (Jia 1986).

The future

The area for green manure crops is not as large as before because farmland is limited and grass used only as manure is not economic. Raising the economic benefit of green manure is important.

In China, green manure cultivation should consider three points.

1. Its many uses. Green manure not only is incorporated as manure, but can also be used for fodder or seeds. Its economic benefits may be increased.
2. Many methods of cultivation. Green manure can be planted not only on farmland, but also on uncultivated land, forest land, orchard, water, or hills.

Suitable crops should be selected so that the area planted to them may be increased.

3. Higher production. China lacks farmyard manure and other types of manure; therefore, organic matter in the soil is not high. Planting green manure is a good way of increasing organic content. Techniques for higher productivity are necessary, so that green manure produced on 1 ha could be applied to 2-3 ha.

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Notes

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Green manure crops in irrigated and rainfed lowland rice-based cropping systems in South Asia

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Future increases in food production must come through increased productivity and crop intensification. Adequate nutrient supplies will be crucial in realizing the full potential of high-yielding varieties grown in intensive cropping systems. Escalating prices for inorganic fertilizers, the wide occurrence of multinutrient deficiencies in intensively cropped soils, and overall reductions in soil productivity demand a fresh look at the role of organic manure. Green manuring is a cheap and feasible alternative to inorganic N sources. Several plant species have been used for green manuring in different regions. Dhaincha *Sesbania aculeata,* a species widely used for green manuring, can be grown on a variety of soils with varying pH (4.5-9.5). Rice-based cropping systems are particularly amenable to green manuring. Research shows almost universal beneficial effects of green manuring on rice yields. Green manure can substitute for up to 60-100 kg fertilizer N/ha. Many studies have shown it can enhance the availability of native or applied P and of micronutrients. Green manuring hastens the reclamation of alkali soils, largely because Increased CO_2 production during decomposition of the green manure crop enhances the solubility of lime. Recent research has attempted to optimize green manuring benefits by deflning growth period, time of incorporation, etc. An alternative to growing a crop exclusively for green manure is to grow a short-duration pulse (e.g., mungbean *Vigna radiata,* cowpea *V. sinensis,* pillipesera Phaseolus trilobus) for a green pod harvest, with straw incorporation. Strategies to optimize nutrient use for crop production must recognize the huge potential offered by green manuring.

Nearl) 75% of the available arable land resources in Asia are already under cultivation (Herrera 1976). Increased food production now must come primarily through increased crop productivity and increased cropping intensity. In India, food production has nearly doubled in the last two decades. This has been achieved through the adoption of high-yielding crop varieties, intensive cropping, and improved management practices, including improved fertilizer use. The Fertilizer Ahsociation of India (1985) estimated that nearly 75% of the improvement in productivity could be attributed to increased fertilizer use. Fertilizer consumption patterns over the last three decades support that contention. Total consumption of nutrients rose from 0.13 million t in 1955-56 to 8.7 million t in 1985-86.

Nearly one-third of the total N consumed in Indian farming is used for rice. Rice is grown over an area of about 40 million ha. A considerable fraction of the P and K fertilizer used is also for rice. But fertilizer production in India lags behind actual consumption, compelling large imports worth more than US$1 billion annually. The increase in fertilizer prices combined with the low purchasing power of farmers is imposing serious limitations on increased crop production and calls for increased efforts to mobilize cheaper and alternative sources of nutrients.

Although the role of organic manure crops in maintaining soil productivity has been well established and their use is widespread, the advent of high-yielding crop varieties in recent years caused organic manure use to decline in favor of mineral fertilizers. Now there is renewed interest in organic manure, largely because increasing costs of fertilizers, greater incidence of multiple nutrient deficiencies, and deterioration in physical soil properties are resulting in reduced yields.

Farmyard manure, compost, and green manure are the organic materials commonly used. Because the availability of farmyard manure and compost is limited, green manure offers greater potential as a feasible and cheaper substitute for fertilizer N.

Green manuring procedures

Green manuring is the practice of incorporating *in situ* easily decomposable plant material (other than crop residues)—either crops grown specifically for organic fertilizer or plant materials brought from outside the field. *In situ* green manuring is done by turning under the entire plant, usually a leguminous crop. When brought from outside, the green matter may consist of leaves, twigs, and loppings from selected trees or bushes.

Species

A large number of crops and plant species have been used as green manure to increase rice production (Table 1). Some of the tree species and other plants used extensively for green leaf manuring in the southern Indian states are *Thespesia populnea, Cassia auriculata, Pongamia glabra, Melia azadirachta, Calotropis*

Table 1. Some common leguminous green manure crops.

Local name	Botanical name	Growing season	Green matter yield (t/ha)	N (%)
Sunn hemp	*Crotalaria juncea*	Wet season	21.2	0.43
Dhaincha	*Sesbania aculeata (bispinosa)*	Wet season	20.0	0.43
Pillipesera	*Phaseolus trilobus*	Wet season	18.3	1.10
Mungbean	*Phaseolus aureus*	Wet season	8.0	0.53
Cowpea	*Vigna sinensis*	Wet season	15.0	0.49
Guar	*Cyanopsis tetragonoloba*	Wet season	20.0	0.34
Senji	*Melilotus alba*	Dry season	28.6	0.57
Khesari	*Lathyrus sativus*	Dry season	12.3	0.54
Berseem	*Trifolium alexandrinum*	Dry season	15.5	0.43

gigantea, Jatropha gossypifolia, J. glandulifera, Gliricidia maculata, Tephrosia purpurea, T. candida, Cassia tora, and *Ipomoea carnea* (Abdul Samad and Sahadevan 1952, Sanyasi Raju 1952).

Techniques

Green manuring techniques differ by rice-growing region. Subramanian and Dorairaj (1952) described the practice used for semidry paddy in Chingleput and North Arcot districts of Tamil Nadu. Rice seed is drilled under semidry conditions in July-August, after the onset of the southwest monsoon. Upon the onset of the northeast monsoon, when water tanks are full, the crop is irrigated. Incorporating green leaf manure before or at sowing is popular in these areas. However, decomposition of incorporated green matter is nonuniform and often incomplete.

An alternate method involves sowing a green manure crop with rice. The green manure crop is pulled out and trampled in about 2 mo after sowing, when the rice crop is irrigated. This practice gave the best results when sunn hemp was used. However, a crop like *Sesbania aculeata* would appear to be more promising, because sunn hemp becomes fibrous with age. In field experiments. yields were 42% higher with green manure.

In Tamil Nadu, Veeraswamy and Kunjamma (1958) suggested using guar *Cyanopsis tetragonoloba* as a vegetable and green manure crop. At 60 d after seeding (DAS), guar yielded about 600 kg green pods ha and 20 t green matter/ ha. The material contained 3.86% N on dry weight basis and decomposed easily.

In the deltaic areas of Godavari and Cauvery, *Vigna sinensis* and *V. radiata* green pods are harvested for vegetables at 50 to 60 DAS. The residues have been used for green manuring. *Phaseolus trilobus* is used as forage and green manure crop. During the fallow season, it is allowed to grow 45-50 d before it is incorporated. In some fields, the farmers graze milk cattle, then allow the crop to regrow for about 1 mo before it is incorporated.

In northern India, a green manure crop, mostly *S. aculeata,* is sown soon after wheat harvest in mid-April. To hasten germination and gain time, sesbania seeds are soaked overnight before they are broadcast in shallow standing water. The green manure crop is incorporated before transplanting rice the end of June or early July.

Performance

The effect of green manure crops *Crotalaria juncea, S. aculeata, V. sinesis,* and *P. trilobus,* incorporated at 60 DAS, on field of the following rice crop was evaluated at Coimbatore (Sanyasi Raju 1952). All the crops produced more than 20 t green matter/ha and contributed 74-134 kg N/ha (Table 2). Green manure plots had about 200% higher grain yields than nonfertilized plots. Soil N status improved considerably with continuous green manuring.

Varadarajan and Sanyasi Raju (1956) studied the effect of different green leaf manures on rice. Green leaves of *Delonix, Calotropis, Gliricidia, Pongamia, Thespesia,* and *Croton sparsiflorus* were incorporated to supply 45 kg N/ha. Performance was compared with no manure and 45 kg N as ammonium sulfate/ ha. Grain and straw yields with ammonium sulfate were 304 and 283% higher than in no

Table 2. Relative performance of some green manure crops.[a]

Green manure crop	Green matter (t/ha)	N added (kg/ha)	Rice-grain yield (t/ha)	Increase (%) over no manure	Soil N[b] (%) with continuous green manuring
Sunn hemp	27.8	134	3.47	198	0.109
Dhaincha	21.1	133	3.62	207	0.141
Pillipesera	22.3	102	3.62	207	0.109
Cowpea	21.0	74	3.33	180	0.101

[a]Source: Sanyasi Raju 1952. [b]Soil N without green manure was 0.079%.

manure plots. Croton leaves gave distinctly higher yield than leaves of other species, and nearly equaled yield with ammonium sulfate.

Dargan et al (l975) evaluated green manuring with *S. aculeata* grown for 65 d. Rice yields in green-manured plots equaled yields in plots that received 80 kg N/ha after fallow (Table 3).

Nagarajah and Nizar (1982) evaluated the effect of incorporating wild sunflower *Tithonia diversifolia* green leaves and stems on nutrient contribution and rice yield. Application of 40 kg N, 10.5 kg P, and 8 kg K with 9 t green manure/ha produced a grain yield equivalent to that obtained with 82 kg N, 12 kg P, and 32 kg K ha.

Joseph (1985) used *Eupatorium odoratum,* a noxious weed, as green leaf manure. Composts of eupatorium and gliricidia leaves and cow, goat, pig, and poultry manures were prepared. Composts at 6 t/ha were compared with 70-34-35 kg NPK/ ha. Yields with composts ranged from 5.1 to 5.7 t/ha; with NPK, yield was 3.7 t/ha.

Maskey and Bhattarai (1984) evaluated some green manure crops (*Artemisia vulgaris, Adhatoda vasica, Helianthus annuus,* and *Eupatorium gladiosa*) commonly used in Nepal in a greenhouse experiment. Leaves were incorporated in the soil in pots at rates equivalent to 100 kg N/ ha. Manuring with dried *A. vasica* gave 54% higher rice grain yield; *H. annuus,* 49%; *A. vulgaris.* 31 %; and *E. gladiosa,* 13%.

Rekhi and Meelu (1983) evaluated the role of green manuring with *P. aureus* grown in summer in a wheat - mungbean - rice rotation in a 3-yr field study. Mungbean cultivar G-65 was sown in mid-April immediately after wheat harvest.

Table 3. Effect of green manuring with dhaincha grown for 65 d on rice yield at different levels of N application.[a]

Rice grown after	Rice yield (t/ha)				
	No N	N40	N80	N120	Mean
Fallow	2.6	3.9	5.6	6.0	4.5
Green manuring	5.6	6.3	7.3	7.7	6.7
CD at P = 0.05					
Fallow vs green manure =	0.4				
N =	0.6				

[a] Source: Dargan et al 1975.

Table 4. Effect of burying mungbean straw on rice yield in wheat - mungbean - rice cropping sequence.[a]

Treatment		Rice grain yield[b] (t/ha)
Mung straw	kg N/ha	
Removed	0	3.17
	60	5.21
	120	7.09
Buried	0	6.46
	60	7.37
	120	8.53
CD at P = 0.05		0.51

[a]Source: Rekhi and Meelu 1983. [b] Av of 3yr.

The crop matured the 4th week of June. In one treatment, whole mungbean was harvested; in another treatment, mungbean pods were picked and the straw incorporated the day before rice was transplanted. Rice variety PR106 was planted the last week of June. Mungbean produced 0.86 t grain/ ha; incorporating the straw added about 100 kg N/ha, which had an effect equivalent to that of 60 kg urea N/ha (Table 4). They ascribed the beneficial effect of mungbean straw incorporation not only to N added, but also to its favorable effect on the availability of soil N.

In studies in acid soils at Trichur (KAU 1984), the combination of azolla and urea or dhaincha and urea (50:50) resulted in higher rice grain yield (Table 5).

Management

Joseph (1986) studied the effect on rice yield of in situ incorporation of *S. aculeata* alone and in combination with inorganic fertilizers in an acid soil of pH 4.9. *S. aculeata* was incorporated at 45 DAS at 25 t green matter/ha, and rice variety Triveni was planted 2 wk later. Incorporation of green manure plus low levels of inorganic fertilizers resulted in higher rice grain yield than yields where higher fertilizer doses were applied alone or with green manure (Table 6). Joseph concluded that a green manure plus low fertilizer application was more economical than higher fertilizer treatments.

Ghai et al (1985) studied the green manuring potential of 38 sesbania accessions, including annual and tree types. The annuals accumulated more biomass and their maturity period was shorter (180-270 d) than that of the tree types.

Table 5. Effect of organic and fertilizer N on rice grain yield.[a]

Treatment	Grain yield (t/ha)
No N	3.8
80 kg N/ha (50% each through dhaincha and urea)	4.5
80 kg N/ha (50% each through azolla and urea)	4.8
80 kg N/ha (50% each through blue-green algae and urea)	4.1
80 kg N/ha through farmyard manure	4.1
CD at P = 0.05	0.5

[a]Source: Kerala Agricultural University 1984.

Table 6. Rice grain yield as influenced by green manuring with dhaincha and fertilizer N application.[a]

Treatment	Grain yield (t/ha)
Green manuring with dhaincha (A)	3.2
NPK at 70-35-35 kg/ha	4.1
A + NPK at 35-17.5-17.5 kg/ha	4.2
A + NPK at 52.5-26-26 kg/ha	3.9
A + NPK at 70-35-35 kg/ha	3.8
CD at P = 0.05	0.49

[a]Source: Joseph 1986.

N content at 30 d ranged from 1.96% for *S. speciosa* to 4.84% for *Sesbania* sp. PL Se 16. Annuals such as *S. aculeata* CSSRI and *Sesbania* sp. PL Se 17 could contribute about 70 kg N/ha at 45 DAS and about 100 kg N ha at 57 DAS.

Bhardwaj (1982) evaluated the effect of *S. aculeata* age at incorporation and the time allowed for decomposition on rice yield. Contrary to the general recommendation that at least 15 d decomposition be allowed before planting rice, his results showed that maximum rice yield was obtained when rice was transplanted almost immediately after incorporating the green manure crop (Table 7). Increasing the time for decomposition resulted in significant yield losses. Age of the green manure crop did not significantly affect rice yield. This would imply that *S. aculeata* could be grown for only 45-50 d instead of the normally recommended 60 d.

Ghai et al (1985) reported that the rate of N accumulated by *S. aculeata* started decreasing after about 50 d and total N accumulation started leveling off (Table 8, Fig. 1).

Although the direct benefit of green manuring on a following rice crop is well established, long-term effects have not been investigated in detail.

Table 7. Rice yield as affected by age and decomposition period of dhaincha as green manure at 2 locations.[a]

Age of dhaincha (d)	Decomposition period (d)	Grain yield (t/ha)	
		Karnal (cv P2-21)	Kanpur (cv P33)
45	0	5.9	5.5
	10	5.6	5.1
	20	4.4	4.9
55	0	6.0	5.4
	10	5.6	5.6
	20	5.1	5.0
65	0	6.2	5.5
	10	5.7	5.3
	20	4.9	5.2
CD at P = 0.05		0.4	0.2

[a]Source: Bhardwaj 1982.

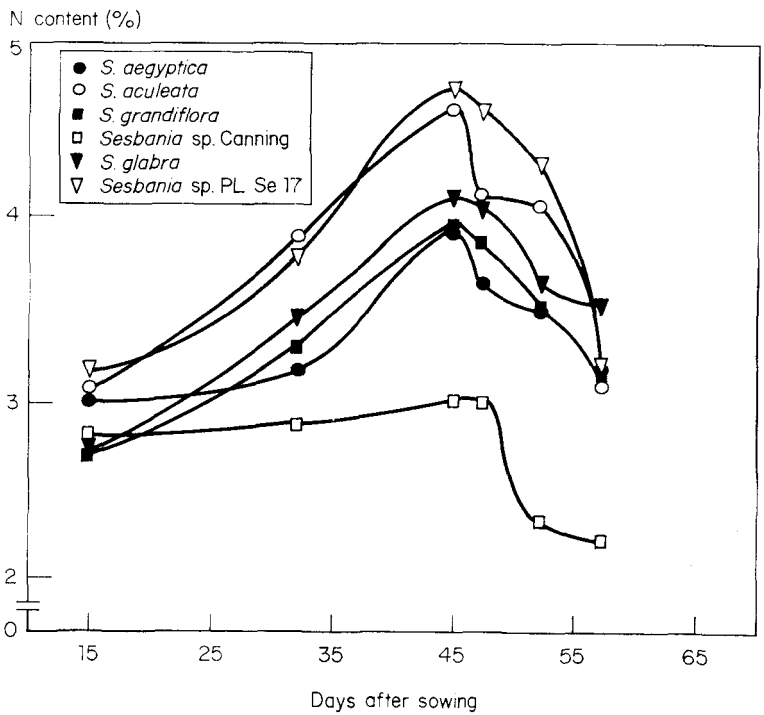
Table 8. Wet biomass and N turned in by *Sesbania* sp. PL Se 17 at different growth stages. [a]

Age (d)	Biomass (t/ha)	N (kg/ha)	N accumulation rate (kg/d per ha)
15	1.50	5.65	0.377
32	4.77	30.06	0.939
45	7.14	71.15	1.581
52	18.28	98.64	1.896
57	26.74	105.87	1.857

[a]Source: Ghai et al 1985.

Sivaraman (1958) reported that increases in rice yields due to green manuring were cumulative, and steadily increased each year in studies conducted in Tamil Nadu. He also observed that green manuring not only increased rice yields, but also improved rice performance under drought.

Bhardwaj and Dev (1985) reported a slight buildup in soil N status following rice harvest (Table 9). However, the effect of green manuring on wheat yield was not significant (Table 10).



1. N content (dry wight basis) of 6 sesbanias at various stages of growth.

Table 9. N content of soil after rice harvest as affected by green manuring. [a]

Age of sesbania at incorporation (d)	N content[b] (%)		
	Kanpur (0.047)	Una (0.056)	Palampur (0.058)
45	0.049	0.049	0.061
55	0.053	0.059	0.069
65	0.055	0.068	0.076
CD at P = 0.05	0.008	0.012	0.010

[a]Source: Bhardwaj and Dev 1985. [b]Initial N content for each site is in parentheses.

Availability of essential nutrients

The benefits of green manuring are generally interpreted in terms of the capacity to substitute for inorganic fertilizer N. The role of green manure in enhancing the availability of other macronutrients and micronutrients has not been documented as extensively. Ranjan and Mothandaraman (1986) reported increased availability of P from rock phosphate applied to rice with green manuring. Karuppiah and Thangamuthu (1986) studied the response to P applied as superphosphate and rock phosphate in combination with organic materials (e.i., *Leucaena leucocephala* leaves as green manure, water hyacinth compost, and farmyard manure). Results showed that the combination enhanced rice yield (Table 11). Beri and Meelu (1980) suggested that P applied to a green manure crop in soils with low P status increased green manure production, N accumulation, and rice yield more than P applied to rice.

Enhanced availability of some micronutrients (e.i., Fe) due to green manuring was reported by Takkar and Nayyar (1986). Intensive studies on the transformation and availability of other micronutrients are needed.

Alkali soils reclamation

Reclamation of alkali soils basically involves replacing Na on the exchange complex with more favorable Ca ions. The solubility of lime, which is nearly always present in

Table 10. Residual effect of green manuring with dhaincha before rice on the yield of the following wheat. [a]

Treatment	Grain yield (t/ha)	Straw yield (t/ha)
Fallow	2.8	4.19
Green manuring with dhaincha	3.0	4.47
CD at P = 0.05	ns	ns

[a]Dhaincha grown after 60 d and buried before growing rice in kharif. Av of 2 yr's data.

Table 11. Effect of application of P and organic fertilizer on rice grain yield.[a]

Treatment	Grain yield (t/ha)	
	Wet season	Dry season[b]
Control	4.0	4.0
Rock phosphate 50 kg P_2O_5/ha	4.4	4.9
Superphosphate 50 kg P_2O_5/ha	5.4	4.2
Green leaf manure 12.5 t/ha	4.9	4.8
Rock phosphate +green leaf manure	5.0	5.3
Superphosphate +green leaf manure	5.9	4.9

[a]Source: Karuppiah and Thangamuthu 1986. [b] Residual effect.

alkali soils in significant amounts, is very low because the pH of alkali soils is high. There is an intimate relationship between soil pH, partial pressure of CO_2, and Ca ion activity in calcareous alkali soils. Evidence is increasing that agronomic or cultural measures that increase CO_2 production in the soil also enhance the soluble Ca status of soils. That, in turn, replaces exchangeable Na, resulting in the improvement of alkali soils.

Soil incorporation of easily decomposable plant materials has resulted in increased and rapid production of CO_2 (Robbins 1986). For this reason, green manuring has been suggested as an important management practice for the reclamation of alkali soils.

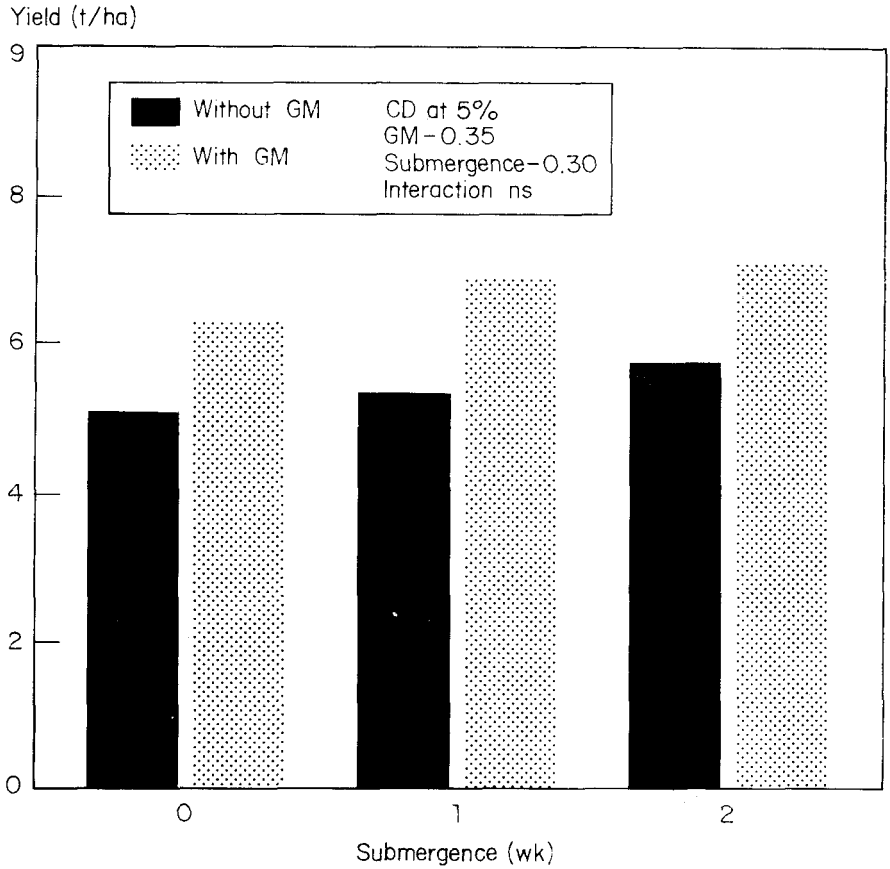
Swarup (1986) studied the effect of green manuring with *S. aculeata* grown for 50 d and of decomposition time on the yield of rice grown in a sodic soil. Green manuring significantly increased rice yield, contributing 111.6 kg N/ha (Fig. 2). Seven days of submergence with incorporated green manure significantly improved yield over no flooding. Continuous submergence improved the sodic soil, and green manuring further decreased pH and exchangeable sodium (Table 12).

Krishnamoorthy et al (1985) observed the benefits to farmers of using gypsum and green leaves of *Delonix regia* in the Trichy region of Tamil Nadu. Initial soil pH ranged from 8.6 to 9.5 and exchangeable sodium percentage was 18.2 to 40.4. They concluded that green manuring could partially substitute for the gypsum required to reclaim alkali soils, and that this practice was more economical than using gypsum alone.

Constraints

Although the value of green manuring for increasing rice production by supplying nutrients and maintaining soil productivity is well established, the practice has not been widely adopted by rice farmers. Farmers' reluctance apparently is due to one or more of the following factors:

- In an intensive cropping sequence, farmers do not wish to set apart 6-8 wk exclusively for growing a green manure crop with no direct benefit.
- When rice is grown after wheat, farmers find it extremely difficult to do farm operations in the intense heat of May and June, immediately after wheat harvest.



2. Response of rice to pretransplanting submergence with and without sesbania green manure (GM). Central Soil Salinity Research Institute, Karnal, India.

- Availability of water for raising a green manure crop may pose restrictions.
- The availability of good seed is a widespread problem.
- Farmers are unable to appreciate the benefits of green manuring, since the benefits sometimes are not as spectacular as those observed from direct application of inorganic fertilizers.

Future efforts

In the face of increasing fertilizer costs and limited supplies, green manuring has a large potential to augment nutrient supplies. Early research efforts to define green manuring practices for different agroclimatic regions have been only modest. Improved experimentation is needed so that crop responses to green manuring can be quantified. The factors responsible for crop responses must be identified to develop sound scientific strategies for green manuring practices.

Table 12. Effect of presubmergence and green manuring with dhaincha on N contribution to rice and properties of a sodic soil.

Treatment		Soil properties[a]			
N source	Presubmergence (d)	At planting		At harvest	
		pH	ESP	pH	ESP
No green manure	0	9.6	45	9.4	36
150 kg N/ha	7	9.6	42	9.3	34
	14	9.5	42	9.3	34
Greenmanure[b]	0	9.3	35	9.0	
30	7	9.2	32	8.9	28
150 kg N/ha	14	9.1	32	8.8	25
CD at P = 0.05					
Green manure			3.2		2.4
Submergence			1.5		1.2

[a]ESP = exchangeable sodium percentage. [b]Biomass turned in = 3.8 t/ha, N turned in = 111.6 kg/ha.

The patterns of nutrient release during green manure decomposition and the patterns of rice crop utilization need to be better understood. The long-term effects of green manuring on soil properties and crop responses need evaluation. Knowledge of the changes in soil physical properties would be particularly valuable. Organic matter decomposition sets up a chain of physicochemical events which alter the form and availability of several nutrient elements. Green manuring has a special place in problem soils—soils of low fertility, those with alkali problems, etc. Identification of species or strains that accumulate high N or biomass is another research area of importance. With advancing knowledge, the practice of green manuring will certainly contribute to increased productivity.

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Notes

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Potential of sesbania as a green manure in saline rice soils in Thailand

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Rice-based cropping patterns in Thailand vary from region to region. Very little economic evaluation is available except in the Northeast region, where crops other than rice showed negative net income. Thus, it appears possible to grow a crop for green manure. Green manure crops can supply P and N and contribute to soil organic matter status. The advantages and disadvantages of 18 species as green manure crops, as well as their seed production, are presented. *Sesbania* spp. show great potential as green manure crops because of their tolerance for salinity, acidity, and flooding.

Population increases cause continuous pressure on agricultural land. To improve land use efficiency, production per hectare must be increased. At the same time, soil fertility and long-term maintenance of soil productivity have to be considered. Population pressure has necessitated developing marginal and problem soil lands for agricultural production.

In the saline soils of Northeast Thailand, a greater than normal loss of organic matter and low fertility need to be rectified. With the high price of chemical fertilizer and the lack of materials for making compost, green manuring with legume species is the best option for fertilizing soil. Use of a natural source of N is the most suitable fertilization method in saline soils (App and Eaglesham 1981, Jefferies et a1 1981, Kumazawa 1984).

Sesbania can be used as a green manure to improve soil fertility and to increase nutrients for the crop. Its use increases the soil's capacity to absorb nutrients and improves soil structure and microbial activity. Soil chemical properties also are improved, and buffering capacity is better. Green manure renders the next crop more tolerant of disease and insects and prevents soil erosion (Dreyfus et a1 1983. Evans and Rotar 1986, Ragland et a1 1986, Singhabutra et a1 1987).

Sesbania rostrata is able to nodulate along its stem as well as roots. Those nodules can fix N and release it to the soil after plowing (Dreyfus et a1 1983). Rinaudo et a1 (1983) found that two-thirds of the N fixed is released to the soil. *S. aculeata* is particularly favorable for saline conditions. It has a high biomass, grows fast, and is salt tolerant (Dargan et a1 1982). In a cropping system of alfalfa - barley - wheat, *S. speciosa* as a following green manure crop contributes to high yields in the ensuing crop (Kanwar et a1 1985).

A good green manure crop for Thailand should have the following characteristics (Chinapun 1982, Sratongkam 1976): fast growth, drought tolerance, well developed root system, a large biomass, tolerance tor· diseases and insects, easy incorporation, and rapid decomposition to yield a large amount of plant nutrients. The green manure should be easy to propagate and easy to eradicate to prevent it from turning into a weed. It should lend itself to use as human food or animal feed and should be easy to introduce into a cropping system. Cultivation should require low labor inputs.

Cropping patterns in Thai villages

Cropping systems vary with physiography and rainfall, factors, that affect the type and yield of crops. Few serious studies have been carried out on cropping systems in Thailand except in the Northeast. Studies focus on rice as the main crop in a cropping system with short-duration legume species before or after rice. Little information is available on the economics of cropping systems.

Northern region

The Northern region is a narrow basin between valleys (Plangkool 1980) that is used for rice growing under prolonged flooding. The native varieties used are photoperiod sensitive, have long duration, and cannot be grown with another crop. Where upland rice is grown, however, short-duration field crops such as mungbean and peanut can be planted before transplanting and after rice harvest (Somrith 1982). Cropping systems research is mainly on short-duration legumes. No economic studies have been undertaken.

Central region

Most of the Central region is a low-lying basin, which is waterlogged for long periods. Rice is the main crop. Cropping systems research is needed to find the most appropriate crop to be planted before and after rice (Phopan 1986). Experiments in Amphur Bang Pae, Chantaburi Province, showed that a crop before rice should be of short duration (such as maize, sweet maize, and mungbean) and should be ready for harvest before flooding in July. Rice should be photoperiod sensitive, of long duration, and tall because the amount of water cannot be controlled.

Crops planted after rice generally give low yields because of water shortage at the end of the growing season. The recommended crop is mungbean, direct seeded after rice (Chandrapanya et al 1982).

Northeast region

The Northeast can be divided into areas for three main crops–upland crops, upland rice, and rainfed rice (Plangkool 1980). Two crops can he planted in a year. Yields vary with environment. First crop peanut and cowpea yields are good, but second crop yields are usually low because of moisture level and insects. Where cassava is the main crop, there is some degree of intercropping. Soybean gives high yields; peanut, mungbean, and cowpea tolerate drought and sandy, low-fertility soil but yields are not high. Where sisal is grown, there is a short period after harvest when

short-duration crops could be grown; however, these crops give low yields even when sisal is harvested early to prolong the growing season.

Peanut grown as a first crop invariably has good growth. Mungbean only grows well in fertile soils. Peanut as a second crop gives low yields because it requires a long growing season and suffers from water shortage. For Ubonratchathani Province in the eastern central area, Chandrapanya et al (l982) reported that a crop can be grown before rice because water is adequate. In experiments in Pimai Nakornratchasima Province to the west, yield of a crop grown before rice was not as high as expected because of flooding and insect infestation. Only short-duration sweet maize escaped insect damage.

Many researchers (Chandrapanya et al 1982, Charoenwatana et al 1978b, Patanothai et al l977) have conducted extensive studies in this area. Charoenwatana et al (1978b) studied crops before rainfed rice. In Khon Kaen, harvest was not good because of heavy rains and flooding. but mungbean and cowpea yielded better than peanut. Lowland rice gave lower yields than upland rice because of the shorter growing season and because of infestation by stem borer and false smut. Short-duration photoperiod-insensitive rice can be grown in the uplands before wet season rice.

In economic studies of rice-based cropping systems, the second crop gave good yields, but the net result was a loss (Table 1) (Chandrapanya et al 1982; Charoenwatana 1978a.b).

Table 1. Economic studies[a] of double-cropping of field crops with rice in rainfed lowland fields (Chandrapanya et al 1982; Charoenwatana et al 1978a. b).

Crop	First crop		Rice		Net income ($/ha)
	Yield (t/ha)	Net income ($/ha)	Yield (t/ha)	Net income ($/ha)	
		Muong village			
Peanut	0.02	−71.76	1.59	155.04	83.28
Mungbean	-	−45.00	1.58	154.28	109.28
Cowpea	-	-44.00	1.01	97.56	53.56
		Jode village			
Peanut	-	−72.52	1.03	98.76	26.24
Mungbean	0.05	−32.76	1.36	132.56	99.80
Cowpea	0.08	−28.80	1.61	157.56	128.76
		Pesen village			
Peanut	0	−73.24	1.89	185.04	111.80
Mungbean	0.03	−36.56	1.61	156.84	120.28
Cowpea	0.14	−18.72	1.53	148.76	130.04
		Koksri village			
Peanut	-	−71.24	1.68	164.36	93.12
Mungbean	0.17	−11.20	3.76	371.84	360.64
Cowpea	0.03	−35.76	1.78	173.76	138.00
		Haad village			
Peanut	0	−37.76	2.16	21 1.84	174.08
Mungbean	0	−38.76	2.08	203.76	165.00
Cowpea	0	48.00	1.79	175.64	127.64

[a]Current prices: rice = $0.12/kg, peanut = $0.24/kg, cowpea = $0.20/kg.

Southern region

The Southern region is mainly upland. The cropping area is dominated by rubber plantations, with some fruit trees. Upland rice is intercropped with rubber and coconut in some areas. In a small area of lowland in Phattalung and Pattani, short-duration crops such as mungbean may be grown before rice. Economic second crops result from intercropping between para rubber and orchards. No serious study has been undertaken on crop types, cropping systems, or their economics.

Role of sesbania

The financial losses with a crop other than rice in the cropping system imply that upland crops are not applicable. Sesbania could play an important role as a substitute second crop to be used as green manure to maintain productivity. In Thailand, a number of studies have been undertaken on other potential green manure crops, especially with sunn hemp *Crotalaria juncea* L. Naklang et al (1980) found that sunn hemp used as a green manure could increase rice yields. It was also considered as a possible fodder crop. It could produce significant forage when planted in bunded ricefields with one buffalo plowing after rice harvest (Shelton 1976). However, many insect pests, especially pod borers, cause marked reductions in both forage and seed yields (Phisikul et al 1980).

Data on other green manure crops and the advantages and disadvantages of several species of green manure crops are compiled in Table 2. However, research on sesbania, with its many species and versatility, is lacking. Local varieties have been

Table 2. Advantages and disadvantages of several species of green manure legumes (Hongpan 1962, Sratongkam 1976, Whyte et al 1969).

Legume	Advantages	Disadvantages
Pigeonpea *Cajanus cajan*	Drought tolerant, used as fodder, good intercrop	Hard stem, difficult to plow; affected by insects (pod borers)
Sunn hemp *Crotalaria juncea*	Short-lived, hollow stem; decomposes fast when plowed; fodder and forage	Hard to set seed Infested by insects when planted in the same area for more than 3 yr; need timing schedule
Sesbania speciosa	Tolerant of insects and drought, has high biomass, can be grown on upland and lowland; when cut and flooded can be ratooned; no need to replant; easy to plow, edible; forage and fodder	Slow to flower; hard stem, large stalk, photoperiod-sensitive; dies if flooded to more than 50 cm; insect infested when pods are nearly ripe; slow to mature in sandy soil
S. cannabina	Fast to flower, short plant, ratoon; good as intercrop with both rice and field crop; high seed yield; forage and fodder	Low biomass; pod borer

Continued on next page

Table 2 continued.

Legume	Advantages	Disadvantages
S. aculeata	Tolerant of drought and salinity, can be grown in upland and lowland	Low biomass; difficult to collect seed; small seeds, cracked pod; hard stem difficult to plow
S. rostrata	High biomass, fast growing after 3 mo; seeds can be continuously collected; can be grown in upland and lowland; can be used as forage	Photoperiod-sensitive large plant; difficult to plow in; slow growing before 3 mo; susceptible to pod-borer infection
Siratro *Macroptilium atropurpureum*	Gives good soil cover; sheds its leaves; biomass greater than that of *Centrosema* spp.	Prostrate stem, dies easily; has to be replanted each year; slow growing
Kudzu *Pueraria phaseoloides*	Gives good soil cover; sheds leaves; biomass greater than that of *Centrosema* spp.	Prostrate stem, dies easily and has to be replanted each year; slow growing
Centro *Centrosema pubescens*	Gives good soil cover; drought tolerant; self-propagating, needs no replanting; forage	Bushy, acts as shelter for mice and snake; difficult to plow, has roots along node; cannot be buffalo-plowed; cracked pods; slow growing
Stylo *Stylosanthes humilis*	Drought-resistant, short plant forage; good as intercrop plant, slow growing	Low biomass; susceptible to anthracnose; slow growing
Cowpea *Vigna* spp,	Edible, short-lived, limited ratoon, forage	Low biomass; prostrate stem
Florida velvet bean *Stizolotium* sp.	Short-lived, forage, easy to establish; easy to collect seed	Low biomass
Mungbean *Phaseolusaureus*	Edible, marketable	Low biomass
Rice bean *P. calearatus*	Good soil cover, edible forage	Prostrate stem, low biomass
Calopogonium *Calopogonium rnucunoides*	Good soil cover, forage	Need to be replanted each year; difficult to collect seed; difficult to plow; itchy leaves, low biomass, slow growing
Mimosa *Mimosa invisa*	High biomass, good soil cover; good intercrop	Cannot be used as forage; has to be replanted each year if seeds are to be collected; habitat of pest such as mice and snake
Verano *Stylosanthes hamata*	Short plant, use as soil cover; forage; good as intercrop	Low biomass; hard to establish; hard to produce seed

used as food plants (the leaves and flowers are consumed as vegetables). The major agricultural potential lies in green manure and, to a lesser extent, in use as animal fodder. *Sesbania* species are a valuable plant resource because of their vigorous growth, adaptation to various soil conditions, and ability to enhance soil fertility (Evans and Rotar 1986).

As green manure

It is well recognized that legumes grown in multiple cropping systems, either in rotation or as intercrops, will increase growth and yields of other crops. For leguminous species of green manure to be most productive, they must be inoculated for N fixation with appropriate strains of rhizobium. The greatest benefit of legume green manure is in transferring fixed N to the main crop. In an experiment in Ubonratchathani Province, northeast Thailand, using green manure gave a rice yield of 2.3 t/ha compared to 1.2 t/ha with no fertilizer (Sawasdee et al 1976).

Rice yields at various locations with and without green manure (*S. speciosa*) are reported in Table 3 (Rice Department 1960). The effect of green manure on yield varies considerably, according to chemical composition and soil characteristics. In general, the loner the C-to-N ratio of the green manure, the higher the crop response (Bin 1983). *S. speciosa* as green manure (C:N 24.2) gave the highest rice yield (1.25 t/ha) (Fig. 1) (Arunin et al 1987).

Incorporation of *S. aculeata* at 30,45,60, and 75 d after seeding (DAS) resulted in no significant difference in rice yield; however, S. aculeata at 30 DAS gave the highest yield—3.68 t/ha compared with 2.53 t/ha from the plot without green manure (Arunin et al 1982).

The amount of N fixed by the green manure crop is somewhat related to the biomass produced; biomass is affected by different methods of cultivation.

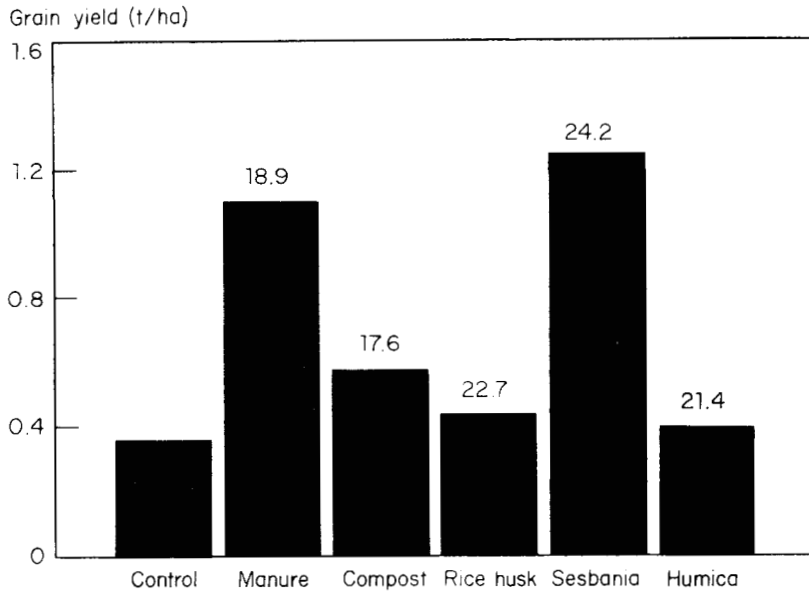
Plant nutrition

N and water are the two major factors governing plant productivity. Rice requires 1.8 to 2 kg K to produce 100 kg grain (Patnaik and Rao 1979). Green manure, especially with legume species, helps meet that need.

Four sesbania species were examined in an experiment on Kularonghai soil series (Table 4). N from *S. rostrara, S. aculeata, S. cannabina, S. speciosa* at 80 DAS

Table 3. Rice yield with chemical fertilizer, green manure *Sesbania speciosa,* **and chemical fertilizer + green manure.**

Location	Av yield of control (t/ha)	Rice yield (t/ha)		
		Chemical fertilizer 2-4-4	*S. speciosa*	*S. speciosa* + chemical fertilizer
Bangkhen	2.8	3.2	3.1	3.8
Rangsit	1.6	1.8	2.0	2.5
Doisaket	2.4	2.6	2.9	3.3
Surin	1.3	1.6	1.8	2.4
Chumpare	1.9	2.2	2.6	3.0



1. Effect of organic fertilizers on grain yield of KDMI 105. Figures on the bars indicate C-to-N ratio

increased from 0.02% to 0.24%, 0.10%, 0.10%, and 0.09%, respectively. Furthermore, the 4 species increased available P (Bray II) from 5 ppm to 141, 70, 69, and 63 ppm, respectively (Singhabutra et al 1987).

At the Bel Air ORSTOM Station in Dakar (Senegal), *S. rostrata* as green manure doubled rice yields. The effect with inorganic N fertilizer was significantly less. Moreover, the N content of grain and straw with *S. rostrata* was significantly higher (50%) than that without fertilizer (Dreyfus et al 1985).

At 45 DAS, *S. rostrata* produced 12-17 t green matter/ha (1.5-3.0 t dry matter/ha); N accumulation was 62-88 kg ha in three 100-m^2 trial plots in farmers' fields (Gines et al 1986).

Sesbania spp. grown alone for one season yielded 22.5-75 t fresh weight/ ha and fixed 1 12.5-375 kg N/ha. When interplanted in the summer in China, sesbania gave a fresh weight yield of 11.2-30 t/ha and fixed 56.2-150 kg N/ha (Bin 1983).

Nodulation

Sesbania's ability to fix N lies in the nodules formed by N-fixing rhizobium, which exists symbiotically with the plant.

Sesbanias all nodulate in the root zone: but *S. rostrata* can bear nodules on roots and stems at the same time (Dreyfus et al 1983).

Arunin et al (1987) studied the difference between a native rhizobium strain (cowpea group) and ORS 571 inoculated into *S. rostrata, S. cannabina, S. speciosa,* and *S. aculeata.* Dry weight and pod weight were greater for *S. rostrata* inoculated with ORS 571 in both flooded and upland conditions (Table 5). *S. aculeata* and

Table 4. Characteristics of four sesbania species.

Character	*S. cannabina* (Retz) Pers.	*S. aculeata* (Willd) Poir. *S. bispinosa* (Jacq) W. F. Wight	*S. sesban* (L.) Merr.	*S. speciosa* Taub.
Leaflet	With a few hairs beneath, pilose, or rarely, pilky	Glabrous	Glabrous or nearly so above, pilose at margin, pubescent beneath	Asymmetrically ovate-lanceolate leaflets in 16-25 pairs 30 mm long, 6 mm wide
Prickles	None	Small or large, few-many on leaf rachis and stem	None	None
Blade of standard	Wider than long, not cordate at base	Longer than wide, not cordate at base	Wider than long, base cordate	24-33 mm long 22-31 mm wide
Blade of keel	0-20% wider than long	5-20% longer than wide	5-7 mm × 3-4/8-9 mm	15-22 mm long 6-9 mm wide at the base
Basal tooth of blade of keel	Narrow, very acute	Narrow, very acute	Narrow, very acute	Horizontal, long or short
Filament sheath	8-10 mm long, almost straight	9-12 mm long, almost straight	9-13 mm long	17 mm or longer
Beak of pod Pods	5-7 mm long 30 seeded 15-18 cm long, not torulose	10-12 mm long Curved 24 cm long (ext. beak) 35-40 seeded	4-5 mrn long Straight or curved 20-30 cm × 2.4 mm 20-40 seed	10-12 mm long More than 3 mm wide, as thick at the margins, 40-60 seed
Seeds	Cylindric, 3 mm long	Elliptic in cross-section, brown not mottled	Subcylindric, 3-3.5 mm long, olive green, mottled with blade	Yellowish brown, not mottled 3-4 × 2.5-3 × 1.5 mm hilum 0.5 mm long

Table 5. Dry weight, pod weight, and grain yield of 4 species of sesbania inoculated with native rhizobium strain and ORS 571.

Treatment	Flooded soil			Upland soil		
	Dry weight (t/ha)	Pod weight (t/ha)	Grain yield (t/ha)	Dry weight (t/ha)	Pod weight (t/ha)	Grain yield (t/ha)
S. rostrata						
Control	1.22	2.18	0.67	1.93	2.64	0.86
With native strain	1.33	2.74	0.71	1.62	2.08	0.69
With ORS 571	1.53	3.58	1.11	3.48	2.64	0.85
S. cannabina						
Control	0.24	0.02	0.01	1.30	2.33	1.05
With native strain	0.21	0.39	0.12	1.08	2.17	1.00
With ORS 571	0.22	0.67	0.22	1.02	1.95	0.87
S.speciosa						
Control	0.57	0.14	0.01	7.75	3.79	1.32
With native strain	0.31	0.09	0.01	8.01	2.98	1.07
With ORS 571	1.22	0.16	0.02	8.12	1.89	0.60
S. aculeata						
Control	2.35	1.94	0.31	8.32	1.74	0.04
With native strain	2.86	1.32	0.15	8.00	2.98	0.53
With ORS 571	2.45	3.09	0.57	5.20	1.36	0.30

S. speciosa inoculated with ORS 571 gave higher yields (dry weight plus pod weight) under flooded conditions and lower yields under upland conditions than those inoculated with the native strain. Yields of *S. cannabina* inoculated with ORS 571 or the native strain were not significantly different.

Stem nodules were not found on *S. rostrata* inoculated with the cowpea group strain in upland and flooded soils.

Singhabutra et al (1987), in a pot experiment using the same sesbania species, found that *S. rostrata* had the highest number of nodules per pot.

S. rostrata exhibits two unique properties: it has high N_2-fixing potential (*S. rostrata* had been measured as fixing 200 kg N_2/ ha in 50 d) and it has the ability to nodulate and fix N even with high rates of combined N in the soil (about 200 kg N/ha). That *S. rostrata* can assimilate both soil and atmospheric N constitutes a significant advantage (Dreyfus et al 1983).

Food and forage

Besides being a green manure, sesbania can be grown as a forage crop and as human food, In Thailand, *S. grandiflora* and *S. roxburghii* flowers are an accepted vegetable.

Research on forage has focused on providing feed for the long dry season with its resultant poor forage and thus poor animal productivity. *Leucaena* has been the most successful species because it is deep rooting; however, it is slow to establish and has poor growth on acidic soils, which has limited its widespread use. *S. sesban* and

Table 6. First year yield and chemical composition of leaf material of Sesbania species at Khon Kaen (Topark-Ngarm and Gutteridge 1985).

Species	Leaf yield (g/plant)		Crude protein	IVDMD[a]
	Wet season	Dry season	(%)	(%)
Sesbania sesban var. *nubica*	683.4	377.0	21.3	67.8
S.sesban	541.6	167.8	26.4	69.1
S. formosa	311.7	87.8	21.5	57.9
S. grandiflora	156.9	25.0	26.5	66.9

[a] In vitro dry matter digestibility.

S. formosa appear promising, with high yields and reasonable leaf retention over the dry season and high nutritive value (Table 6) (Topark-Ngarm and Gutteridge 1985).

Research on forages in Thailand needs to be directed toward incorporating persistent, productive species into existing cropping systems. More emphasis should be placed on the evaluation of leguminous forage species because they can make significant contributions to animal feed supplies under sophisticated management.

Tolerance for adverse conditions

Flood tolerance

Selection trials for green manure species have singled out Sesbania species for their ability to withstand flooding. In China, sesbania survived for 15-20 d in water 5-30 cm deep (Evans and Rotar 1986).

Tolerance of sesbania for flooding develops after the seedling stage. Although a few centimeters of standing water aids germination of *S. bispinosa,* the seedlings appear to need several weeks of nonflooded conditions before they can readily withstand flooding.

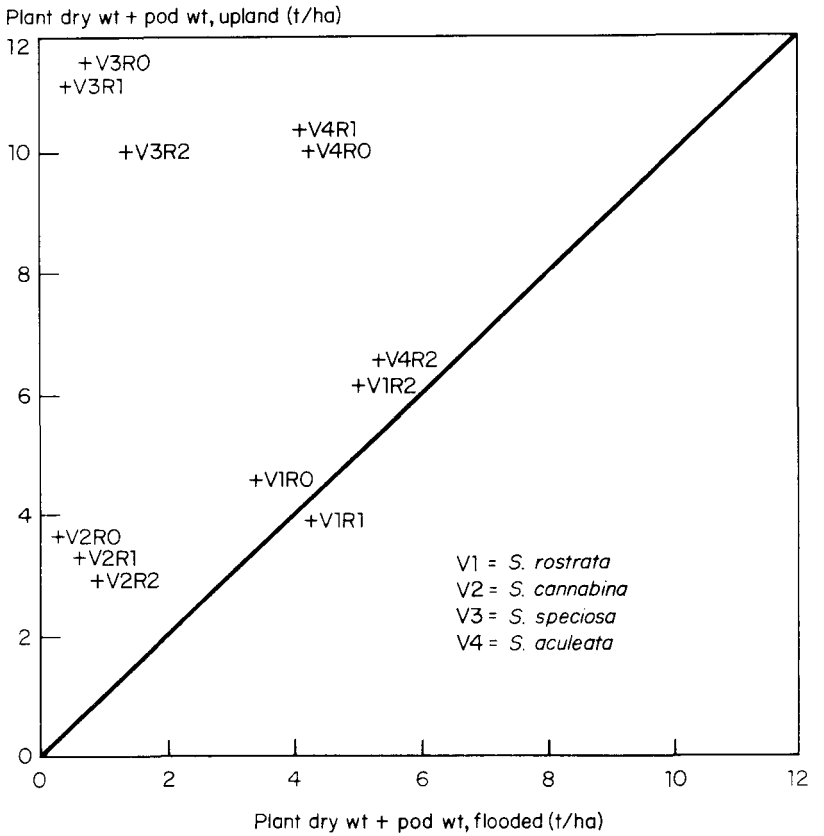
The basis for flood tolerance in sesbania is the development of aerenchyma, a spongy tissue having enlarged cells with large intercellular spaces. This development allows the plant to avoid anoxia in the root zone.

In a study of the performance and yields of 4 *Sesbania* species under flooded (30 cm deep) and upland conditions, the ability to tolerate flooding was in the order *S. rostrata* > *S. aculeata* > *S. cannabina* > *S. speciosa* (Fig. 2) (Arunin et a1 1987).

Salt tolerance

Many *Sesbania* species are tolerant of saline and alkaline conditions. African species are segregated in habitat according to the degree of salinity in the edaphic environment. This tolerance may be related to water requirement; species with greater adaptation to drought might be expected to encounter increasing salinity as soils dry out or as seasonal surface water evaporates (Evans and Rotar 1986).

Singhabutra et a1 (1987) studied the effect of salinity levels–0.56, 1.89, 4.40, 5.64, and 6.18 dS/m–on *Sesbania* spp. As salinity increased, plant height, fresh weight, and number of nodules decreased in *S. rostrata, S. cannabina, S. speciosa,* and *S. aculeata.* There was no significant difference among salinity levels.



2. Yield of *Sesbania* spp. subjected to prolonged 30-cm-deep flooding with and without (RO) inoculation with native rhizobium strain (R1) and ORS 571 (R2).

Acid tolerance

Reports on the tolerance of *Sesbania* species for acid conditions are few and mostly insubstantial. *S. cannabina* has been reported to be acid tolerant. Reports from Vietnam that *S. sesbania* is grown successfully on acid sulfate soils have not been verified (Evans and Rotar 1986). No research has been carried out in Thailand on sesbania tolerance for acidity.

Conclusion

In Thailand, two or three crops a year are possible only in irrigated areas. In rainfed areas with a rice-based cropping system, usually only the rice crop gives adequate yields; the yield of the second crop is uneconomical. Planting sesbania as a green manure crop to replace the second crop has great potential for soil improvement in the rainfed areas. Sesbania has been chosen because it is tolerant of a range of adverse edaphic conditions, such as salinity, and can fix N at a high rate. However, more research is needed on seed production and utilization.

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Notes

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Stem-nodulating legumes. as green manure for rice in West Africa

G. Rinaudo, D. Alazard, and A. Moudiongui

In West Africa, the stem-nodulating legumes *Sesbania rostrata* and *Aeschynomene afraspera* generally behave as wild annual plants in periodically flooded soils. They are particularly sensitive to photoperiod and temperature; at the latitude of Senegal (15 °N), they grow well during the rainy season (Jun-Sep). *S. rostrata* and *A. afraspera* are fast-growing and fix N_2 more actively than most root-nodulating legumes. Stem nodules are less affected than root nodules by the inhibitive action of flooding and combined N. Stem nodules result from the infection of predetermined sites with specific strains of *Rhizobium.* In nature, when soils already harbor native stem strains, nodules appear on the lower parts of the stems; however, their distribution is often irregular. Stem inoculation is generally recommended to optimize N_2 fixation. When used as green manure at the beginning of the rainy season, *S. rostrata* and *A. afraspera* can provide more than 100 kg N/ha to a rice crop, resulting in significant yield increases. *S. rostrata* also acts as a plant trap for the pathogenic nematodes *Hirschmanniella oryzae* and *H. spinicaudata,* the prevalent species in flooded ricefields in West Africa.

Nitrogen is one of the most important factors governing plant productivity: to produce 100 kg of grain, rice requires 1.8-2.0 kg N (Patnaik and Rao 1979). The plant absorbs N from three major sources: soil N, fertilizers, and biological N_2 fixation. In West Africa, soil N reserves are limited, and N fertilizers are often too expensive for African farmers. Biological N_2 fixation presents an appealing alternative to fertilizers that has often been underutilized. Roger and Watanabe (1984) reviewed the potential for practical utilization of biological N_2 fixation technologies in rice.

It is well known that long-term productivity may decline unless efforts are taken to maintain soil fertility. The utility of green manure for increasing soil productivity has been recognized from early times in some rice-growing areas, particularly China, India, and Northeast Asia (Jiao Bin 1983, Singh 1984, Watanabe 1984, Wen Qi-Xiao 1984). The potential benefits are many. Green manure can increase soil N content, concentrate P and significantly increase the available phosphate content in the soil, maintain and renew soil organic matter, and improve soil structure and physical characteristics (Jiao Bin 1983). N_2-fixing plants that have been used as green

manure include annual cultivated legumes (various species belonging to the genera *Astragalus, Crotalaria, Sesbania, Medicago, Cassia,* and *Vigna*), nonlegumes (*Coriaria sinica),* leaves and cuttings of cultivated or wild perennial legumes, and wild annual legumes.

Growing a legume green manure crop before rice is probably among the most efficient ways to improve soil productivity. Unfortunately, legumes quite often are not appealing because they do not directly yield food or cash. However, introducing green manure into a cropping system could be economically justifiable, if the legume has high N_2-fixing potential, shortens soil immobilization time, and substantially increases yield of the subsequent crop.

The ORSTOM Soil Microbiology group has been making progress with this technology in Senegal by using stem-nodulating legumes *Sesbania rostrata* and *Aeschynomene afraspera.* These plants are promising tropical species: they have a very high N_2-fixing potential, are fast-growing, and are tolerant of excess water.

Legume-rhizobium symbiosis

Legumes that are able to form aerial N_2-fixing nodules on their stems belong to three genera: *Sesbania, Aeschynomene,* and *Neptunia.* The stem-nodulating ability is restricted to *S. rostrata* in *Sesbania* (Dreyfus and Dommergues 1981) and to *N. oloracea* in *Neptunia* (Schaede 1940). It is widespread in *Aeschynomene:* 15 stem-nodulating species have been identified and divided into 3 cross-inoculation groups (Alazard 1985).

Stem nodulation

Among the stem-nodulating legumes, *S. rostrata* and *A. afraspera* have received particular attention because their stem nodulation is more extensive. Their most distinctive characteristic is the presence of predetermined nodulation sites on the stem. Those sites always include an adventitious root primordium, which can develop into N_2-fixing nodules when infected by specific strains of *Rhizobium.* The root primordium pierces the epidermis, resulting in a circular fissure through which the rhizobia penetrate (Tsien et al 1983). In *S. rostrata,* the sites are regularly arranged in three or four vertical lines along the stem and on lateral branches (Duhoux 1984). In *A. afraspera,* they are distributed at random along the principal stem and lateral branches (Alazard and Duhoux 1987). In both cases, the sites exhibit two unique characteristics: their position is not dependent on *Rhizobium* infection and they form continuously throughout stem growth.

Rhizobium strains

The bacteria that form nodules on legumes belong to the genus *Rhizobium* or *Bradyrhizobium* (Jordan 1984). *Rhizobium* strains are fast-growing; *Bradyrhizobium* strains are slow-growing. Two types of strains have been isolated from *S. rostrata.* Stem-nodulating strains nodulate both stems and roots. Root-nodulating strains nodulate only roots. Although the stem-nodulating strains are fast-growing, they are closely related to the genus *Bradyrhizobium* and possibly

could be incorporated into a new N_2-fixing bacteria, genus *Azorhizobium* (Dreyfus et al 1987). The root strains belong to the genus *Rhizobium* (Dreyfus, pers. comm.).

Preliminary results with stem-nodulating rhizobia isolated from *Aeschynomene* plants suggest that the strains are intermediate types, with both fast and slow growing characteristics, and could probably be considered members of a particular group of *Rhizobium* (Alazard and Garcia, unpubl.). No cross-inoculation between *Aeschynomene* sp. and *S. rostrata* has been found.

Climate requirements

The stem-nodulating legumes *S. rostrata* and *A. afraspera* usually behave as wild annual plants and are characterized by high sensitivity to climate variations. At the 15 °N latitude of Senegal, they grow well in periodically flooded soils during the rainy season (Jun-Sep). Plants are 2 m or taller at 3 mo. Both species sometimes nodulate profusely on the lower parts of temporarily. submerged stems. However, waterlogging is not a prerequisite to the formation of stem nodules.

Effect of climate on growth parameters

To evaluate the effect of climatic factors on some growth parameters and N_2-fixing activity of *S. rostrata*, we monitored seven growth cycles at the ORSTOM Station, Dakar, Senegal, beginning in 1983. Mean temperatures varied between 17 and 38 °C; daylength varied from 11 h to 13 h. *S. rostrata* was particularly sensitive to temperature and photoperiod.

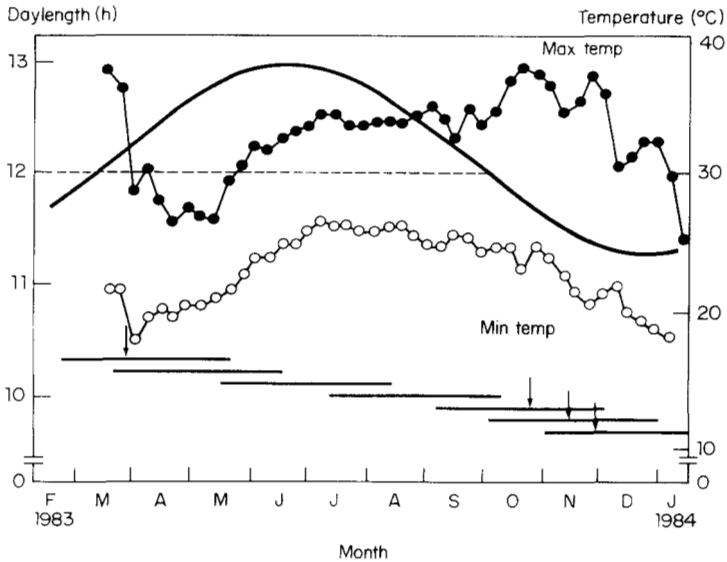
Flowering. S. rostrata needed a relatively long photoperiod. Flowering occurred 4-6 wk after seeding when plants were sown before April or after August (daylength less than 12 h). If plants were sown between April and July, flowering did not occur during the 13 wk growth cycle (Fig. 1). Similar results were obtained at IRRI in 1984 (IRRI 1985).

Plant height and nitrogen content of aerial part. S. rostrata grew well with relatively long days and high temperatures from June to September. Nine weeks after seeding (WAS), plant height was 2.13 m with 12 Jul seeding, but only 0.35 m with 1 Nov seeding. N content was 1.62 g N/plant with 12 Jul seeding and 0.09 g N/plant with 1 Nov seeding (Table 1).

Growth parameters. Stem N_2-fixing activity (acetylene reduction activity [ARA]) varied widely with climatic conditions. At 9 WAS, activity in 12 Jul-seeded plants was 171 µmol C_2H_4/plant per h; in 1 Nov-seeded plants, it was 18 µmol C_2H_4/plant per h.

Nitrogen fixation

S. rostrata and *A. afraspera* exhibit very high N_2-fixing capacity. In microplot trials of *S. rostrata* during the 1980 rainy season. N_2 fixation estimated by the N balance method was at least 26.7 g N/m^2 (Rinaudo et al 1983). N_2 fixation estimated by acetylene reduction assay (Hardy et al 1968) was about 200 µmol C_2H_4/plant per h in 2-mo-old plants (Alazard and Duhoux 1987, Rinaudo and Moudiongui 1987).



1. Flowering behavior of *Sesbania rostrata* in response to daylength and mean weekly temperatures, Plants were sown in 30-liter PVC pots with a diameter of 30 cm and filled with 20 kg of Bel-Air soil (4 plants/pot). After 3 wk growth, the soil was kept waterlogged. Plants were inoculated by spraying the stems with a culture of *Rhizobium* ORS 571 3 wk after seeding, then at 2-wk intervals. Growth cycle = 13 wk. Arrows indicate beginning of flowering.

Potential N_2 fixation

We estimated N_2 fixation by *S. rostrata* during the 1985 rainy season using the ^{15}N isotope dilution method and the difference method. There was good agreement between the methods. The results are as follows:

1. About 30 g N/m^2 could be fixed in 53 d by *S. rostrata,* which confirms its high N_2-fixing potential (Table 2).

Table 1. Effect of *Sesbania rostrata* **planting date on growth parameters and N_2-fixing activity (acetylene reduction activity [ARA])at 5, 7, and 9 wk after seedingORSTOM Dakar, Senegal, 1983.**

Planting date	Plant height (m)			N content (g/plant)			Stem ARA (µmol C_2H_4/plant per h)		
	5	7	9	5	7	9	5		79
22 Feb	0.19	0.38	0.85	0.01	0.08	0.37	8	46	71
22 Mar	0.18	0.39	0.84	0.02	0.09	0.33	2	25	93
17 May	0.31	0.72	1.34	0.04	0.24	0.73	21	156	164
12 Jul	0.76	1.54	2.13	0.14	0.80	1.62	65	172	171
6 Sep	0.72	1.49	1.80	0.19	0.77	1.08	62	169	144
4 Oct	0.28	0.52	0.77	0.02	0.09	0.22	6	31	40
1 Nov	0.23	0.29	0.35	0.01	0.03	0.09	3	9	18

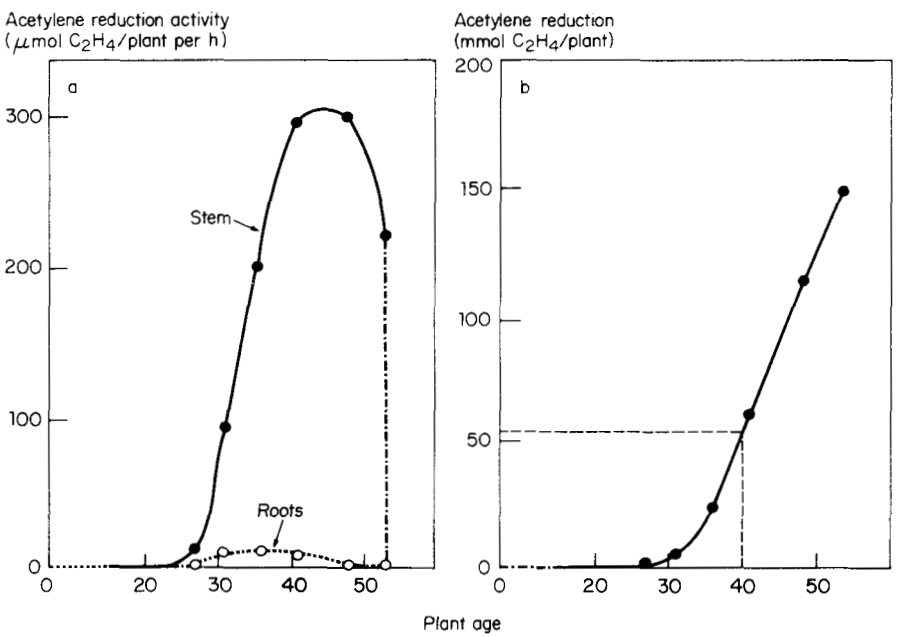
[a] Mean of 4 replications, WAS = weeks after seeding.

2. Because of stem nodulation, *S. rostrata* can actively fix N_2 even in waterlogged conditions (Saint Macary et a1 1985). In an experiment with plants grown on waterlogged soil, root nodulation was poor. N_2-fixing activity was due mainly to stem nodules (about 96% of total ARA) (Fig. 2).
3. Because acetylene reduction is an indirect method of estimating N_2-fixing activity, integrating it into the curve that represents stem nodule activity provides a cumulative curve that allows a qualitative estimate of N_2 fixed at different plant ages (Fig. 2). We found that a) N_2 fixation in *S. rostrata* became significant 35 d after seeding (DAS), 14 d after inoculation; b) the N_2 fixed accumulated linearly

Table 2. N_2 fixation by 53-d-old *S. rosfrafa* as estimated by 2 different methods (Rinaudo and Moudiongui 1987).

Method	N_2 fixation expressed as		
	N (%) derived from N_2 fixation	g N2/pot[a]	g N2/m^{2a}
Direct isotope dilution	38.5	2.09 t 0.52	30.3 2 7.3
Difference	43.5	2.38 2 0.20	33.5 f 2.8

[a]Mean value f confidence interval (P=0.05). Containers were 30-liter PVC pots filled with Bel-Air soil, each with 4 plants inoculated with *Rhizobium* ORS 571 at 21 and 31 d after seeding.



2. N_2-fixing activity (acetylene reduction) of *S. rostrata* as afunction of plant age. a) acetylene reduction activity, b) cumulated values.

between 35 and 53 DAS; and c) at 40 DAS, S. rostrata had fixed only 35% of the total N_2 fixed during growth.

Mineral nitrogen

Applying mineral N to legumes is known to reduce both nodulation and N_2 fixation rate. Another advantage of stem-nodulating legumes is their ability to nodulate and fix N_2 in the presence of combined N. This ability was first observed with *S. rostrata* by Dreyfus and Dommergues (1980) and with Aeschynomene scabra by Eaglesham and Szalay (1983).

The effects of mineral N on N2 fixation by A. afraspera were studied by Becker et a1 (1986) in hydroponic culture and pot experiments. In both experiments, root nodulation and related N_2-fixing capacity were strongly inhibited by increasing amounts of mineral N. Stem nodulation and related nitrogenase activity were unaffected (Table 3, 4).

Recently, hydroponically grown *S. rostrata* was continuously irrigated with an automatic system that maintained the initial N concentration throughout the experiment (Moudiongui and Rinaudo 1987). In such conditions, stem and root

Table 3. Influence of calcium nitrate on Nrfixing activity (ARA) of hydroponically grown *A. afraspera* [a] (Becker et al 1986).

N concentration (mM NO_3^-/liter)	Plant dry wt (9)	Stem ARA (pmol C_2H_4/h)		Root ARA (pmol C2H4/h)	
		Per plant	Per g nodule dry wt	Per plant	Per g nodule dry wt
0	0.6 b	1.1 b	69.2 a	1.0 a	45.8 a
3	0.7 a	1.3 a	69.6 a	0.5 b	23.5 b
6	0.7 a	1.2 b	58.8 b	0.3 c	14.9 c
9	0.7 a	1.0 b	47.6 c	0.3 c	11.1 d
12	0.7 a	0.8 c	42.0 c	0.2 c	8.5 d
15	0.7 a	0.7 c	35.1 d	0.1 d	5.0 e

[a] In a column, data followed by the same letters do not differ significantly by DMRT (P=0.05). Plants were grown in 125 ml glass tubes. Stems and roots were inoculated 30 DAS with *Rhizobium* strain ORS 322. The nutrient solution was changed once a week to inoculation, then every 2 d.

Table 4. Influence of urea on N_2-fixing activity (ARA) of pot-grown *A. afraspera*[a] (Becker et al 1986).

N treatment (kg N/ha)	Plant dry wt (9)	Stem ARA (µmol C_2H_4/h)		Root ARA (pmol C_2H_4/h)	
		Per plant	Per g nodule dry wt	Per plant	Per g nodule dry wt
0	32.2 d	84.9 d	89.5 a	16.4 a	28.6 a
50	37.9 c	98.0 c	87.2 a	14.8 a	29.5 a
100	56.4 a	130.5 a	86.0 a	9.7 b	20.4 b
200	43.4 b	117.3 b	68.7 b	5.6 c	9.8 c

[a] In a column, data with the same letters do not differ significantly by DMRT (P=0.05). Containers were 30-liter PVC pots filled with Bel-Air soil, with 3 plants/pot. Soil was kept waterlogged after the first week. *Rhizobium* culture (ORS 322) was sprayed on the soil surface 1 d before transplanting, then on the stems of 30d-old plants.

Table 5. Influence of ammonium nitrate on N_2-fixing activity (ARA) of hydroponically grown plants of *S. rostrata*[a] (Moudiongui and Rinaudo 1987).

N concentration (mM NH_4NO_3/liter)	Plant dry wt (g)	Stem ARA (µmol C_2H_4/h)		Root ARA (µmol C_2H_4/h)	
		Per plant	Per g nodule dry wt	Per plant	Per g nodule dry wt
0	6.45 c	7.72 a	72.2 a	6.35 a	58.0 a
1.5	7.45 bc	2.76 b	36.8 b	1.15 b	17.0 b
3.0	8.31 ab	1.15 c	19.0 c	-	-
6.0	9.38 a	-	-	-	-

[a]In a column, data with the same letters do not differ significantly by DMRT (P=0.05). Plants were inoculated with *Rhizobium* ORS 571 30 d after seeding and continuously irrigated with an automatic system. For each treatment, the nutrient medium reservoir was connected to a multi-channel peristaltic pump which irrigated 5 free-draining pots simultaneously at 300 ml/pot per d. Measurements were taken on 50-d-old plants.

nodulation and related ARA were inhibited by high mineral N concentrations (Table 5). As was anticipated, root nodules were more affected than stemnodules. In plants grown in the field, however, the behavior of *S. rostrata* in relation to combined K is similar to that of *A. afraspera.* Stem nodulation and related N_2-fixing activity remained unaffected, even with 200 kg N/ha.

The difference in the ability of stems and roots of *S. rostrata* and *A. afraspera* to nodulate in the presence of combined N may be explained by the following:

1. Roots are more affected than stems because they are in direct contact with the mineral N. An effect of this type was noted for split root systems of white clover (Carrol and Gresshoff 1983).
2. Photosynthate deprivation of nodules has been correlated with increasing amounts of mineral N (Houward 1980, Wong 1980). The abatement of stem nodule activity may be explained by greater carbohydrate availability in stem nodules than in root nodules.
3. The difference in response of root and stem nodules to combined N may be partially explained by differences between the two types of infection process involved. Root infection occurs via root hairs, which are very sensitive to combined N (Dazzo and Brill 1978, Munns 1968). In stem infection, no root hairs have been observed on the root primordium nor in the fissure encircling it; that provides an optimal environment for the specific *Rhizobium* (Tsien et a1 1983).

The ability of *S. rostrata* and *A. afraspera* to nodulate on the stems and to fix N_2 even with high levels of combined N is an advantage in assimilating both soil and atmospheric N.

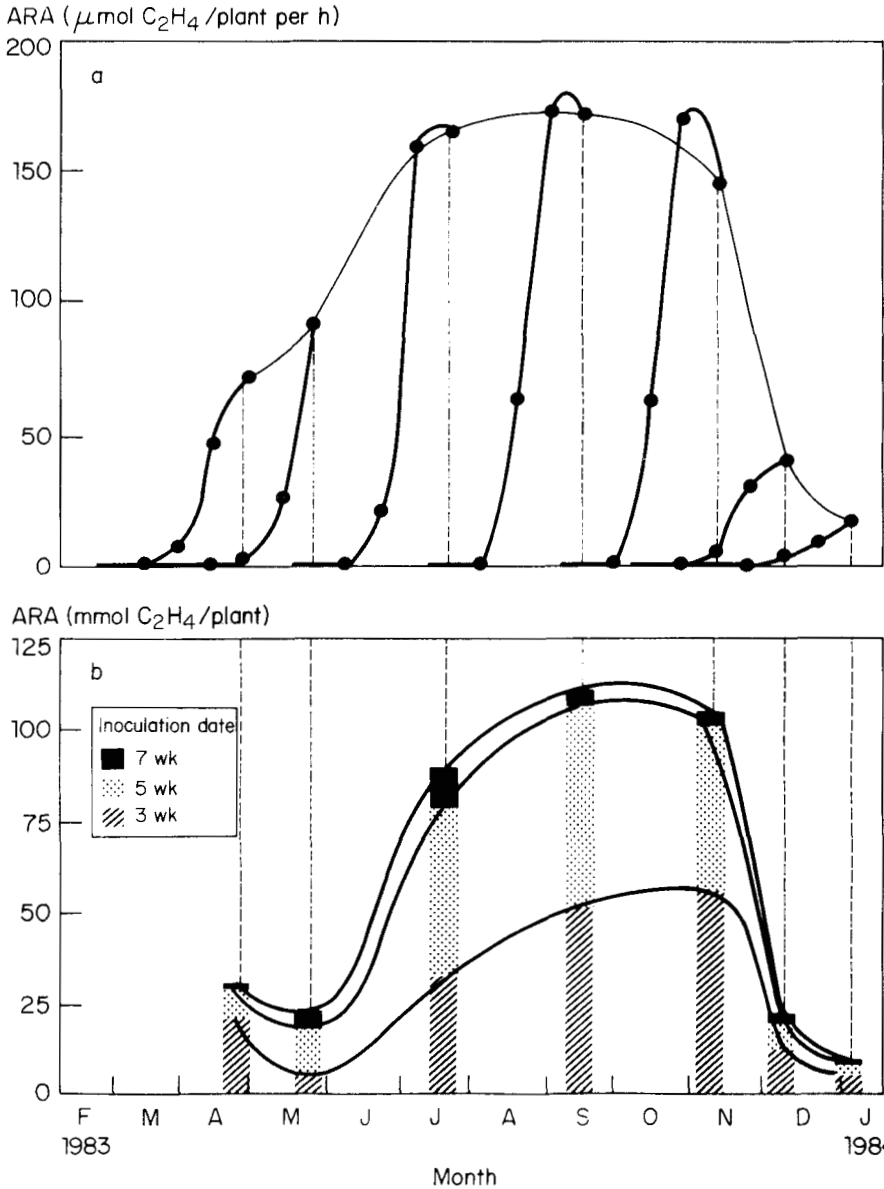
Inoculation

In nature, when soils already harbor native stem strains of rhizobia, nodules are usually localized on the lower parts of the stems, although in some cases they appear along the length of the plant. Distribution of the stem nodules is often irregular. Dust, rain, wind, and insects probably play a significant role in spontaneous stem nodulation.

When soils do not harbor specific *Rhizobium* strains, seeds can be inoculated with a Rhizobium culture (*S. rostrata: Rhizobium* type ORS 571; *A. afraspera:*

Rhizobium type ORS 322) entrapped in an alginate polymer (Jung et al 1982). Seed inoculation induces good root nodulation but only partial stem nodulation.

Satisfactory stem nodulation is obtained by spraying the shoots with a suspension containing about 10^8 bacteria/ml, using the following bacterial suspensions: liquid culture of *Rhizobium,* colloidal suspension obtained by mixing



3. N_2-fixing activity (ARA) of *S. rostrata* as a function of plantlng date. a) ARA as a function of plant age, b) contribution of stem portions inoculated 3, 5, and 7 WAS to total activity of 9-wk-old plants.

entrapped rhizobia (alginate polymer) in a phosphate buffer (0.06 M, pH 6.8), or suspension obtained from stem nodules crushed with water and passed through a filter.

Inoculation is generally recommended to optimize N_2 fixation by stem-nodulating legumes. The problem is choosing a suitable inoculation date.

Figure 3 shows the N_2-fixing activity (acetylene reduction) of *S. rostrata* as a function of plant age and planting date. Plants were inoculated at 3, 5, and 7 WAS. The N_2-fixing activity of 9-wk-old plants was the sum of activities of stem portions inoculated successively at 3, 5, and 7 wk.

The activity of each stem portion has been integrated to calculate the contribution of stem nodules—initiated at different inoculation dates—to total activity during growth.

Results show that the activity was mainly due to nodules initiated 3 and 5 WAS. If we attribute the nodules initiated by 3-wk-old plants to spontaneous nodulation (which affects the lower parts of the stems), then the most suitable date for inoculation is 5 wk. The corresponding stem nodules contributed about half the total N_2-fixing activity.

Using stem-nodulating legumes as green manure

Microplot experiments

In microplot experiments during several rainy seasons, use of stem-nodulating legumes *S. rostrata, A. afraspera,* and *A. nilotica* as green manure significantly increased rice grain and straw yields and the N content of both grain and straw (Alazard and Becker 1987; Rinaudo et al 1982, 1983: Rinaudo and Moudiongui 1987).

Experiments with *S. rostrata* were performed with two soils: Bel-Air soil, a typical sandy soil of Senegal (common name: Dior), and Tilene soil, an alluvial soil of the Senegal valley. In both cases, rice grain yields, N uptake by the plant, and number of productive tillers were markedly influenced by green manure (grain yields more than doubled). Significant responses to residual N were obtained with the second rice crop (Table 6, 7).

Similar results were obtained with *A. afraspera* and *A. nilotica* (both species form the second cross-inoculation group of the genus Aeschynomene and develop profuse stem nodulation) (Table 8). Furthermore, it could be expected that the N remaining in the soil after a rice crop would benefit a second crop, as was observed with a *S. rostrata* crop. Only 25-35% of the total N accumulated by Aeschynornene was transferred to the rice crop (Alazard and Becker 1987).

Experiments on 25-m^2 plots

We collaborated with the Senegalese Institute of Agricultural Research (ISRA) and the West Africa Rice Development Association (WARDA) to perform larger scale irrigated experiments.

At the ISRA station at Djibelor (Casamance, south of Senegal), S. rostraru green manure had a more marked effect on rice yields than did organic matter (Table 9). It doubled grain yield (Diack 1986).

Table 6. Effect of *S. rostrata* green manure on yield and N content of 2 successive rice crops[a] (Rinaudo et al 1983).

N treatment	Grain (g/m^2)		N uptake (g/m^2)		Tillers ($no./m^2$)		Increase (%) in grain yield	
	1	2	1	2	1	2	1	2
S. rostrata green manure	596 a	329 a	18.17 a	6.47 a	146 a	105 a	181	43
Mineral fertilization [60 N as $(NH_4)_2SO_4$]	381 b	225 b	7.21 b	4.15 b	121 b	62 b	80	-2
Control	212 c	230 b	4.02 c	4.13 b	63 c	68 b	-	-

[a]First crop: rice variety Moroberekan, Bel-Air soil on 1-m^2 microplots; second crop: rice variety IKP. Bel-Air soil: typical sandy soil of Senegal (92% sand) with 0.4% C and 0.026% N. In a column, data with the same letter do not differ significantly by DMRT (P=0.05).

Table 7. Effect of *S. rostrata* green manure on yield and N content of 2 successive rice crops[a] (Rinaudo and Moudiongui 1987).

N treatment	Grain (g/m^2)		N uptake (g/m^2)		Tillers ($no./m^2$)		Increase (%) in grain yield	
	1	2	1	2	1	2	1	2
S. rostrata green manure	1081 a	569 a	17.24 a	8.92 a	402 a	265 a	160	46
Mineral fertilization (100 N as urea)	784 b	405 b	11.99 b	5.76 b	347 b	245 b	89	4
Control	415 c	391 b	5.37 c	5.61 b	213 c	236 b	-	-

[a]First crop: rice variety IKP; second crop: rice variety KM998. Tilene soil: typical alluvial soil of the Senegal valley (clay 58%, loam 18%) with 1.16% C and 0.063% N. In a column, data with the same letter do not differ significantly by DMRT (P=0.05).

The objective of experiments at the WARDA Fanaye station (north of Senegal) was to determine if stem-nodulating legumes as green manure for rice in the Senegal valley constitute an alternative to N fertilizers. With *S. rostrata* green manure, more than 50% of the amount of chemical N fertilizers recommended for rice culture in the Senegal valley (120 kg N/ha) was saved (Camara and Diara 1986) (Table 10).

Table 8. Effect of *Aeschynomene* green manure on yield and N content of a rice crop[a] (Becker and Alazard 1986).

N treatment	Grain (gm^2)	N uptake (g/m^2)	Tillers ($no./m^2$)	Increase (%) in grain yield
A. afraspera green manure	881 a	23.9 a	193 a	82
A. nilotica green manure	895 a	22.4 a	190 a	85
Mineral fertilization (100 N as urea)	612 b	11.4 b	145 b	27
Control	483 c	9.0 c	123 b	-

[a]Variety Moroberekan on Bel-Air soil. In a column, data with the same letter do not differ significantly by DMRT (P=0.05).

Table 9. Effect of *S. rostrata* green manure and application of organic matter on rice yield. ISRA station, Djibelor. Casamance (Diack 1968).

N treatment	Grain (t/ha)	Straw (t/ha)	Tillers (no./m^2)	Increase (%) in grain yield
S. rostrata green manure	4.50 a	12.36 a	465 a	96
Organic matter[a]	2.92 b	7.68 b	318 b	27
Control	2.30 b	5.93 b	301 b	-

[a]compost + farmyard manure, In a column, data with the same letter do not differ significantly by DMRT (P=0.05).

Table 10. Effect of *S. rostrata* green manure on rice yield in the Senegal valley.[a] WARDA station of Fanaye (Camara and Diara 1986).

N treatment		Grain (t/ha)	Straw (t/ha)	Tillers (no./m^2)
Mineral fertilization (kg N/ha)	*S. rostrata* green manure			
0	-	2.3 c	2.5 b	238 b
60	-	4.3 b	5.5 a	310 a
120	-	6.2 ab	7.6 a	363 a
0	+	4.5 b	5.7 a	325 a
30	+	5.9 ab	7.6 a	405 a
60	+	6.8 a	7.7 a	400 a

[a]In a column, data with the same letter do not differ significantly by DMRT (P=0.05).

Effect of *S. rostrata* on pathogenic nematodes

Nematode species *Hirschmanniella oryzae* and *H. spinicaudata* are prevalent in flooded ricefields in West Africa. In microplot experiments on flooded soil infested with *H. oryzae,* the nematode population in the soil decreased rapidly in the presence of *S. rostrata,* resulting in a significant increase in rice yield (Germani et a1 1983). Similar results were obtained with *H. spinicaudata* (Germani, pers. comm.). *S. rostrata* might have been a trap-crop for the nematodes.

Trap-crop action against *H. oryzae* was confirmed by Pariselle and Rinaudo (1987): however, they observed that the large input of N from *S. rostrata* incorporated as green manure was responsible for most of the yield increase.

Conclusion

Among the stem-nodulating legumes, S. rostrata and *A. afraspera* have received particular attention. They are characterized by extensive stem nodulation, are fast-growing, and fix N_2 more actively than most root-nodulating legumes. Stem nodulation is less affected by excess water than root nodulation. Another significant advantage is the ability of stem-nodulating legumes to nodulate and fix N_2 with levels of combined N high enough to inhibit root nodulation.

The value of a green manure crop depends not only on the green matter or N it accumulates, but also on its ability to accumulate maximum nutrients before it is

incorporated. In West Africa, promising results have been obtained with *S. rostrata* and *A. afraspera* as green manure for rice at the beginning of the rainy season. Total dry matter yields of about 10 t/ha have been obtained from both species at 8-9 wk growth. That represents an accumulation of more than 200 kg N/ha.

Assuming that about 50% of the N accumulated in legumes originates from biological N_2 fixation, it appears that green manuring with stem-nodulating legumes could provide about 100 kg N/ha to a rice crop. Results obtained at IRRI (1985, 1986) are consistent: *S. rostrata* was more effective than other *Sesbania* species as a premonsoon green manure for lowland rice.

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Farm-level management systems for green manure crops in Asian rice environments

D. P. Garrity and J. C. Flinn

Little comparable information is available on characteristics of farm-level green manure production systems practiced in Asian countries. We conducted a regional survey of current green manure management systems to develop a uniform database for cross-country comparison. The environmental niches and cropping patterns into which green manure crops fit were documented. An analysis of establishment practices and biomass incorporation methods highlighted widely differing methods. The overall benefits and costs of green manure use were examined. Green manure seed costs varied greatly among countries. The major determinants of profitability are land preparation and incorporation costs and yield effects on the rice crop. Current use of green manure crops is primarily in irrigated areas. Rainfed areas that experience early season waterlogging may have the greatest potential for green manure technology.

"Green manures have always loomed larger in the agronomist's mind than in the farmer's, except in parts of China. With increasing pressure on the tropical world's cultivated land for food production, I cannot see them becoming any more significant" (M. J. T. Norman 1982).

Norman's statement highlights the ambiguity on the green manure issue that confronts rice researchers. As interest in the potential for green manure crops to supply a greater share of rice nutrients is renewed, analyses of farm-level constraints to the use of green manure technology are needed—to help focus research and to help develop policy guidelines to promote its adoption, if it is shown to be feasible.

Substantial literature has accumulated on the positive contributions of green manure to increased rice yields and improved soil physical, chemical, and microbiological conditions for greater sustained production (Meelu 1986, Meelu and Morris 1987). A critical issue for wider adoption appears to be the practical and economic feasibility of green manure production systems at the farm level. But the literature on development of green manure production practices that increase the overall profitability of rice-based farming systems is meager.

With the substantial constraints to wider use of green manure crops, the environmental niches in which they are most likely to be grown in the future need to

be defined. Total hectarage of green manure crops in Asia is by far the highest in China (Norman 1982). Farmers of other countries do use green manure on a limited scale, but the rice cultural systems in which green manure is grown, the species used, the crop management practiced, and the constraints faced vary widely.

We surveyed green manure crop management systems in South, Southeast, and East Asia to establish a uniform database for cross-country comparisons. We were interested in studying the environmental niches in which farmers currently use green manure—even if those areas are limited—and in comparing farmers' cultivation practices. Of particular concern were a comparison of establishment practices used, methods and difficulties in green manure biomass incorporation, production and distribution of green manure crop seed, and overall benefits and costs of green manure use. We present preliminary results of this project here.

As we examined the economic balance sheet of green manure cultivation in various rice environments in Asia, we reached tentative conclusions concerning the viability of current production systems. We examined the environments in which opportunity costs are virtually zero for alternative land uses during the green manure growth period. We found that while current green manure cultivation in these environments (predominantly rainfed wetlands) is small, rainfed wetlands may hold the greatest potential for future green manure expansion.

Green manure farm-level management systems

A 12-page questionnaire was distributed to individuals knowledgeable about farm-level use of green manure crops in South, Southeast, and East Asia where such crops are known to be currently used. Individuals contacted included extensionists, agronomists, and soil scientists. Responses to date have been received from China (2), Taiwan (1), India (4), Bangladesh (1), and the Philippines (1). A follow-up will include respondents from additional countries and locations and provide an opportunity to verify the data extracted from the first survey. However, we judge that the green manure areas represented by the responses received to date cover most of the green manure hectarage in the region.

To maintain focus, the survey was limited to questions about mesophytic herbaceous plants used as green manure. Perennial woody species used as green leaf manure and aquatic plants such as azolla or blue-green algae were not included, nor were species that possess green manure properties but are also harvested for economic returns, such as fodder crops and grain legumes. Responses about green manure crops in upland rice-based systems were sought, but none were received.

The scope was limited to practices currently used by farmers and to perceived productivity gains realized from the use of green manure. Questions did not cover productivity gains occurring on research plots.

Limitations to the use of survey information of this nature are recognized. Respondents were requested to respond on some topics with which they may have limited experience. In countries or regions where green manure systems are highly variable, respondents were asked to give information only on the major systems. The data cannot be considered comprehensive, but rather indicative.

Green manure species and their environmental niches

Table 1 lists the green manure species reported to be grown by farmers in the countries surveyed. Also indicated are species previously grown as green manure whose cultivation has been discontinued. Figure 1 compares the major rice-based cropping systems in which green manure crops are currently grown and the rice environments in which they occur. Respondents diagrammed major crop sequences with and without a green manure crop.

The most important green manure crop in Asia is Chinese milk vetch *Astragalus sinica* L., which is grown on 3.17 million ha of fully and partially irrigated wetlands in southern and central China. Chinese milk vetch, common vetch *Vicia sativa* L., and bird vetch *Vicia cracca* L. are grown as postrice crops in the winter

Table 1. Green manure crops currently and previously grown by farmers in selected Asian countries. Source: Regional Survey on Farm Level Management System for Green Manure Crops.

Country	Green manure crops now grown	Previously (but no longer) grown
China	1. Milk vetch *(Astragalus sinicus* L.) 2. Bird vetch *(Vicia cracca* L.) 3. Common vetch *(Vicia sativa* L.) 4. Sesbania *(Sesbania cannabina* Pers.) 5. Broad bean *(Vicia faba)* 6. Radish *(Raphanus sativus* L.) 7. Azolla *(Azolla filiculoides* Lamk. and *Azolla imbricata* (Roxb) Nakai)	1. Slender groundnut *(Glycine gracilis* Skvor.) 2. Joint vetch *(Aeschynomene indica)* 3. Water peanut *(Alternanthera philoveroides* (Mart.) Grisels.)
China (Taiwan)	1. Sesbania, Sesbeans *(Sesbania roxburghii* Merr.) 2. Sunn hemp *(Crotalaria juncea* L.) 3. Rape *(Brassica campestris* L.) 4. Berseem clover *(Trifolium* sp.) 5. Soybean *(Glycine max* [L.] Merr.)	1. *Carthamus tinctorius* L. 2. *Mucuna capitata* 3. Velvet bean 4. *Tephrosia*
India (southern)	1. Dhaincha *(Sesbania aculeata)* 2. Sesbania *(Sesbania speciosa)* 3. Wild indigo *(Tephrosia purpurea)* 4. Pillipesara *(Phaseolus triloba)* 5. Sunn hemp *(Crotalaria juncea)* 6. Aviri *(Indigofera tinctoria)*	

Continued on next page

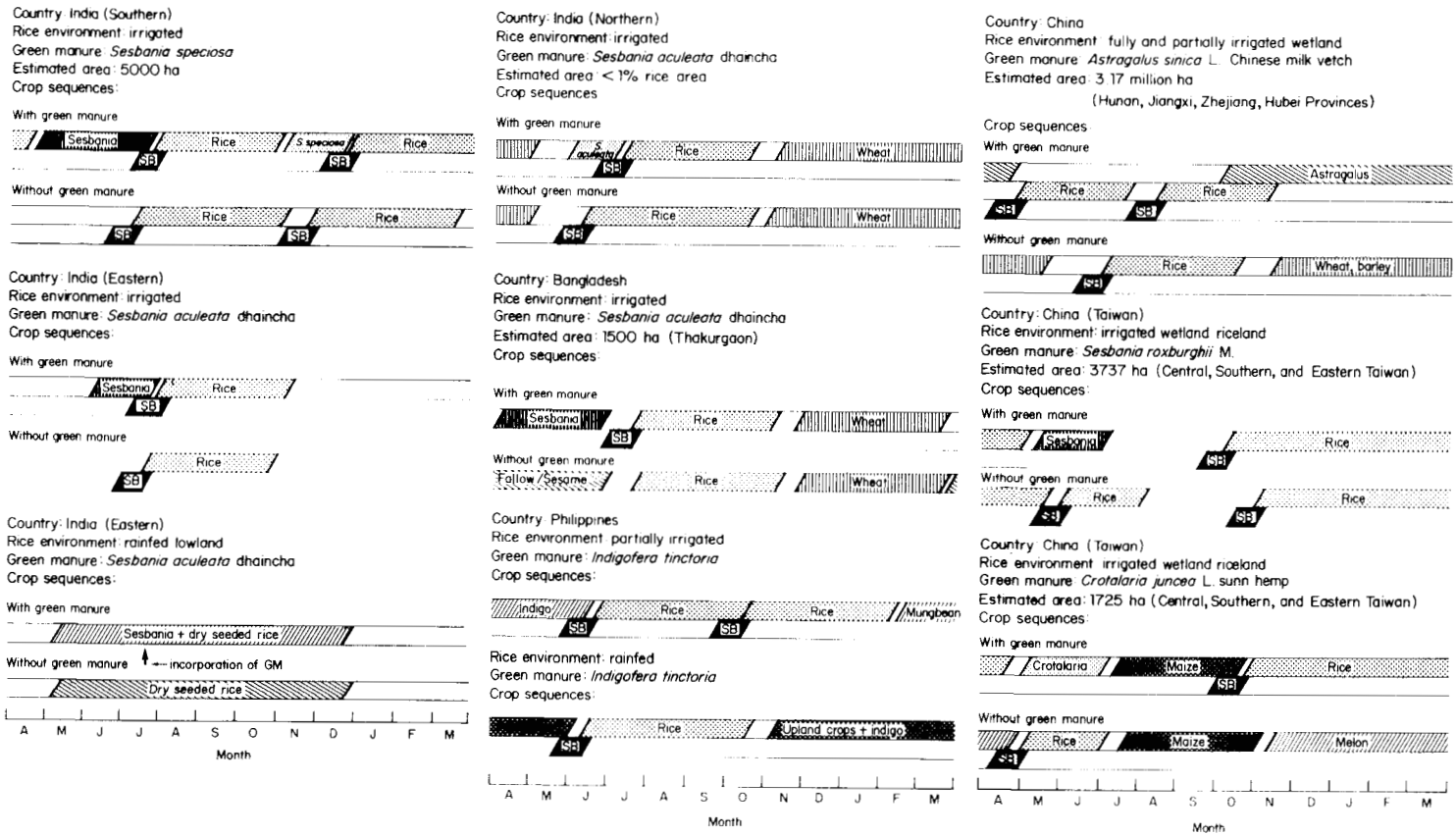
Table 1 continued.

Country	Green manure crops now grown	Previously (but no longer) grown
India (eastern)	1. Dhaincha (*Sesbania aculeata*) 2. Sunn hemp (*Crotalaria juncea*) 3. Clusterbean (*Cyamopsis tetragonoloba*) 4. Cowpea (*Vigna sinensis*) 5. Horsegram (*Dolichos biflorus*) 6. Senji (*Melilotos parcisflorus*)	
India (Chhotanagpur Plateau)	1. Dhaincha (*Sesbania aculeata*) 2. Sunn hemp (*Crotalaria juncea*) 3. Berseem (*Trifolium alexandrinum*)	
India (northern)	1. Dhaincha (*Sesbania aculeata*) 2. Sunn hemp (*Crotalaria juncea*) 3. Berseem (*Trifolium alexandrinum*)	
Bangladesh (northwest)	1. Dhaincha (*Sesbania* spp.) 2. Sunn hemp (*Crotalaria juncea*) 3. Black gram	1. Mungbean (*Vigna radiata* (L.) Wilezik) 2. Cowpea (*Vigna Unguiculata* (L.) Walp.)
Philippines	1. Indigo (*Indigofera tinctoria*) 2. Azolla	

season. Seed is relay-broadcast into the second rice crop during its reproductive period. The practice of relay broadcasting to establish a green manure crop—which overwinters and is incorporated before the first rice crop of the next year—is apparently unique to China. In other areas surveyed (except the Philippines), *Sesbania* species were the dominant green manure crops. In the Philippines, *Indigofera tinctoria* is the only green manure crop cultivated to a significant extent.

Several *Sesbania* species are used in Asia: *S. aculeata* is an important species in South Asia, *S. speciosa* in southern India, *S. roxburghii* in Taiwan, China, and *S. cannabina* in mainland China. The *sesbanias* are cultivated primarily as prerice green manure during the premonsoon and early monsoon period Apr-Jul. In China, *S. cannabina* also is transplanted as an intercrop in the first rice crop and incorporated at land preparation for the second rice crop.

Survey responses implied that the use of green manure in rainfed wetland rice-based systems is extremely limited. The major exception is the mixed cropping of *S. aculeata* with dry seeded or wet seeded rainfed lowland rice in eastern India. In this situation, green manure is adapted for a short dry to wet season transition and a short rice-growing season. *S. aculeata* seed is mixed with rice and the crops broadcast together on dry soil. The green manure is incorporated 45-60 d after seeding in an operation called *beusaning.* The field is plowed and cross plowed with



1. Rice environments and and crop sequences including green manure crops in several Asian countries. SB seedbed. Source: Regional Servey on Farm Level Management Systems for Green Manure Crops.

standing water and the *Sesbania* plants trampled into the mud. This operation thins the rice crop and may control weeds.

Indigofera cultivation in the Philippines is an example of a cropping system in which the green manure crop is planted during the wet to dry season transition period. It grows slowly during the dry season and is incorporated during the dry to wet season transition before wet season rice.

Green manure cropping is practiced predominantly on irrigated ricelands. A common observation of survey respondents (visible from examining the crop sequences practiced with and without green manure diagrammed in Figure 1) is that in irrigated areas, crop alternatives compete directly with green manure for land resources. During the winter season in mainland China, expanding use of land for wheat, barley, or rape production is reducing the area planted to *Astragalus* and other green manure crops. In Taiwan, green manure competes directly with rice or maize. In South Asian irrigated areas, the possibility of growing a short-duration grain legume, such as mungbean, rather than a green manure during the time gap after the wheat harvest and before rice planting is gaining widespread attention (Meelu and Morris 1987). As Chen Lin-Zhi (1987) has indicated, "green manure crops and agricultural crops compete for space and time, a competition between land utilization and land upkeep."

Soil fertility and textural classes vary among microregions where green manuring is practiced in Asia (Table 2). Waterlogging is a major environmental determinant of the opportunity costs of using land for green manure or for alternative crops. Respondents in China and parts of India indicated that waterlogging does not occur during the green manure crop growth period. Thus, alternative economic crops should be very competitive in those areas, as is implied in Figure 1.

In green manure-producing areas in northern and eastern India and Bangladesh, waterlogging occurs during the green manure crop cycle. Waterlogging-tolerant *Sesbania* species are grown in those situations. Alternative crop possibilities are limited, strengthening the potential for green manure in those areas.

Economics of green manure

Land preparation and seeding

Tillage and seeding operations are major components of the labor and cash outlay by farmers who grow green manure crops. Effective stand establishment at low cost is essential to the economic viability of the system. It is interesting that conventional land preparation is used in green manure cultivation in all situations covered by the survey except for relay-cropped milk vetch in China. Land preparation varies, from one to three plowings and harrowings for prerice *Sesbania* in India to as many as six plowings with a traditional (desi) plow in Bangladesh. In Taiwan, a single tractor plowing is adequate to prepare ricelands for *S. roxburghii*.

In those cases where land preparation is specifically for green manure crop establishment, the cost of the operation cannot be shared with another crop. In two situations, however, land preparation for green manure is combined with that for a

Table 2. Land preparation and seeding practices currently used by farmers who cultivate green manure (GM) crops in some Asian countries.[a] Source: Regional Survey on Farm Level Management Systems for Green Manure Crops.

	China		Taiwan, China	Southern India	Chhotanagpur, India	Northern India	Eastern India (*S. speciosa* and *S. aculeata*)		Bangladesh	Philippines
	Chinese milk vetch	Bird vetch	(*S. roxburghii*)	(*S. speciosa*)	(*S. aculeata*)	(*S. aculeata*)	Irrigated	Rainfed lowland	(*Sesbania* spp.)	(*Indigofera*)
Land preparation for GM										
No tillage (NT) or conventional tillage (CT)	NT	NT	CT	CT	CT	CT	CT	CT	CT	CT
Plowings (no.)	n/a	n/a	1	1	2	n/c	3	3	6	1[b]
Harrowings (no.)	n/a	n/a	1	0	1	3	3	3	3	1[b]
Tillage equipment used	n/a	n/a	Tractor	Desi plow	Desi plow, plank	Desi plow or tractor disc harrow	Desi plow and ladder	Desi plow and ladder	Desi plow	Harrow
GM seeding rate (kg/ha)	45-60	45-75	25-30	15-30	10	40	50	15-20	15	5
Seeding method	Broadcast	Broadcast	Broadcast	n/c	Broadcast	Broadcast	Broadcast	Broadcast	Broadcast	Broadcast or drill in furrows
Following rice crop dry seeded (DSR), wet seeded (WSR), or transplanted (TP)	TP	TP	TP	TP	TP	TP	TP	DSR or WSR	TP	TP
Soil fertility in GM areas high (H), medium (M), or low (L)	M or L	M or L	M	M	H	M	M or L	M or L	L	M or L
Soil texture in GM areas sandy (S), loamy (L), or clayey (C)	L or C	L or C	L	C	L or C	L	L or C	L	S	S or L
Field waterlogged for periods exceeding 2-3 d during GM growth	No	No	No	No	No	Yes	Yes	Yes	Yes	No

[a] n/a = not applicable, n/c no comment made by respondent
[b] Ladderings

market crop. That dramatically reduces green manure establishment costs. In the Philippines, *Indigofera* is sown as an intercrop with postrice dry season crops mungbean, maize, or tobacco on irrigated and rainfed land. Indigo has slow initial growth and farmers observe no negative competition of the green manure crop and the main crop. In eastern India, in the rainfed lowlands where mixed cropping of *S. aculeata* and dry seeded rice is practiced, land preparation for the green manure crop involves no additional investment of labor, power, or capital. Normal tillage practices for rice are followed, with or without the inclusion of a green manure intercrop.

The quantity of green manure seed used by farmers varies by crop species and locality. In India. *Sesbania* seeding rates range from 10 to 50 kg ha. When *Sesbania* is intercropped with rainfed rice, farmers use 15-20 kg/ ha. In China, seeding rates for vetches are higher (45-75 kg/ ha). In all situations surveyed except the Philippines, green manure is broadcast seeded whether it was monocropped, mix-cropped, or relay-cropped. In the Philippines, *Indigofera* is drilled in rows as an intercrop with dry season upland crops.

Green manure incorporation

Successful cultivation of a green manure results in a dense stand that may exceed 20 t fresh weight/ha. Thorough incorporation of this material into the soil for the transplanted rice crop is difficult for most Asian farmers (Table 3). The average age of *Sesbania* at incorporation varies from 30 to 70 d. Overwintered interseeded green manure crops in China stay in the field more than 180 d.

Various strategies are used for green manure incorporation. In most cases, farmers slash the green manure by hand, then plow under the biomass. In Taiwan and Bangladesh, green manure is cut by machine, then plowed under. In Taiwan and the Philippines, it is plowed in directly. In Taiwan, direct plowing is possible using 4-wheel tractors. In the Philippines, direct incorporation is possible because the *Indigofera* stand is not dense.

The man-animal time required to incorporate preen manure varies. Farmers in Taiwan spend no additional time plowing under *S. roxburghii* before rice. *Sesbania* incorporation increases the time spent in land preparation for transplanted rice in India from 20 to more than 50%. The additional effort in northern Bangladesh was reported to be 100%.

The frequency with which farmers resort to slashing green manure confirms their inability to incorporate the crop directly with the available tillage equipment. Slashing creates a serious labor bottleneck during the incorporation period. In most areas, incorporation occurs at the same time that peak operations of land preparation and transplanting are underway for rice establishment. Labor shortage should not be underrated as a green manure production constraint.

Incorporating green manure with animal power was noted as being particularly difficult in South Asia, where farmers use the desi plow. This implement does not incorporate biomass efficiently because it does not turn under surface residues. Wherever animal-powered tillage implements are used, this limitation will be very serious.

Table 3. Methods and issues of green manure incorporation in selected Asian countries.[a] Source: Regional Survey on Farm Level Management Systems for Green Manure Crops.

	China (Chinese milk vetch)	Taiwan, China (*S. roxburghii*)	Southern India (*S. speciosa*)	Chhotanagpur, India (*S. aculeata*)	Eastern India (*S. aculeata* and *S. speciosa*)	Northern India (*S. aculeata*)	Bangladesh (NW) (*Sesbania* spp.)	Philippines (*Indigofera*)
Method of incorporation								
Plowed in directly	●							●
Knocked flat, then plowed in								●
Slashed by hand, then plowed in	●		●	●	●	●		
Cut by machine, then plowed in		●					●	
Plowing equipment used: 4-wheel tractor (T), hand tractor (HT), or animal power (AP)	T or AP	T	AP or T	AP	AP	AP	AP. T	AP, T
Plowings required (no.)	1[b]	n/c	2	2	12	3-4	6[b]	1[b]
Average age of GM at incorporation (d)	180+	50-70	45-65	30-55	40-50	40-55	50-65	173.4
Incorporation difficult for farmers?	No	n/c	Yes[c]	No	Yes[d]	Yes[c]	Yes[d]	No
Man and animal time to incorporate GM and prepare land for rice								
Rice alone (man-animal days)	n/c	1.5	10	15-16	6	n/c	38	10
GM then rice (man-animal days)	n/c	1.5	12	20-25	8	n/c	76[e]	10
% increase		0	20	33-56	33		100	

[a] n/c - no comment made by respondent
[b] Followed by 2-3 harrowings
[c] Incorporation with country plow difficult
[d] Incorporation time-consuming when GM is older or when standing water not present in the field.
[e] GM incorporation requires 1-2 more plowings than for rice alone

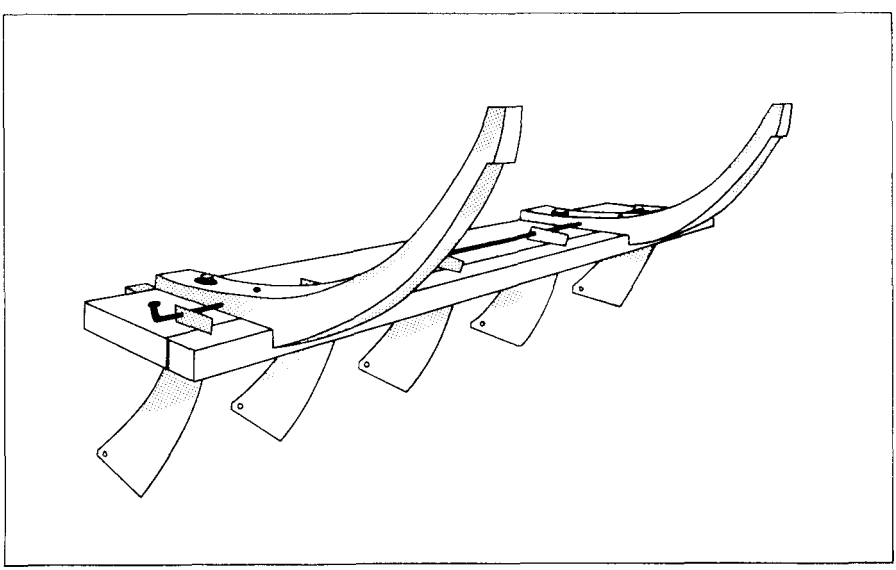
IRRI has helped develop two power tiller attachments to incorporate green manure biomass. An attachment of ring knives to power tiller cage wheels utilizes wheel slippage and weight of the power tiller to cut the green manure into small pieces (Khan et al 1986). The "turtle" floating power tiller cuts and incorporates green manure biomass in one pass (Calilung and Stickney 1985).

A local animal-drawn implement used by farmers in the Cagayan Valley, Philippines, shows promise for green manure incorporation. The implement, called a slicer (Fig. 2), is used to incorporate fallow weed vegetation before transplanting rainfed wetland rice. The slicer flattens *Sesbania rostrata* crops on the first pass through the field while five sharp blades slice off branches. On the second pass, at a right angle to the first, plant stems are sliced into 25-cm sections and driven down into the mud. Conventional plowing and harrowing follow without significant additional effort. Time spent on incorporation operations above that charged to conventional land preparation for rice is about 2.5 man-animal d/ha.

Seed sources, seed costs, and seed production

Information on seed production and distribution for green manure crops in Asia is extremely limited. In our survey, farmers reported difficulties obtaining seed or growing their own seed in China, southern India, Bangladesh, and the Philippines (Table 4). Purchasing or growing seed was not considered a problem by respondents in eastern and northern India.

In China, northern India, and Bangladesh, most farmers purchase seed from the market or private dealers. In southern and eastern India, most farmers grow their own seed, either by leaving random *Sesbania aculeata* plants to mature in ricefields



2. Simple local implement (slicer) used by farmers in the Cagayan Valley, Philippines, that flattens and chops *Sesbania* biomass before incorporation by animal-drawn plow.

Table 4. Green manure seed sources, seed costs, and seed production at the farm level.[a] Source: Regional Survey on Farm Level Management Systems for Green Manure Crops.

	China (Chinese milk vetch)	Taiwan, China *(S. roxburghii)*	Southern India *(S. speciosa)*	Chhotanagpur, India *(S. aculeata)*	Eastern India *(S. aculeata* and *S. speciosa)*	Northern India *(S. aculeata)*	Bangladesh (NW) *(Sesbania* spp)	Philippines *(Indigofera)*
Seed sources for green manure (in rank order)								
• Farmers grow own	2	4	1	/	1	2	2	2
• Exchange among farmers	4	3	2	/	3	3	-	-
• Purchase from market	1	1	3	/	4	1	1	1
• Purchase from government	3	2	4	/	2	-	-	-
Is there a conventional market for seed?	Yes	Yes	Yes	Yes	No	Yes	No	Yes
Do farmers have difficulty obtaining or growing seed?	Yes[b]	Yes[c]	Yes[d]	No	No	No	Yes	No
Price paid for seed by farmer (US$)	0.55-0.80 (Rmb 2·3)	1.40-2.00 (NT 50-70)	0.50 (Rs 6)	0.33-0.40 (Rs 4·5)	0.58-0.67 (Rs 7-8)	0.20	0.33	1.25 (₱ 25.00)
Price paid to seed producers (US$/kg)	0.08-0.11 (Rmb 0.3-0.4)	0.85-1.40 (NT 30·50)	0.40 (Rs 5)	0.16-0.25 (Rs 2·3)	n/c n/c	0.20	0.16	0.68 (₱ 13.65)
Does government encourage seed production, or produce and distribute seed?	Yes	Yes	No	Yes	Yes	No	Yes	No
Where on farm is seed produced?	Upland, single crop riceland	Paddy field	Field bunds	Field bunds	Paddy land, bunds	Paddy land	Riverside	Paddy fields, riverside, upland
Is hard-seededness a problem?	Yes	n/c	No	No	No	No	Yes	No
How do farmers overcome it?	Cool temperature	n/c	n/a	n/a	n/a	n/a	n/c	n/a

[a] n/a = not applicable, n/c = no comment made by respondent
[b] Due to low seed production in lowlands.
[c] Management of seed crop is difficult because of tall height, late maturity.
[d] Seed storage is difficult because of stored product pests.

Table 5. Insect pests and diseases observed in green manure crops grown in some Asian countries. Source: Regional Survey on Farm Level Management Systems for Green Manure Crops.

Green manure	Country	Designation	Plant parts affected		Damage level		
			Vegetative	Pods or seeds	Very serious	Important	Minor
		Insects					
Chinese milk vetch *Astragalus sinicus* L.	China	*Aphis fabae*	●			●	
		Taeniothrips distalis Karug					
		Taeniothrips sfosdati					
		Phytomyza paniculafae Saskawa					
		Phytomyza horticola Gowreau					
Sesbania roxburghii M.	China (Taiwan)	Cabbage looper	●			●	
		Cabbage worm	●			●	
S. speciosa and *S. aculeata*	India (southern)	Leaf roller	●			●	
		Mealybugs	●			●	
		Pod borer		●	●		
S. speciosa and *S. aculeata*	India (eastern)	Caterpillar	●			●	
		Pod borer		●		●	
S. aculeata	India (north)	none					
Sesbania aculeata	India (Chhotanagpur)	none					
Sunn hemp *Crotalaria juncea*	China (Taiwan)	Pests are rare.					
Rape *Brassica campestris* L.	China (Taiwan)	Pests are rare because of cool weather.					
		Diseases					
Chinese milk vetch Astragalus sinicus L.	China	*Sclerotinia trifoliorum* Erik.	●			●	
		Oidium sp.					
		Stemphylium astragali Yoshii					
S. speciosa L.	India (southern)	Virus disease	●				●

or by planting or transplanting along ricefield bunds. A conventional market for green manure seed is found in most localities except eastern India and Bangladesh. Governments are encouraging green manure seed production, or are producing and distributing seed in most areas. but that does not provide a major source of seed to farmers except in Taiwan, mainland China, and eastern India.

In India, prices of green manure seed range from US$0.20 to 0.67/kg for *Sesbania* species. In mainland China, prices are US$0.55-0.80/kg for *Astragalus.* In Taiwan, prices reach US$1.40-2.00/kg. Prices received by seed producers range from as low as 15% of the market price in mainland China to the full market price in eastern India.

Seed production was considered a severe constraint in Taiwan, where green manure seed costs are much higher than elsewhere in Asia. Late maturity, excessive plant height (which makes pest control and harvesting difficult), and low seed yield of local *Sesbania* species are major limitations to more competitive seed prices. Breeding an earlier maturing, shorter green manure plant was suggested as an important objective.

Pests and diseases

Green manure production in several regions is reduced by biological stresses. Several insect pests and diseases were reported from China and southern and eastern India (Table 5). Podborers, leaf rollers, and mealybugs in India and cabbage loopers in Taiwan are important insects on *Sesbania. Aphis fabae* is a serious insect pest and *Sclerotinia trifoliorum* Erik. is an important disease on *Astragalus sinicus* in China.

Farm-level yield benefits

In fertilizer application rates of farmers producing rice with and without green manure (Table 6), two observations were consistent across the region.

First, farmers substantially reduce inorganic N fertilizer rates when green manure cultivation is practiced, but in no case does green manure substitute entirely for inorganic N. Farmers view organic and inorganic nutrient sources as complementary or synergistic. They do not find green manure crops adequate sources for the full nutrition of the rice crop.

Second, estimates of grain yields were consistently higher with green manure than with high rates of inorganic N alone. Estimated yield increases attributed to green manure were about 15% in China and southern India and reached about 25% in eastern India and Bangladesh.

Green manure was seldom produced every year on a given field. In China, a crop is usually grown once in 3 yr. In this rotation, a grain crop is taken the second year and the land is fallowed the third year.

A major concern was that green manure production may delay the rice crop beyond the normal transplanting time. However, this does not appear to be a significant problem. The optimum time to transplant after green manure incorporation was reported to be between 7 and 15 d in all areas where a delay is maintained between the 2 crops. In some areas, early rice growth may be depressed after green manure incorporation.

Table 6. Yield effects and inorganic fertilizer equivalent of green manure (GM) cultivation.[a] Source: Regional Survey on Farm Level Management Systems for Green Manure Crops.

	China (Chinese milk vetch)	Taiwan, China (*S. roxburghii*)	Southern India (*S. speciosa*)	Chhotanagpur, India (*S. aculeata*)	Eastern India (*S. aculeata* and *S. speciosa*)	Northern India (*S. aculeata*)	Bangladesh (NW) (*Sesbania* spp.)	Philippines (*Indigofera*)
Approximate rate of Inorganic N applied to rice								
Without GM (kg N/ha)	180	1st: 120-150 2d: 100 130	100	80-100	60	100-120	80	88
With GM (kg N/ha)	120	1st: 120-150 2d: 30 39	60	40-50	30	60-80	60	38
Approximate yield farmers obtain								
Without GM (t/ha)	5.2	1st: 70 2d: 5.0		4.0	3.0	6.0-7.0	3.0-5.0	4.5
With GM (t/ha)	6.0	1st: 7.5 2d: 5.3	10-15% increase	5.0-6.0	3.8	6.0-7.0	4.0-6.0	4.6
Frequency of GM cultivation	1 yr in 3[b]	1 yr in 2 or 2 yr in 3	Every year[d]	Skip some years	Annual	Skip some years	Skip some years	Annual
Reduction in weed growth and weeding costs with GM	n/c	No difference	Slight	Yes	No difference	Yes[e]	Yes, large	Yes, large
Rice crop establishment delay caused by GM	No	No	No	No	1 week	No	No	No
Optimum time to transplant after GM incorporation (d)	10-15	n/c	7-10	n/c	n/c	7	10-15	4-7
Early rice growth depressed by GM	Yes[c]	No	Sometimes	No	Yes	No	Yes	No
Potential for expanded GM use	n/c	Large	Large	Modest	Large	Modest	Large	Moderate
Status of area planted to GM	Decreasing	Increasing	Decreasing	Increasing	Stable	Decreasing	Increasing	Decreasing

[a]n/c = no comment by respondent.
[b]This is the case in most ricelands In poor soil, GM is cultivated continuously.
[c]Farmers Incorporate some N fertilizer to avoid this problem.
[d]Continuously cultivated except in years when drought prevents sowing.
[e] One weeding is saved.

Respondents judged that there is a modest to large potential in most areas to increase the use of green manure. However, there was less consistency in whether the area under green manure is expanding or contracting. In mainland China, Philippines, and southern and northern India, respondents estimated that use of green manure is decreasing; in Taiwan, India (Chhotanagpur Plateau), and Bangladesh, respondents reported increasing use. In irrigated areas that do not experience waterlogging, upland crops that produce direct cash income are competing with green manure.

Economic balance for green manure production

Data from four sites were sufficient to permit the construction of an economic balance sheet for green manure production (Table 7). These figures are at best tentative. The financial analysis seeks to compare costs and benefits between the combined use of green manure and inorganic N and inorganic N alone.

Overall, added costs to produce a green manure crop varied from a low of $25/ha in the Philippines to over $100/ha in India. In each case, these costs represent the opportunity costs. not necessarily the paid-out costs of producing a green manure crop. Opportunity cost of land is not included in the calculations, and may add substantially to the cost of green manure production if alternative crops are availahle.

Fertilizer savings varied from a low of S11 ha in eastern India to more than $25/ha in the Philippines. These figures may be conservative; farm-effective prices are usually higher than the market or official prices used in this analysis. Nonetheless, savings in inorganic fertilizer are substantially less than the added cost of growing the green manure, except for the Philippine case. Green manuring cannot be financially justified in terms of fertilizer savings alone.

The added value of rice from the beneficial effects of green manure exceeded $80/ha. except in the Philippines. These added benefits may be overestimated because a) yield gains–assuming they are realistic for farm conditions–are gross. not farmer-effective (harvester's and landlord's shares have not been deducted), and b) official and market rice prices tend to overestimate farmer-effective prices because marketing charges are not deducted.

Accepting these caveats, added benefits from green manure probably exceed $100/ha at 3 sites (China and 2 in India) and may exceed $40/ha in the Philippines. The ratio of added benefits to added costs exceeds 1.0 in China and the Philippines. demonstrating the financial profitability of green manure in these locations. However, the sites may represent contrasting situations: in China, the opportunity cost of land is possibly large (e.g., with a wheat or oilseed crop); in the Philippines, it may be low because it is difficult to produce an upland crop before rice in the region where indigo is grown. Whether the area under green manure expands or decreases will likely depend on alternative uses of land.

In India, the estimated ratio of benefits to costs is less than 1.0, implying that the green manure technology practiced by farmers is not profitable. That is unlikely; farmers rarely pursue activities that are not privately profitable. This may lead one to query the data, but a more important point may be that farmers do not value owned

Table 7. Estimates of costs and benefits of green manure production in irrigated rice-based farming systems in Asia.

	China (central)	India (south)	India (east)	Philippines (northwest)
costs				
Land preparation				
Plowing		19.40	75.67	
Harrowing		0.00	23.28	
Seeding				
Green manure seed	35.44	9.00	31.25	6.45
Labor	0.43	0.81	0.49	0.60
Sesbania incorporation				
Slashing	8.60	16.17	9.70	
Plowing		64.67	38.80	
Harrowing	9.30			17.50
Added costs (DC)	53.77	110.05	179.19	24.55
Benefits				
Reduction in inorganic N				
kg/ha	60.00	40.00	30.00	45.00
$/ha	19.96	15.11	11.34	25.78
Change in 1st crop rice yield				
t/ha (DC)	0.75	0.75	0.80	0.10
$/ha	97.50	83.06	88.60	15.15
Carry-over effects				
$/ha (5% DC)	2.69	5.50	8.96	1.23
Added benefit = AB	120.15	103.68	108.90	42.15
DB/DC	2.23	0.94	0.61	1.72

[a]Opportunity cost for land not included because of lack of data. Therefore, added costs underestimated where alternative crops are possible. Prices are officially reported prices and as such possibly represent market as opposed to farmer-effective prices.

Data sources:

China

An economic analysis of hybrid and conventional rice in Jiangsu Province, *China*

Land preparation cost for rice production = $18.59/ha

Assumption: 50% of LP cost for rice will be cost of incorporation for GM

Paddy price — $0.13/kg

Wage rate — $0.86/d.

Hybrid rice survey (Amanda Te) 1982

Price of urea — 0.225 jin/yuan

India

Agricultural Situation in India, September 1986

Animal rent by region (2 x wage rate)	Wage rate
South — 40 rupees/d	20 rupees/d
East — 24 rupees/d	12 rupees/d

Exchange rate: IMP Financial Statistics

China 1$ = 2.94 yuan

India 1$ = 12.37 rupees

Philippines 1$ = 20 pesos

For land preparation

1 plowing = 6 animal d/ha

2 plowings = 6 + 4 = 10 animal d/ha

3 plowings = 6 + 4 + 3 = 13 animal d/ha

3 harrowings = 4 animal d/ha

resources (e.g., their own animals and labor) at market price when evaluating the relevance of this technology.

The wedge between market-determined opportunity costs and farmer valuation of resources is usually greatest in labor-slack periods. This implies that there is merit in evaluating green manure within a whole-farm framework to ensure that a) the opportunity cost of owned resources is set with respect to alternative farmer uses, and b) the opportunity cost of land is also internalized in the analysis.

The balance sheet provided in Table 7 is at best indicative. Nonetheless, the data highlight the importance of a) cost of land preparation and green manure incorporation, and b) incremental yields gained with green manure (over and above those realized with inorganic N alone) as determinants of the financial viability of this practice.

Green manure cultivation in rainfed environments

Single-crop, transplanted rainfed wetland rice is estimated to cover more than 20 million ha in Asia. Large areas of the single-crop ricelands have poor internal and surface drainage and experience unpredictable short-term waterlogging during the dry to wet season transition period. This is particularly common in ricelands on the floodplains of the major river systems.

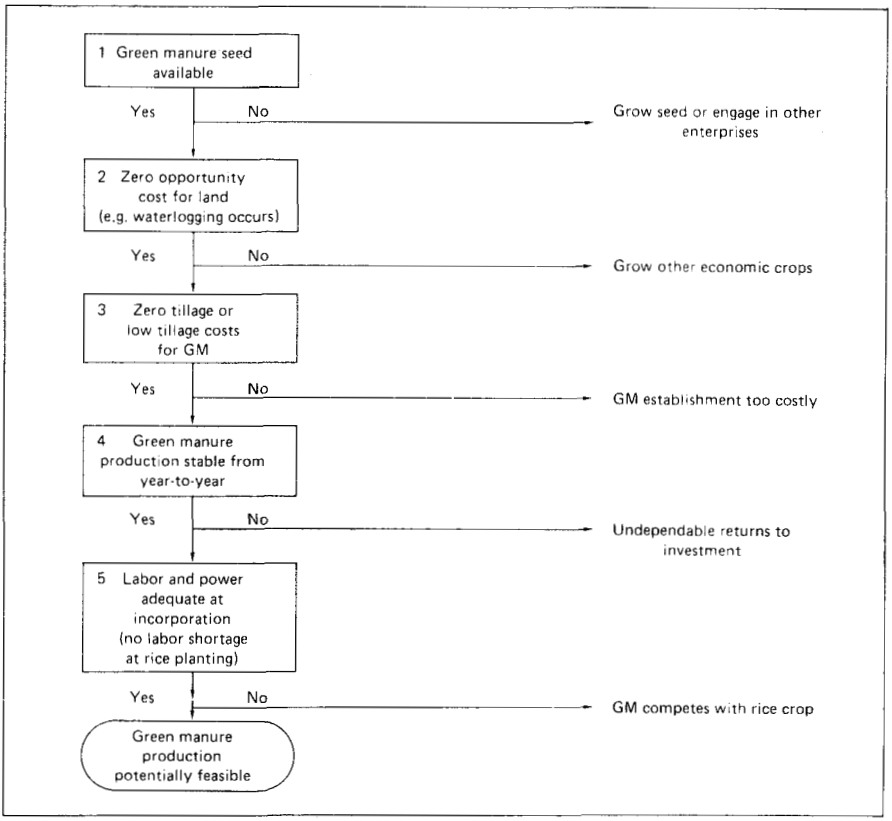
Green manure crops are rare on rainfed ricelands at present. Our analysis suggests that waterlogging-prone rainfed areas are the largest potential environmental niche for green manure cultivation in the future. This implies that a large relocation of green manure production may occur, with declines in fully irrigated areas and increases in rainfed areas.

Environmental, technological, and economic factors will dictate the feasibility of green manure expansion in rainfed areas. Numerous necessary minimum conditions must be met before farmers can or will grow green manure (Fig. 3). Restructuring will require a determined research effort on problems of green manure production in environments with uncertain moisture dependability.

The research agenda

Our analyses, the perspective of others (Norman 1982), and the long-term reduction reported in green manure use (e.g., in China) suggest that green manuring is not now a viable practice for rice farmers in many parts of Asia. However, we also recognize that inorganic fertilizers are derived from nonrenewable resources and that green manure crops may have definite ecological advantages as well as provide opportunities for resource-poor farmers to increase and sustain the productivity of their farming systems. The current, less favorable economic comparison between green manure and sole use of inorganic fertilizer is not a sufficient basis to forgo investment in a vigorous research program to increase yields through greater use of resources within the farm.

Competitiveness requires that the unit cost of producing N from green manure sources be reduced and the beneficial impacts of green manure on future crop



3. Decision tree: minimum necessary criteria for green manure production in a particular environment.

production be maximized. A research agenda leading to more cost-effective green manure technology could

- Identify cost-efficient methods of producing green manure crops that will
  - reduce green manure establishment costs,
  - reduce green manure incorporation costs, and
  - identify cost-efficient methods of increasing N fixed per day the green manure crop is in the field.
- Identify management practices that will increase the gain in rice yield from green manuring over and above that realized by N substitution alone. In the process, quantify the short- and long-term relationship between green manure plus inorganic N and inorganic N alone.
- Use a farming systems framework to
  - identify environmental niches where green manure offers the greatest potential;
  - explore other ways to increase the economic benefit of green manure (e.g., harvest as fodder or grain);

- quantify the opportunity cost of land and other inputs (e.g., labor and power) to green manure production;
- examine existing systems of green manuring practiced by farmers and identify the parameters leading to area expansion or contraction.

• Quantify the externalities (i.e., benefits to society at large) of green manure use:
- examine the likelihood of reduction in groundwater or atmospheric pollution with green manure adoption. Could similar reductions be achieved more cost-effectively by other means (e.g., by increased efficiency in the use of mineral fertilizer)?
- if externalities are large (i.e., public benefits exceed private profits), should and can the government subsidize green manure technology to increase private profitability?

This research agenda is strongly interdependent and requires the input of scientists in a range of disciplines, such as plant breeders, agronomists, pest management specialists, and economists. An interdisciplinary perspective on increasing the cost effectiveness of integrated nutrient management appears to be a precondition to developing green manure technology suited to Asian rice farmers.

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Notes

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Microbiologcal aspects of green manure in lowland rice soils

N. S. SubbaRao

Green manure legumes are often nodulated by slow-growing *Rhizobium* sp. (cowpea miscellany); *Lathyrus* is nodulated by *R. leguminosarum;* clovers, by *R. trifolii.* In nature, stem nodulation of *Aeschynomene* is restricted to *A. aspera, A. indica, A. elaphroxylon, A. evenia, A. paniculata,* and A. sp.; in *Sesbania,* it is restricted to *S. rostrata.* Root infection is by epidermal entry of *Rhizobium* in *Aeschynomene;* no infection threads have been seen. Stem nodules arise exogenously, root nodules are endogenous. In *S. rostrata,* both intracellular and intercellular epidermal infections take place at predetermined primordia on the stem; distinct branched infection threads are known to exist. In *A. indica* collected in India, a photosynthetic purple bacterium of the family Rhodospirllliaceae has been shown to inhabit stem nodules, either singly or with *Rhizobium,* in distinct zones of the nodule. This novel endophyte has not been isolated in pure culture. In *Aeschynomene,* both root and shoot leghaemoglobin are identical in size, with a molecular weight of 14,500. Studies are underway on the genetic determinants of stem nodulation in *Aeschynomene* and the location of *nif* genes. Field research on the microbiology of anaerobic decomposition of legumes is scanty. A few laboratory studies have indicated injurious effects of volatile aliphatic acids, phenolics, and alcohols produced by microbial action.

Waterlogged rice ecosystems provide a congenial habitat for a variety of N_2-fixing microorganisms and systems that contribute to the N status of the soil. These include the fixed N derived through the *Azolla-Anabaena* system, blue-green algae, and other heterotrophic N_2-fixing bacteria. Another source of fixed N that can be made available to the rice crop is selected nodulated legumes. They serve as green manure when they are incorporated into waterlogged fields, then puddled.

Recent use of *Sesbania rostrata,* a stem-and root-nodulating species of legume, as a green manure crop (Dreyfus et al 1985) has revived interest in the science and art of green manuring. This review summarizes knowledge on the salient microbiological aspects of green manuring with nodulated legumes.

Two factors need to be considered in discussing the microbiological aspects of green manuring. The first relates to the rhizobiology of nodulating species of green manure legumes, the second to the microbiological aspects of fresh residue decomposition in anaerobic waterlogged ricefields.

In recent years, attempts have been made to understand more about the nodulation aspects of *Sesbania* and *Aeschynomene;* this review concentrates on those two genera because detailed studies of other species of legumes have not been undertaken. Similarly, while we have data on the decomposition of organic matter in arable soils, there is a paucity of information on the processes of fresh green residue degradation in anaerobic rice soils. These limitations need to be taken into account in planning future studies on the use of green manure in lowland rice soils.

Stem-nodulating legume species

Allen and Allen (198 1) listed nine genera of legumes that have been used as green manure crops in wetland rice cultivation: *Aeschynomene, Astragalus, Crotalaria, Indigofera, Lathyrus, Pongamia, Tephrosia, Trifolium,* and *Sesbania.* They also listed 39 genera whose species are being used as general green manure in plantation crops: *Arachis, Atylosia, Cajanus, Calopogonium, Canavalia, Cassia, Cochlianthus, Cullen, Derris, Dipogon, Dolichos, Dunbaria, Erythrina, Flemingia, Gliricidia, Kummerowia, Lablab, Lespedeza, Leucaena, Lupinus, Mastersia, Melilotus, Mimosa, Mucuna, Ormocarpum, Pachyrrhizus, Parkia, Phaseolus, Pisum, Psophocarpus, Pteroloma, Pueraria, Shuteria, Stylosanthes, Tetragonolobus, Trigonella, Uraria, Vicia,* and *Vigna.* (It would be worthwhile to explore whether any of these general species also have potential as green manure crops for rice.)

Table 1 lists some characteristics of rhizobia and root nodulation in some species of legumes commonly used in wetland rice cultivation in Asia. In general, the rhizobia from nodules of these legumes belong to the cowpea miscellany; they quite often have limited cross infectivity with other legumes. In recent years, the occurrence of nodules on stems of *Aeschynomene* and *Sesbania rostrata* has been highlighted (Table 2). It has been assumed that stem nodules and root nodules contribute jointly to nitrogen nutrition for rice.

Aeschynomene

The genus *Aeschynomene* consists of about 150-250 species, ranging from herbs to small and medium-sized trees. Almost half the species are water-loving and grow in wet ricefields, flooded areas, marshes, and near lakes and river beds. The members of the genus are tropical in habitat and are distributed primarily in the Americas, less frequently in Africa, Australia, and the Pacific area (Allen and Allen 1981).

Jaensch (1984) observed stem nodules on *A. elaphroxylon.* Hagerup (1928) did not observe stem nodules on *A. aspera.* Suessenguth and Beyerle (1935) noticed stem nodules on preserved specimens of *A. paniculata* from Brazil and *A. indica* from Sudan. In the USA, Quesenberry and Ocumpaugh (198 1) evaluated a collection of world germplasm for use as forage legumes. Their report mentions *A. americana* as an important forage legume in Florida and cites as other potential species *A. brasiliana, A. elegans, A. evenia, A. falcata,* and *A. villosa.* Strangely, they do not mention stem nodulation.

Several workers have reported the occurrence of nodules on stems of various species of *Aeschynomene.* Natural stem nodulation in *A. aspera, A. indica,*

Table 1. Nodulation and rhizobial characteristics of some important green manure leguminous species used in lowland rice cultivation (based on Allen and Allen 1981).

Genus and no. of species	Species used as green manure	Nodule characteristics	Rhizobia characteristics	Remarks
Aeschynomene L. (150-250)	All species in the Orient	Round and ovoid; the root nodules arise endogenously and stem nodules, exogenously; infection through cortical cells. Infection threads are not seen.	Cross infection with *Stylosanthes mucronata, S. guianensis,* and *Phaseolus lathyroides.*	Some species also possess stem nodules.
Astragalus L. (1500-2000)	*A. chinensis* *A. cicer* *A. falcatus* *A. sinicus* in Japan and Taiwan	Ovoid, finger- or rosette-shaped.	Fast-gowing as well as slowgrowing isolates. Not all astragalii rhizobia nodulate all species of the genus. Cross infection with *Phaseolus* and clover but not on *Lupinus, Glycine,* certain *Trifolium* spp., *Pisum,* and *Vigna* species.	
Crotalaria L. (550)	*C. alata* *C. anagyroides* *C. ferruginea* *C. juncea* *C. laburnifolia* *C.sericea* *(C. spectabilis)* *C.usaramoensis*	Cylindrical with branched pink tips.	Cowpea type, promiscuous with many distinct groups,	
Indigofera L. (800)	*I. arrecta* *I. hirsuta* *I. suffruticosa* *I. tinctoria* in orient	Oval-shaped. Infection through cortical cells.	Cowpea type	

Continued on next page

Table 1 continued

Genus and no. of species	Species used as green manure	Nodule characteristics	Rhizobia characteristics	Remarks
Lathyrus L. (130)	*L. cicera* *L. hirutus* *L. ochrus* *L. sativus* *L. sylvestris* in India and Java	Elongated when young, having numerous infection threads, well-defined meristem, old nodules showing branded tips.	*R. leguminosarum* with mutual kinship between *Pisum, Vicia,* and Lens and their rhizobia.	-
Pongamia Vent. (1)	*P. pinnata* Syn. *P. glabra* in wet tropics	No description	Cowpea type	-
Tephrosia Pers. (400)	*T. purpureum* *T. candida* in Puerto Rico	Copious nodulation	Cowpea type	Leaf N = 4.18-4.83%
Trifolium L. (250-300)	*T. alexandrinum* in India	Elongated nodules often club-shaped with apical meristem. Infection through root hairs.	*R. trifolii,* fast-growing limited to *Trifolium* spp.	-
Sesbania Scop. (70)	*S. aculeata* *S. paludosa* *S. cannabina* *S. rostrata* in Orient	In adult plants, distinct nodules clustered along the taproot, often multilobed due to disrupted apical meristem. High longevity of nodules with functional infection threads.	Restricted host range. Rhizobia from alfalfa, clover, pea, soybean, and lupines failed to nodulate *Sesbania* spp. Some reciprocal affinity between cowpea, soybean, and *Sesbania* rhizobia.	*S. rostrata* has stem nodules.

Table 2. Reports on stern nodulation in *Aeschynomene* **spp. and** *Sesbania rostrata.*

Country	Species	Authors
India	*A. aspera* *A. indica*	Arora (1954) SubbaRao et al (1980) SubbaRao and Yatazawa (1984)
Mali	*A. aspera*	Hagerup (1928)
Ghana	*A. elaphroxylon*	Jenik and Kubikova (1969) quoted by Allen and Allen (1981)
Venezuela	*A. villosa* *A. evenia*	Barrios and Gonzalez (1971)
Brazil	*A. paniculata*	Suessenguth and Beyerle (1935)
USA	*A.* spp.	Eaglesham and Szalay (1983)
Japan	*A. indica*	Yatazawa and Yoshida (1979)
Senegal	*S. rostrata*	Dreyfus and Dommergues (1981a, b)

A. elaphroxylon, A. villosa, A. evenia, A. paniculata, and *A.* spp. is restricted to India, Mali, Ghana, Venezuela, Brazil, USA, and Japan. Many workers have reported root nodulation in various species of *Aeschynomene* in Zimbabwe, Venezuela, Java, South Africa, Zambia, Mali, South America, Puerto Rico, Argentina, Trinidad, and India (Table 3).

Table 3. Instances of root nodulation in *Aeschynomene.*

Country	Species	Authors
Zimbabwe	*A. abyssinica, A. aphylla, A. bracteosa, A. gazensis, A. grandistipulata, A. inyangensis, A. megalophylla, A. mimosifolia, A. minutiflora, A. nilotica, A. nodulosa, A. paniculata, A. rhodesiaca, A. schimperi, A. schliebenii, A. trigonocarpa*	Corby (1974)
Venezuela	*A. brasiliana, A. evenia, A. histrix, A. pratensis, A. rudis*	Barrios and Gonzalez (1971)
Java	*A. americana, A. falcate*	Keuchenius (1924) quoted by Allen and Allen (1981)
S. Africa	*A. elaphroxylon, A. micrantha, A. nodulosa, A. nyassana, A. rehmanni*	Grobbelaar et al (1967)
Zambia	*A. fluitaris, A. mediocris*	Verboom (1966) Verdcourt (1973)
Mali	*A. aspera*	Hagerup (1928)
South America	*A. hispida* *A. laxiflora, A. paniculata*	Suessenguth and Beyerle (1935)
Puerto Rico	*A. puertoricensis*	Dubey et al (1972)
Argentina	*A. rudis*	Rothschild (1970) quoted by Allen and Allen (1981)
Trinidad	*A. sensitiva*	DeSouza (1966) quoted by Allen and Allen (1981)
India	*A. aspera* *A. indica*	Arora (1954) SubbaRao and Yatazawa (1984) SubbaRao et al (1980)

In a greenhouse study, Eaglesham and Szalay (1983) found that a strain of *Rhizobium* isolated from submerged stem nodules of *A. indica* (BTA : 1) effectively nodulated the roots of *A. denticulata, A. evenia, A. indica, A. pratensis, A. rudis, A. scabra,* and *A. sensitiva,* but failed to nodulate *A. americana, A. brasiliana, A. elegans, A. falcata, A. fasicularia, A. histrix, A. paniculata,* and *A. villosa.* When the same strain of *Rhizobium* was used to induce stem nodules on cuttings, stem nodules were seen on *A. scabra, A. denticulata, A. indica, A. pratensis, A. rudis,* and *A. evenia* but not on *A. brasilianu* and *A. elegans.*

Adding combined N to the nutrient medium in which the plants were growing did not inhibit stem nodulation of *A. scabru.* The stem nodules were larger in *A. scabra* plants that were flooded than in those which were not. Under nonflooded conditions, the addition of combined N reduced root nodulation more than it did stem nodulation.

SubbaRao et al (1980) isolated rhizobia from root and stem nodules of *A. aspera* (now identified as *A. indica*) and tested them for cross infection on *Cajanus cajan* (pigeonpea), *Cicer arietinum* (chickpea), *Pisum sativum* (pea), *Trifolium repens* (clover), *Medicago sativa* (lucerne), *Lens culinaris* (lentil), *Glycine max* (soybean), *Vigna sinensis* (cowpea), *Vigna radiata* (mungbean), *Vigna mungo* (urd bean), and *Arachis hypogaea* (peanut). *Aeschynomene rhizobia* did not nodulate the roots of any of those representatives of different cross inoculation groups of legumes, but when re-inoculated on *Aeschynomene,* could reproduce root nodulation. Interestingly, other species of *Rhizobium* did not nodulate the roots of *Aeschynomene.* It was difficult to produce stem nodulation on *A. indica* in the greenhouse.

I surveyed the root and stem nodulation habit of *Aeschynomene* in Tamil Nadu, West Bengal, and Delhi, India. Two species of *Aeschynomene* that conformed to the description of *A. aspera* and *A. indica* could be identified. *A. aspera* is a relatively large bushy shrub; *A. indica* is herbaceous and small. Varieties in the two species differed among the collection sites. Differences were reflected in plant size, flower, pods, seed, and seed color.

A major, consistent difference between the two species is that *A. aspera* possesses stem nodules but not root nodules; *A. indica* has both (Fig. 1). In *A. aspera,* the stem nodules are confined to the region of the stem subjected to flooding during the rainy season, but are restricted to the crown area (hypocotyl) under dry conditions.

When monsoon flooding takes place, as in a typical ecosystem called Veeranam Lake near Chidambaram in South India, *A. aspera* plants grow profusely and develop abundant stem nodules on the floating stem. During the summer when the lake is dry, the elongated shoot gradually shrinks and is telescoped into whorls of leaves truncated into small emergences on a rhizomatous stem, which pushes an unusually elongated taproot vertically down into the soil in search of moisture. The plants, which barely survive under the shade of other bushes in the summer, flourish again with the onset of the monsoon. Similar observations have been made in Delhi, Madurai, and Haringhata, where *A. aspera* did not bear root nodules but had only stem nodules near the crown. Plants raised in pots in Delhi from seeds of *A. aspera*

1. Stem nodules on *Aeschynomene* indica (× 2 magnification) (photo supplied by Dr. A. R. J. Eaglesham, Boyce Thompson Institute for Plant Research, Cornell University, Ithaca, N.Y., USA).

collected from Chidambaram confirmed the observations; myriad stem nodulated plants could be raised from cuttings without root nodules.

A. indica plants from Madurai and Delhi were similar, with distinctive green stem nodules as well as typical root nodules. In no instance could stem nodulation be successfully reproduced in *A. aspera* or *A. indica* under artificially inoculated and bacteriologically controlled conditions.

In Japan, Yatazawa and Yoshida (1979) report that wetland ricefields are known to support the growth of *A. indica* plants having N_2-fixing stem and root nodules. *Rhizobium* isolates of stem nodules induced the formation of root nodules. The presence of combined N was found to diminish nodulation in soil and solution cultures of plants.

There is a paucity of information on the cultural and biochemical characteristics of rhizobia from *Aeschynomene;* they are generally placed in the cowpea group (Carroll 1934). In a recent study, Annapurna Murty and SubbaRao (unpublished) isolated 50 *Rhizobium* strains from stem nodules of *A. aspera, A. indica,* and *Neptunia oleracea.* Cultural characteristics, cross inoculation, and nodulation abilities of these isolates were studied under axenic conditions. The mode of infection and histology of *A. indica* and *A. aspera* stem nodules were also studied. The bacterial isolates formed root nodules on their homologous host. The rhizobia1 isolates from stem and root nodules of *A. indica* were slow-growing and specific, readily forming root nodules only on their hosts. None could form stem nodules on inoculation in Gibsons test tubes or in paper cups under a controlled humidity (water-saturated) environment. However, rhizobia from stem nodules of *A. aspera* were interchangeable, since they nodulated roots of *A. indica* as well.

Rhizobia from nodules of *Neptunia oleracea* (another aquatic and stem-nodulating legume) and *Cajanus cajan* did not nodulate *Aeschynomene,* and vice versa. *A. indica* plants growing in waterlogged conditions (submerged) in nature showed less nitrogenase activity in general than plants growing in soil with normal water-holding capacity (unsubmerged). The stem nodules of *A. indica* had higher nitrogenase activity than did root nodules.

In other words, nitrogenase activity was high when plants with stem nodules were not submerged in water (Table 4). Infection of rhizobia through root hairs was not observed; it is presumed that the mode of entry is through epidermal cells of cortex. The stem nodules have parenchyma, with chlorophyll around the central bacteroid zone (which is deep red because of leghaemoglobin).

Nodule samples of *A. indica* collected from Madurai were fixed and taken to Charles F. Kettering Research Laboratory (now Battelle/C. F. Kettering Laboratory), Ohio, USA, in 1978 for cytological examination of both stem and root

Table 4. Nitrogenase activity of whole plants of naturally growing *A. indica* plants[a] (Annapurna Murty and SubbaRao, IARI, New Delhi, 1987, pers. comm.).

Age of plant (d)	C_2H_4 produced (nmol/h per gram dry weight)	
	Not submerged in water	Submerged in water
14	7,505 ± 351	2,336 ± 166
21	1,138 ± 47	872 ± 49
28	13,027 ± 710	2,154 ± 143
35	1,391 ± 103	610 ± 45
42	566 ± 33	1,096 ± 115

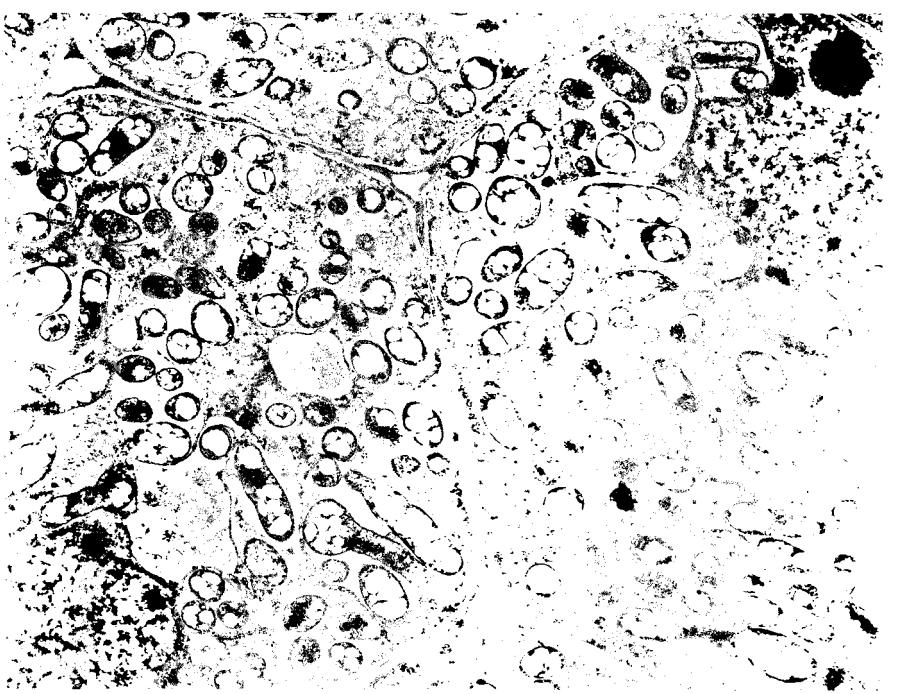
[a]Delhi field situation in submerged and unsubmerged conditions, mean of 10 replications.

nodules. Both light and transmission electron microscopic examinations revealed the presence of either *Rhizobium* or a coccoid bacterium (Fig. 2). Occasionally, both types of endosymbionts were present in the same nodule. They occupied different well-separated sections or zones, never within the same cell.

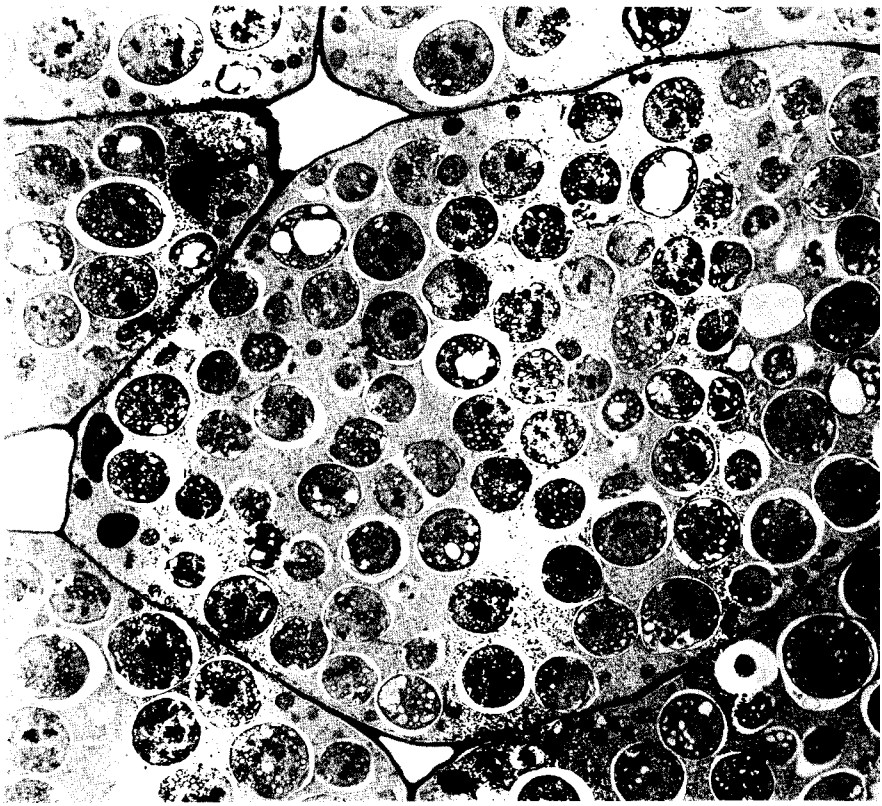
In 1979 and 1981, similar observations were made with nodule samples of *A. indica* from Chidambaram and Delhi. Ultrastructural observations revealed that the new endophyte is a spherical prokaryote, 2.5-3.5 μm in diameter, with a cell wall typical of gram-negative bacteria and a striking resemblance to a purple photosynthetic bacterium belonging to Rhodospirilliaceae (Fig. 3). This was supported by fluorescence excitation spectrum studies of isolated spherical endophyte cells (E. Dolan, D. E. Fleischman, G. R. Seely, and G. Alter of Battelle/C. F. Kettering Research Laboratory and Wright State University, Ohio, pers. comm.).

Attempts to isolate the unusual endophyte from *A. indica* nodules in pure culture have not met with success. Experiments on re-inoculation of aseptically grown *A. indica* plants remain to be done.

Arora (1954) studied the histology of root and stem nodules of *A. indica* using light microscopy. She observed a central bacteroid region surrounded by cortical parenchymatous cells. A ring of vascular bundles was observed in the inner part of the nodule cortex; there was no localized meristem. The stem nodule was exogenous, the root nodule endogenous in origin.



2. Transverse section of stem nodule of *A. indica* collected from India showing rhizobium (picture taken at Battelle/C F. Kettering Research Laboratory, USA).



3. Transverse section of stem nodule of *A. indica* collected in India showing the novel endophyte belonging to Rhodospirilliaceae (picture taken at Battell C. F. Kettering Research Laboratory, USA).

Ultrastructural characteristics of stem nodules of *A. indica* (Vaughn and Elmore 1985) showed a distinct central infected zone, with cells containing bacteroid and an uninfected nodule cortex. Extensive invaginations of the inner membrane, which could be the site of nitrogenase activity, were noticed in the bacteroids. No vacuoles were observed in the infected cells of mature nodules, confirming the earlier light microscopic observations. Bacteria traversed the middle lamellae and invaded the host cell by growth of plasmalemma and dissolution of the wall material. Infection threads, however, were not observed. Whether the abundant lenticels present on the stem are the portals of entry of *Rhizobium* is still an open question.

The presence of leghaemoglobin (a pink pigment akin to blood haemoglobin) in root nodules of legumes has long been recognized as a vital factor in controlling the rate of oxygen flow to the bacteroids, which are the sites of N_2-fixation. Legocki and Szalay (1983) carried out one-dimensional polyacrylamide gel electrophoresis (PAGE) of soluble cytoplasmic proteins from mature stem and root nodules of *A. scabra* and found that the leghaemoglobin in root and stem nodules were identical in size, approximately 14,500 MW. In 5-wk-old mature nodules, the

leghaemoglobins are more abundant in stem (11% wt/wt of total cytoplasmic protein) than in root nodules (7%).

Further analysis of tissues of both stem and root nodules revealed the presence in both of a single electrophoretically distinguishable component, in contrast to the slow moving (Lbs) and fast moving (LbF) components of soybean leghaemoglobins (Ellfolk 1972). Purified stem and root leghaemoglobins indicated an apparent polypeptide heterogeneity in the *Aeschynomene* leghaemoglobins. Both the stem and root nodule pigments resolved into four components, designated Lb, LbB_1, LbB_2, and LbB_3. The latter three components were at about the same level in both stem and root nodules, the single component (Lb) was abundant in stem tissue.

Further studies could unravel the genetic determinants of the differential disposition of leghaemoglobin components in stem and root nodules.

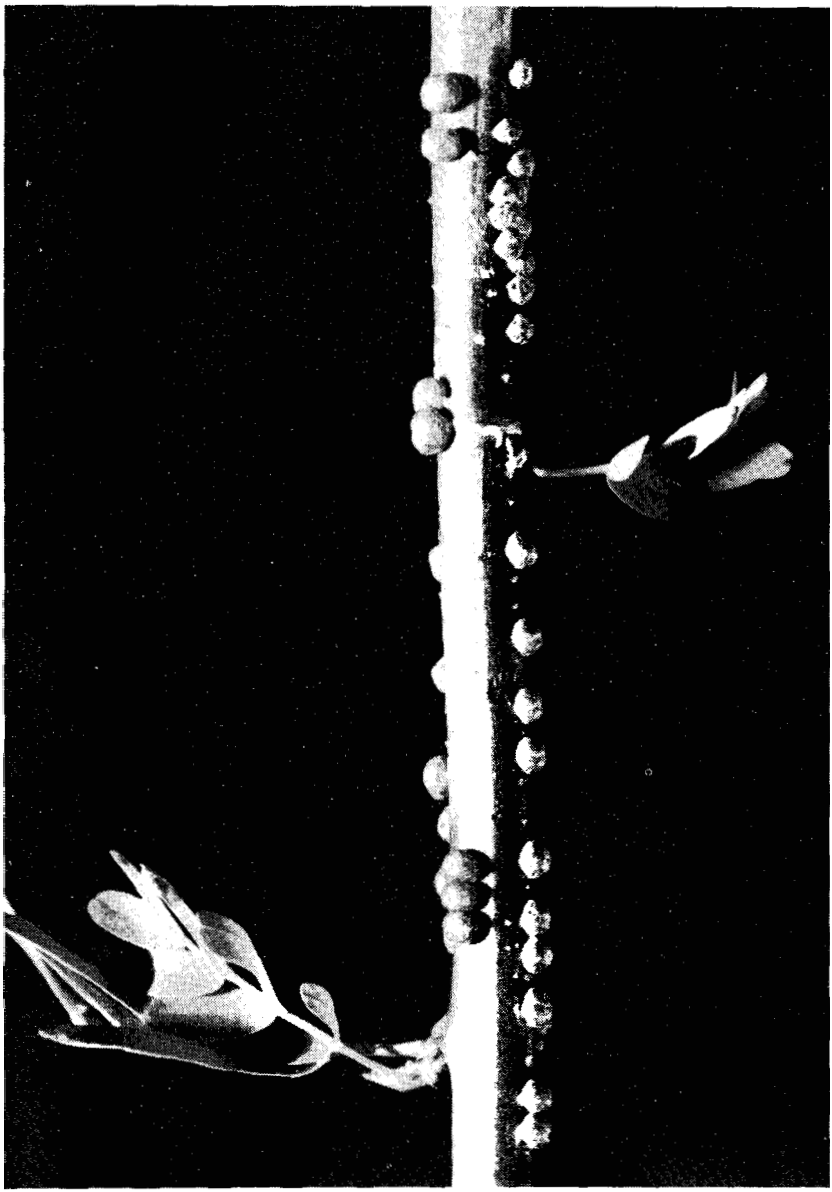
Electrophoretic analysis of total DNA from stem *Rhizobium* BTAil showed the presence of at least one large plasmid of 150-160 kb, 100-107 Md in size, designated as pBTAil. It was not lost at 42 °C, suggesting adaptability of the strain to the elevated temperatures at which *Aeschynomenz* usually grows (Legocki and Szalay 1983). It is not clear whether *nod* and *nif* genes of stem rhizobia are located in this plasmid, in other plasmids, or in the chromosome.

Sesbania

The genus *Sesbania* has about 170 species—annual or perennial herbs and shrubs and small to medium, slender, fast-growing trees widespread in the warmer latitudes of both hemispheres. *S. rostrata,* an annual plant that thrives well in flooded soils of the Sahel region of West Africa during rains has N_2-fixing stem nodules (Dreyfus and Dommergues 1981a,b; Duhoux and Dreyfus 1982; Duhoux and Alazard 1083). Many species have been grown as soil cover or green manure crops able to tolerate soil salinity (Holland 1924, Sandmann 1970, Satyanarayana and Gaur 1965).

Stem nodules of *S. rostrata* arise from predetermined nodulation sites on these stems (Fig. 4). Those sites are small points (Protuberances) arranged vertically, waiting to be infected by *Rhizobium* (Dreyfus et al 1985). The protuberances become epidermal domes and eventually are pierced by root primordia measuring 0.2-0.8 mm. Such root primordia remain inactive on the stem until their base is infected by a specific *Rhizobium* strain. As the plant grows, these preformed locations are produced continuously; thus, nodulation takes place continuously.

Several studies have been done on root nodulation characteristics of *Sesbania* spp. in different countries (Harris et al 1949) (Table 5). Dreyfus et al (1985) describe the nodulation patterns in inundated and noninundated soils. In addition to stem nodules, plants 15-30 d old display 2 types of root nodules. A cluster of large, elongated nodules appear, each with an apical meristem at the crown level and at the base of the main (tap) root. These 0.2- to 1.5-cm-long nodules are lobed (2-3 lobes). Harris et al also observed small spherical nodules on lateral roots that looked like a string of spherical (1-2 mm diameter beads). The large crown nodules disappear rapidly when the plant grows in inundated soil; the nodules on lateral roots survive, float, and develop a green cortex. The root nodules weigh 2-4g, stem nodules weigh 15-40 g.



4. Stem nodules on *Sesbania rostrata* (life size) (photo supplied by Dr. A. R. J. Eagleaham, Boyce Thompson Institute for Plant Research, Cornell University, Ithaca, N.Y., USA).

Stem nodulation is profuse and takes place on both the main stem and the branches. Dust, insects, and other vectors carry rhizobia and inoculate them to predetermined sites. The nodules vary in shape from spherical to irregular, with a central red zone surrounded by green cortex.

Table 5. Root nodulation studies of *Sesbania* nodulated by *Rhizobium* sp. (cowpea).

Country	Species	Authors
Australia	*S. bispinosa*	Bowen (1956), Beadle (1964)
South Africa	*S. bispinosa*	Grobbelaar et al (1967)
	S. sesban	
	S. macrantha	
	S. cinerascens	Grobbeiaar et al (1964)
	S. coerulescens	Grobbelaar and Clarke (1972, 1975)
	S. transvaalensis	
	S. mossambicensis	Mostert (1955)
India	*S. cannabina*	Mann (1906)
	S. speciosa	Raju (1936)
		Rangaswami and Oblisami (1962)
USA	*S. drummondii*	Wilson (1939)
	S. cavanillessi	Alien and Alien (1981)
	S. grandiflora, S. longifolia	
	S. macrantha, S. exaltata	
	S. macrocarpa, S. roxburgii	
	S. sesban	
	S. tomentosa	Johnson and Allen (1952a, b)
Zimbabwe	*S. bispinosa*	Corby (1974)
	S. brevipeduncula	
	S. coerulescens	
	S. greenwayi, S. macrantha	
	S. microphylla, S. mossambicensis	
	S. rogersii, S. rostrata	
	S. sesban	
Taiwan	*S. microphylla*	Allen and Allen (1981)
West India	*S. sericea*	DeSouza (1966) quoted by Alien and Allen (1981)
Pakistan	*S. sesban*	Allen and Allen (1981)
Mexico	*S. sonorae*	Allen and Allen (1981)
Philippines	*S. speciosa*	Allen and Allen (1981)
		Banados and Fernandez (1954)
Senegal	*S. rostrata*	Dreyfus et al (1985)

Dreyfus et al (1985) describe the *modus operandi* of infection in detail. Rhizobia1 cells reach the root primordia through the fissure encircling the primordia. The bacteria penetrate the intercellular space and multiply concurrently with the meristematic activity of some of the cells of the primordium by an unknown activating mechanism, resulting in pockets of intercellular infection. Sooner or later, infection threads originate from the pockets of infection. These threads divide and penetrate the meristematic cells, releasing rhizobia 5-6 d after infection. When the rhizobia are enclosed in the peribacteroid membrane, symbiotic N_2 fixation begins concurrently with leghaemoglobin accumulation. This intercellular as well as intracellular infection is unique to *S. rostrata.* Tsien et a1 (1983) also saw the formation of branched intercellular infection threads in developing nodules of *S. rostrata.*

Dreyfus et a1 (1985) describe two types of *Rhizobium* strains: those infecting both root and stem and those infecting the stem alone. The stem strains (type

ORS 571) are fast-growing and can grow with atmospheric N as their sole N source. However, an external supply of nicotinic acid as both vitamin and N was required. This requirement was 10 times higher under N_2-fixing conditions *ex planta* than in the presence of ammonia (Dreyfus et al 1983). *Nif* mutants of this strain have been obtained and N_2 fixation genes of the wild strains have been cloned in a plasmid. When this plasmid was transferred by conjugation to a *nif* mutant, both *ex planta* and *in planta* genetic complementation were observed (Elmerich et al 1982).

The N_2-fixation potential of *S. rostrata* (Dreyfus et al 1985) is much higher than that of soybean. The acetylene reduction value for *S. rostrata* is 600 µmol C_2H_4/h per plant, as opposed to 14-120 µmol/ h per plant for soybean. In N balance studies, the N contribution has been estimated as about 200 kg N_2/ha in 50 d (Rinaudo et al 1982a,b). *S. rostrata* has been observed to be capable of assimilating both soil and atmospheric N, with fixation. Nodulation continues in the presence of high amounts of combined N (Dreyfus et al 1983).

Cultural characteristics of Sesbania rhizobium. Johnson and Johnson (1952a) studied the cultural and physiological reactions of 39 strains of rhizobia from 6 species of the genus *Sesbania* (*S. macrocarpa, S. longifolia, S. grandiflora, S. aculeata, S. sesban, S. tomentosa*), 52 strains of rhizobia from plants contained in 7 of the common cross inoculation groups, 8 strains of *Agrobacterium radiobacter,* and 10 strains of *A. tumefuciens.*

All the *Sesbania* strains were typical rhizobia, as evidenced by their gram-negative short rods (1.0-2.0 µ long) and slightly swollen appearance in the bacteroidal stage. Young cells were uniform; older cells exhibited variation in cell shape, size, and staining properties. Two types of colonies were recognized in growth characteristics: those isolated from nodules of *S. macrocarpa* and *S. longifolia* produced large, moist, raised, mucilaginous colonies; those from *S. grandiflora, S. tomentosa, S. aculeata,* and *S. sesban* were smaller in diameter, more compact, opaque, and less mucilaginous. The first group of strains were culturally similar to the fast-growing rhizobia from clover, peas, and beans; the second group were slow-growing and more like cowpea-type rhizobia. There appears to be a relationship between tolerance of rhizobial strains for crystal violet dye in media and their ability to produce extracellular polysaccharide gum.

Detailed nodulation studies on 39 strains of *Sesbania* rhizobia and 52 strains of 6 well-recognized rhizobia, including the cowpea type, showed that strains of *Sesbania* rhizobia had a marked degree of host specificity and brought about ineffective responses in bean and cowpea plants (Johnson and Johnson 1952b). None of the bean and cowpea strains produced nodules on the *Sesbania* spp.

The infectivity of *Sesbania* rhizobia showed considerable variation. Sixteen of the 39 strains did not produce any positive growth response on *S. grandiflora.* Four strains behaved similarly with *S. exaltata* and *S. sonorae.* It was noteworthy that all the strains isolated from *S. grandiflora* and *S. aculeata* benefited the growth of all five *Sesbania* species. Interestingly, none of the strains of *S. tomentosa* were effective on *S. macrocarpa* and *S. grandiflora,* but were effective on the three other *Sesbania* species. All the Sesbania strains failed to nodulate *Cyanopsis tetragonoloba, Erythrina indica, Crotalaria anagyroides, Indigofera suffruticosa, Canavalia campylocarpa,* and *Phaseolus lathyroides.*

Rangaswami and Oblisami (1962) noticed some reciprocal affinity among cowpea, soybean, and *Sesbania* rhizobia.

It is possible to conclude that *Sesbania* rhizobia appear to be a special group of cowpea-type rhizobia; they require further serological delineation.

Dhaincha *(Sesbania)* differ in response to inoculation with different strains of rhizobia, as shown by the total number of nodules formed and dry matter yield (Table 6). Experiments at the Microbiology Division, Indian Agricultural Research Institute, New Delhi, show that incorporation of dhaincha residues resulted in the release of maximum available plant nutrients (N, S, and P). Additions of wheat straw resulted in immobilization of P and N: that could be altered only by the addition of N-rich oil cake or chemical N (Gaur 1986). These results suggest that green manure in the form of *Sesbania* releases more available plant nutrients than do cereal straws.

Survival of Rhizobium in flooded soils. Osa-Afiana and Alexander (1979) studied the effect of soil moisture on survival of *Rhizobium* in the laboratory. Both *R. trifolii* and *R. japonicum* had higher survival in a silt loam soil at 10% moisture than at 22, 35, and 45% moisture levels. At higher moisture levels, *R. trifolii* numbers fell rapidly in the initial stages but the decrease slowed with increasing time in incubation. The decline of both *R. trifolii* and *R. japonicum* was greater in nonsterile soil than in sterile soil. In nonsterile soil, adding rhizobia increased the population of native protozoa. Adding sucrose as an energy substrate to flooded soils greatly enhanced the rate of decline in rhizobia1 numbers; this was pronounced in *R. trifolii.* The decline in rhizobial numbers in sugar-amended flooded soil was associated with the accumulation of butyric, acetic, propionic, and formic acids as soil pH fell to 6.0. No such observation was made in flooded soil without sugar amendment. Liming the sugar-amended flooded soil improved *R. trifolii* survival noticeably, with organic acid accumulation. These results suggest a possible role in the decline of *Rhizobium* populations of protozoa at moderate moisture levels and of organic acids at the pH of flooded soils.

Table 6. Effect of *Rhizobium* inoculation on nodulation and yield of *Sesbania* (dhaincha) in a floodplain sandy loam soil. Mymensingh, Bangladesh (M.Z.H. Bhuiya, M. S. Hoque, and M. H. Mian, Bangladesh Agricultural University, Mymensingh).

Treatment	Nodules (no./plant)		Dry matter yield[b] (g/plant)		Dry matter yield (t/ha)
	35 d	65 d[a]	35 d	65 d	40 d
Uninoculated	77.1	44.9	44.95	263.81	1.0
Rhizobium strain					
BAU 952	86.6	50.9	51.86	330.09	1.5
BAU 953	87.2	72.0	54.71	289.19	1.2
BAU 975	83.1	68.3	59.3	295.89	1.3
BAU 979	82.3	69.1	55.03	355.69	1.4
BAU 980	93.2	73.1	61.88	330.79	1.5
± SE	ns	6.6	ns	ns	0.11

[a]Significant at the 5% level. [b]Mean of 10 plants.

Strains of bradyrhizobia that nodulate peanut *Arachis hypogaea* and cowpea *Vigna unguiculata* differ in their ability to survive flooded soil conditions (Boonkerd and Weaver 1982). The numbers did not decline for some strains, even up to 45 d of flooding. For 1 strain, the decline in population was only 10% with incubation at 25 °C and 1% with incubation at 35 °C.

Weaver et al (1987) evaluated survival of *R. japonicum* under flooded rice soils. Populations of soybean rhizobia were 1×10^4/g soil after rice followed by soybean. Rice after soybean under flooded conditions did not reduce the number of bradyrhizobia.

Survival of Rhizobium in legume green mutter-amended soils. Rhizobium proliferates in the vicinity of plant roots. It is assumed that legumes stimulate the population of rhizobia more than nonleguminous plants, even though the patterns of organic substances exuded by plant roots do not substantially differ qualitatively. Pena-Cabriales and Alexander (1983) measured the number of rhizobia in organic matter-amended soil in the laboratory and found that the addition of maize leaf residues did not stimulate *R. japonicum* and *R. lupini* but resulted in a decline in numbers of *R. meliloti* and *R. trifolii.* On the other hand, additions of alfalfa residues reduced the numbers of *R. meliloti, R. japonicum,* and *Rhizobium* sp. (cowpea) and increased that of protozoa.

Microbiological decomposition of green manure

Under waterlogged and extremely reduced conditions, organic substances are often formed in response to microbial activity. These substances—aliphatic acids, phenolic acids, ethylene, carbon dioxide, and hydrogen sulfide—may influence rice plant growth and nutrient uptake considerably. When grown in culture solution with 6 mM acetic acid, the plants died within 3 wk (Takijima 1963). Fourteen-day-old rice seedlings grown in solutions containing 10 mM concentrations of acetic, propionic, or butyric acids died. The plants could tolerate 40 mM acetic and butyric acid (Tanaka and Navasero 1967).

The type of injury depends upon the nature of the monobasic aliphatic acid, its concentration, and its molecular weight (which increases, in order, in formic, acetic, propionic, and more butyric acids) (Rao and Mikkeisen 1977, Takijima 1964). Invariably, acetic acid is predominant, followed by propionic and butyric acids. The level of acetic acid was about 10 mmol/ kg soil when legume leaves were used as the organic amendment. Additions of green manure encouraged more butyric acid production than other acids; that has been attributed to the activity of *Clostridium* (Takeda and Furusaka 1975). Many kinds of enterobacteria, *Clostridium,* and sulfate-reducing bacteria can produce acetic acid. probably from pyruvic and lactic acid. Most of these experiments were done in the laboratory.

Wang et al (1967) found that residues of sugarcane leaf and *Crotalaria juncea,* a green manure species, produce volatile fatty acids (mainly acetic), nonvolatile aliphatic acids (mainly tartaric), and phenolic acids.

Because of microbial activity, ethylene, carbon dioxide. and hydrogen sulfide may accumulate in wet soils. In rice, ethylene and carbon dioxide may stimulate

growth (Suge 1971). Hydrogen sulfide damage in flooded rice soils is not clearly understood, but it may retard translocation of carbohydrates, nitrogen, and phosphorus from the basal part of the shoot to the growing organs and may contribute to iron toxicity, because of the production of ferrous sulfides (Yoshida 1981).

Methanol, ethanol, n-propanol, and n-butanol were measured in soils in which sugarcane leaves and residues of *C. junceu* had been incorporated (Wang et a1 1967). When *Crotalaria* and *Gliricidia* were added to the soil, methanol was formed in large amounts, followed by ethanol and butanol. It is likely that these alcohols injure rice.

Knowledge about anaerobic decomposition in lowland rice aquatic environments, especially after green manuring, is scanty and restricted to that from a few laboratory experiments. Microbiological aspects of green manuring need to be studied in a coordinated manner in several rice-growing countries. Such a project will doubtless be difficult–it is relatively more difficult to work with anaerobic microorganisms than with aerobic ones–but worthwhile.

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Notes

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Effect of green manure on soil organic matter content and nitrogen availability

D. R. Bouldin

Many green manure crops furnish a succeeding rice crop with N equivalent of 50 to more than 100 kg fertilizer N/ha. In several experiments, green manure had important effects on soil properties other than ability to supply N. In the long run, those effects may be economically more important than the value of green manure as N source. As a first approximation, green manure contains two fractions: one decomposes during the first rice crop, the other decomposes slowly over several years. With most green manure crops, the first fraction is 50-80% of the total N. Residual effects(N supply to a second crop) are relatively small when green manure is applied only once, but the cumulative effects of several annual applications are expected to be appreciable. This review summarizes current knowledge on the effects of green manure on available N, soil organic matter, and soil productivity and presents a model of organic N availability.

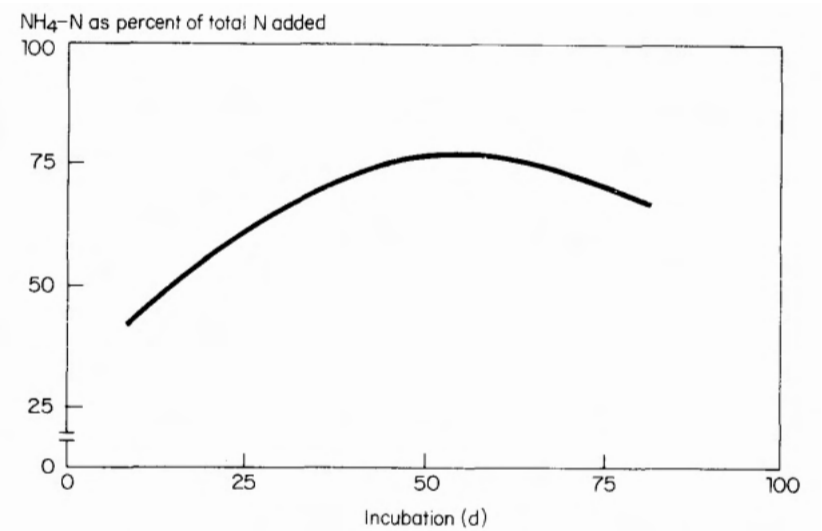
Two conflicting principles are involved in examining the influence of green manure on soil organic matter.

The first principle is that the primary value of green manure is as a source of N to a succeeding crop or crops. This value is realized when the green manure decomposes and its organic N is changed into the inorganic form.

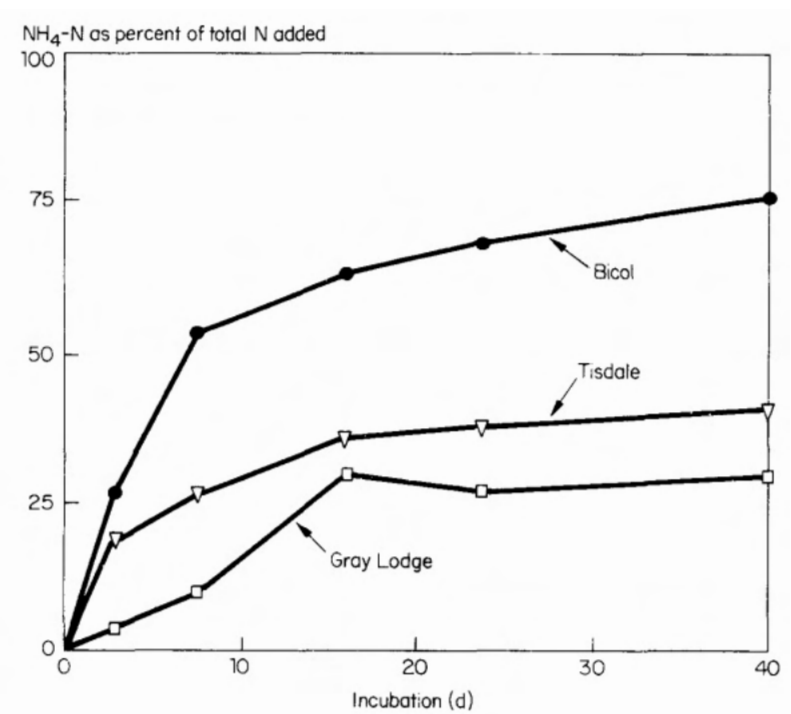
The second principle is that accumulation of organic matter in the soil occurs when the green manure does not decompose. In this case, the organic N is not available to plants.

Thus, if a green manure decomposes rapidly and releases its N quickly, it is an excellent source of N for the first crop following incorporation, but it will have little impact on the organic matter content of the soil and a low residual effect on N supply. However, a green manure that decomposes slowly, releasing little of its N for the first crop, will have a large effect on organic matter content and some residual effects on N supply to future crops.

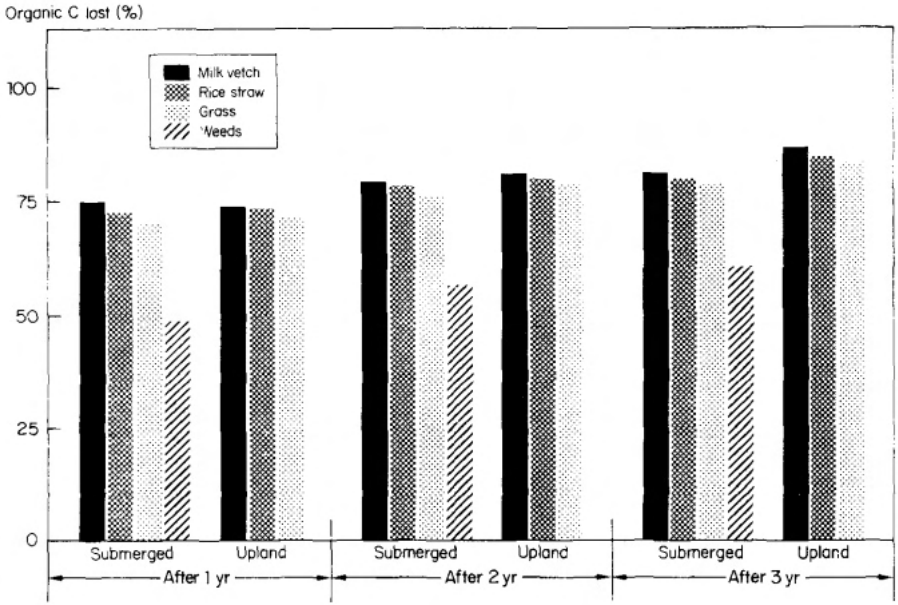
Figures 1 and 2 illustrate accumulation of NH_4-N in soils incubated with sesbania and azolla green manure. An important feature with both crops is that accumulation of NH_4-N is initially rapid, but slows markedly within a fairly short time. This behavior is typical of most organic amendments (Faassen and Smilde 1985).



1. Mineral N content of fallow soil amended with *Sesbania cannabina,* plotted against days of incubation under flooded conditions (Bhardwaj and Dev 1985).



2. Mineral N content of fallow soil plotted against days of incubation for different azolla strains. Points are experimental observations, lines are drawn for reference purposes (recalculated from Ito and Watanabe 1985).



3. Percentage of C lost from 4 organic materials under upland and submerged conditions at 2 sites (Lin et al 1985).

Another generalization is that the fraction of organic material that does not undergo rapid decomposition is resistant to decomposition. Its rate of decomposition is very slow relative to that of the rapidly decomposing fraction. This behavior is illustrated by the decomposition of several materials over 3 yr under both upland and flooded conditions (Fig. 3). The results were almost identical at both sites.

A simple two-component model is used here. The organic material is treated as if there were two distinct components: one decomposes rapidly, the other, slowly. This model was chosen because the data necessary for more comprehensive models were not available. An excellent review of several models of organic matter behavior in upland soils was prepared by Faassen and Smilde (1985). Similar models could be applied to paddy soils, provided the necessary data were available. The two-component model is a first approximation.

The conceptual framework is that organic materials are composed of two fractions; one decomposes rapidly, usually during the first crop following incorporation, the other decomposes slowly, over a long period. The first fraction determines the potential supply of N to the first crop, the second fraction determines the residual effects on N supply and soil organic matter. N in the first fraction will be referred to as fast-N, N in the second fraction as slow-N.

Fast-N

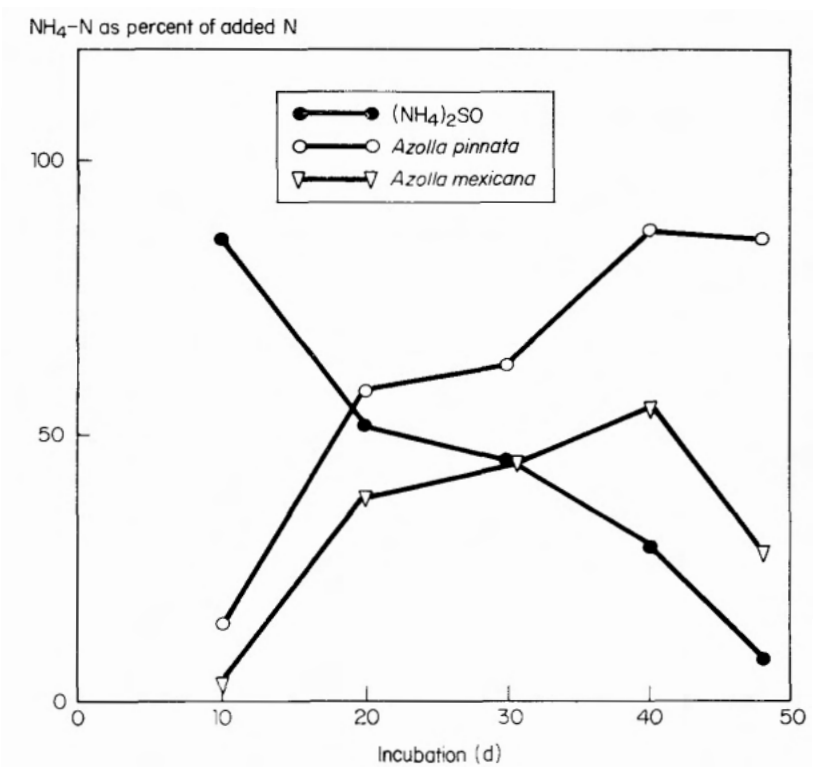
Procedures commonly used to estimate fast-N are a) incubation—this measures accumulation of inorganic N; b) ^{14}C—this measures loss of C from ^{14}C-labeled green

manure crops: and c) ^{15}N—this measures residual ^{15}N or ^{15}N content of green manure crops.

Results with incubation procedures are not always useful in estimating fast-N because the amount of N in the residues added was not reported or the loss of inorganic N was rapid (surmised from losses of NH_4-N from fertilizer treatments or decreases in NH_4-N in the later stages of incubation, when mineralization is less than losses). Figure 4 illustrates the case when N losses from $(NH_4)_2SO_4$ are rapid and NH_4-N declines in the later stages of incubation of the organic sources.

Incubation studies using several sources are reported by Mulongoy (1986), Ito and Watanabe (1989, Bhardwaj and Dev (1989, Saha et a1 (1982), and Nagarajah (1987). In all cases, fast-N as a percentage of total N varied widely, from about 25% to 75%. Substantial N losses are evident in some of the studies; the lower figures may be a consequence of those losses rather than limited mineralization.

In some cases, ^{15}N procedures may underestimate fast-N because some of the mineralized ^{15}N is exchanged with soil N through the action of microorganisms. This effect is documented by Bouldin (1986) with fertilizers and by Westcott and Mikkelsen (1985) for fertilizers and green manure crops. When the amount of ^{15}N



4. Percent of added N as NH_4-N, plotted against days of incubation under flooded conditions (Singh et al 1981)

remaining in the soil is the criterion used, some inorganic N and root residue may be included in the residual N.

Estimation of fast-N with C is not reliable because the amount of N mineralized concurrently with C is not known. Estimates of fast-N based on loss of isotopes during the first crop cycle reported in Table 1 illustrate the wide variability of fast-N as percentage of total N among the different organic materials, soils, and incubation procedures.

Table 2 gives the results of experiments where the organic material was labeled with ^{15}N and the recovery of the tagged organic N was measured by crop uptake. The range is 25-50% recovery of tagged N. Also listed are some associated recoveries of fertilizer N. Usually, recovery of fertilizer N was higher than recovery of green manure N. Not all green manure N is mineralized; there will be some residual N.

Table 1. Estimates of fast-N, based on amount of N or C lost from organic amendments during the rapid decomposition phase.

Reference[a]	Material	Decomposition (%)	Remarks
A	Crotalaria	Soil 1: 54	Residual ^{15}N
		Soil 2: 39	
B	Milk vetch	50	Residual ^{15}N
		17	Residual, 2nd crop
C	Milk vetch	76	Residual C
	Rice straw	74	
	Grass	72	
	Azolla	51	
D	Azolla	26	Residual ^{15}N
	Anabaena	49	
	Nostoc	53	
E	Azolla	44	Residual ^{15}N

[a]A = Huang et al 1981, B = Moand Qian 1983, C = Lin et al 1985, D = Miam and Stewart 1985a. E = Miam and Stewart 1985b.

Table 2. Estimates of fast-N, based on crop recovery of ^{15}N from ^{15}N-enriched organic materials.

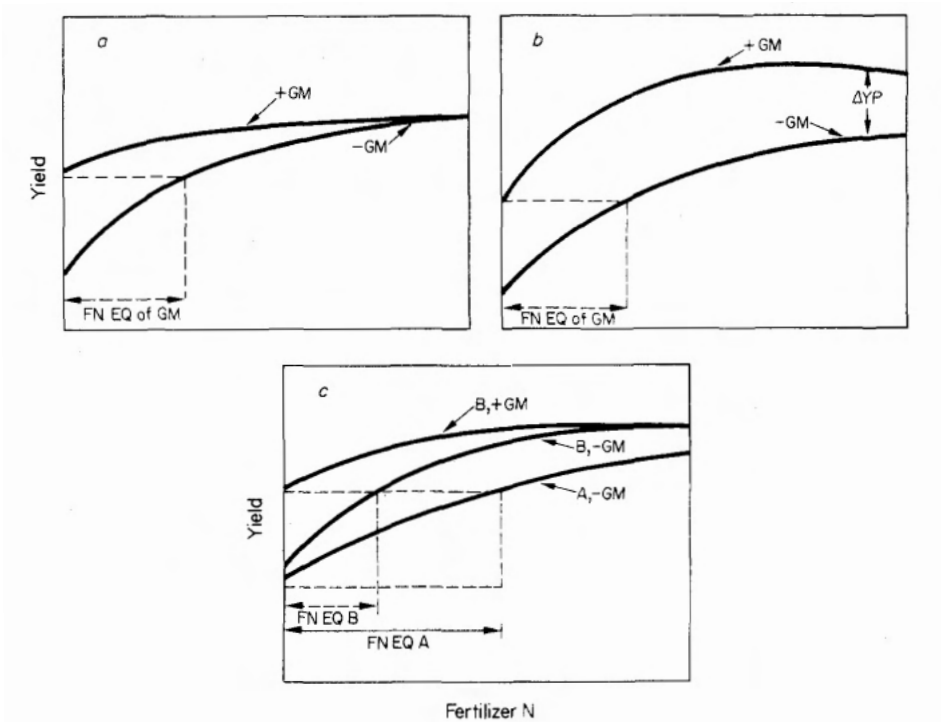
Reference[a]	Source	^{15}N recovery (%)	Remarks
A	Azolla	34	Recovery $(NH_4)_2SO_4$-N = 60%
B	Green manure	25	Average of several experiments
	Pig manure	17	
	Compost	17	
C	Crotalaria	Soil 1: 45	Recovery $(NH_4)_2SO_4$-N = 57%
		Soil 2: 39	Recovery $(NH_4)_2SO_4$-N = 57%
		Soil 3: 38	Recovery $(NH_4)_2SO_4$-N = 60%
		Soil 4: 34	Recovery $(NH_4)_2SO_4$-N = 58%
D	Azolla	52	
E	Milk vetch	30	Recovery urea N = 25%
F	Bluegreen algae	38	

[a]A = Mian and Stewart 1985a, b, B = Lu 1981, C = Huang et al 1981, D = Ito and Watanabe 1985, E = Mo and Qian 1983, F =Wilson eg al 1980.

These results are consistent with the original concept that a substantial fraction of N in green manure mineralizes rapidly (during the first crop). Another result common to all procedures is that variability among green manure crops is quite high. Any preliminary study of green manure should include incubation procedures for determining fast-N as a fraction of total N.

In a number of experiments, green manure and other organic amendments were compared with two or more quantities of fertilizer N, using rice yield as the criterion. In other experiments, green manure crops were grown in rotation with rice and effects compared with two or more quantities of fertilizer N.

Green manure may influence N supply and a wide range of other soil properties. Two possibilities are illustrated in Figure 5. In Figure 5a, the green manure acts as replacement for "X" amount of fertilizer N, to produce a given yield. In Figure 5b, the green manure has had an effect on yield potential that no amount of fertilizer N can overcome. Yield potential is viewed as the yield obtained when N is no longer a yield-limiting factor. A third effect is the influence of green manure in response to the first increments of fertilizer, expressed as kg grain/kg fertilizer N.



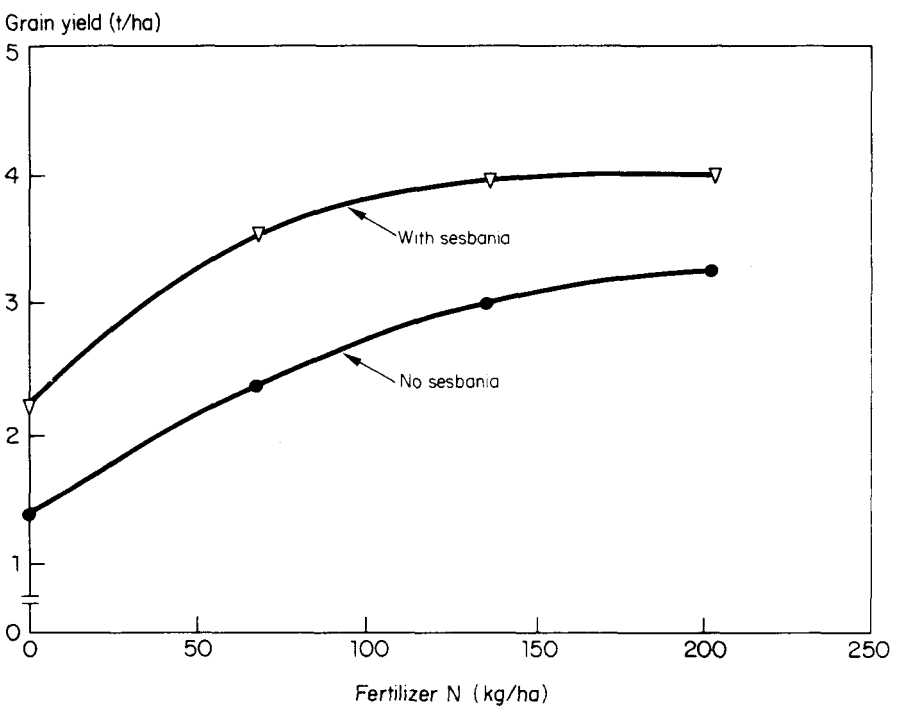
5. Conceptual framework for interpreting field experiments with green manures, FN EQ of GM = fertilizer-N equivalent of green manure, δYP = difference in yield potential. a) Yield potential does not differ; hence, green manure serves only as a replacement for fertilizer N. b) Green manure is replacing some fertilizer N and is also increasing the yield potential. c) The fertilizer N equivalent depends upon the source/method/time of fertilizer application. Fertilizer B is an efficient fertilizer and fertilizer A is inefficient; the FN EQ of the green manure is low when compared to B, but high when compared to A.

Figure 5c illustrates a serious weakness in the concept of fertilizer N equivalent. It is based on a response to fertilizer N that depends on both source of N and the timing and placement of the N source. The fertilizer N equivalent of green manure is shown to be different, depending upon whether the green manure is compared with fertilizer A or fertilizer B.

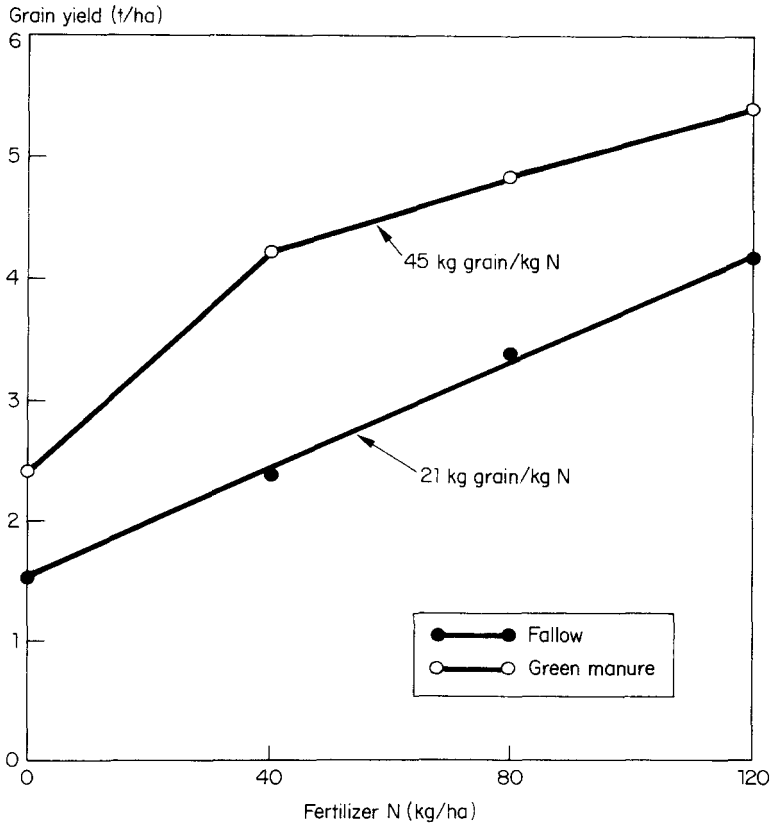
All these considerations have an extremely important impact on economic interpretation.

Figures 6, 7, 8, and 9 illustrate selected experiments where green manure is seen to contribute substantial amounts of N to the crop when yield with green manure but without fertilizer N is compared with yield with fertilizer N but without green manure. The fertilizer N equivalent of green manure is 60 kg/ha in Figure 6, 40 kg/ha in Figure 7, and 60 kg/ ha in Figure 8. In Figure 7, this is roughly 30% of the total N in the green manure; in Figure 8, it is 60% of total N.

Mungbean straw containing 100 kg N/ha was equivalent to more than 120 kg fertilizer N/ha; yield increases were 14 kg grain/kg N for fertilizer and 22 kg grain/kg N for mungbean straw (Meelu and Rekhi 1981). Wild sunflower and azolla also add substantial amounts of available N to the soil supply (Nagarajah and Nizar 1982, Mandal and Bharati 1983). Roger and Watanabe (1986) and Ladha et a1 (1987) have summarized fertilizer N equivalents in other experiments.



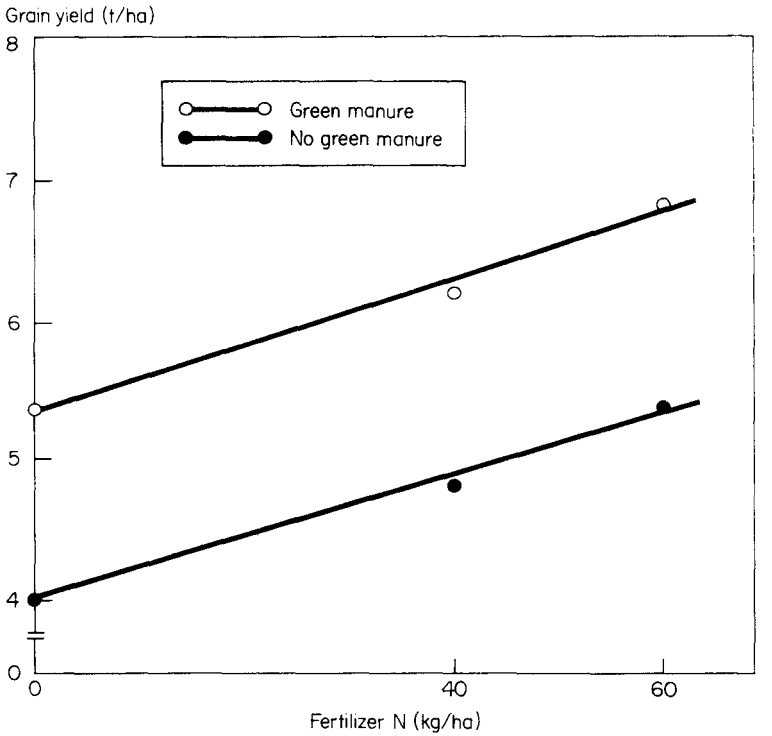
6. Yields of rice in fallow - rice -wheat and green manure - rice -wheat rotations, plotted against fertilizer N added. Points are experimental observations, lines are arbitrarily drawn for reference purposes. Av of 2 yr (Bhatti et al 1985).



7. Yields of rice in fallow - rice - wheat and green manure - rice - wheat rotations, plotted against fertilizer N added. Points are experimental observations, lines are arbitrarily drawn for reference purposes. Av of 2 yr (Tiwari et a1 1980).

However, most of the experiments illustrated that the green manure crops have effects on soil productivity in addition to supplying N. In Figure 6, it is clear that no amount of fertilizer N without green manure will give a yield equal to that obtained with green manure and fertilizer N combined. In fact, yields without green manure are of the order of 3 t/ha; when enough N is added to eliminate N as a yield-limiting factor, yields with green manure are about 4 t/ha. Figure 9 illustrates another aspect of the effects of green manure. The mineral N in fallow plots was also determined periodically. The relationship between the two shows that, in urea-treated plots, rice took up a smaller fraction of mineral N than in the green manure plots. A hypothesis is that urea N created NH_3 toxicity and decreased root density and root activity.

The figures demonstrate that, in some soils, green manure crops are more than just sources of N. They influence soil properties in addition to enhancing the N supply. Because complete N response curves are not available in all cases, judgments cannot be made about whether or not larger amounts of fertilizer N would ultimately give yields that would match those obtained with green manure in the



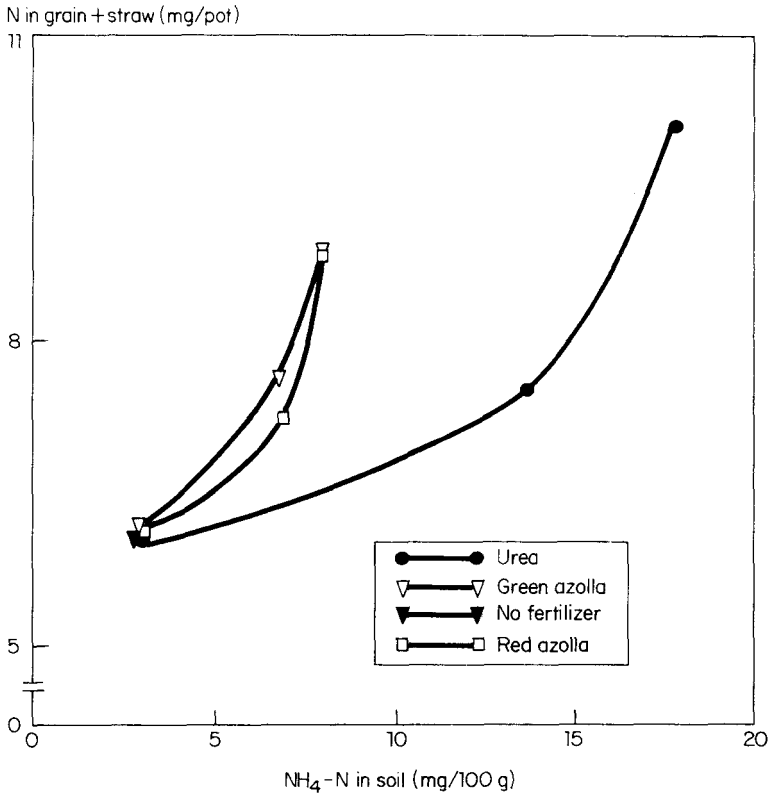
8. Yields of rice in the dry season, plotted against fertilizer N added for rice with and without green manure. Points are average of 2 yr, lines are arbitrarily drawn for reference purposes. The green manure was a mixture of leaves and stems of *Sesbania bispinosa* and *Ipomoea crassicaulis* applied at a rate of 10 t/ha and supplying 200 kg N/ha. Average yield increase was 24 kg grain; kg fertilizer N and 7 kg grain/kg N from green manure (Chatterjee et al 1979).

experiments shown. But the results in Figure 6 show that yield potential with optimum fertilizer N is different in the presence or absence of green manure.

Bin (1983), Houng (1976), Kumazawa (1984), Oh (1979), Tanaka (1978), Venkataraman (1984), and Ishikawa (1987) reviewed the effects of adding composts and other organic materials. They concluded that organic matter had beneficial effects other than as a source of N, but they differed in regard to the size and importance of such effects.

Another useful parameter for evaluating N from green manure is yield increase/ kg N for the approximately linear portion of the response curve. Values were 7 kg grain/ kg organic N in Figure 7, 22 kg grain/ kg organic N in Figure 8. Mungbean and cowpea used as green manure yielded about 23 kg grain/kg N, equaling that from fertilizer N (Morris et a1 1986a,b).

Another important factor is illustrated clearly by Figure 7. Grain yield/ kg fertilizer N was 21 kg without green manure and 45 kg with green manure. The green manure increased grain yield from about 1.5 to 2.5 t/ha. Fertilizer N increased grain yield from 21 to 45 kg grain/ kg N. In Figure 6, there is also a substantial increase in kg grain/ kg fertilizer N for the first increment of fertilizer.



9. N content of grain + straw in rice grown in the greenhouse, plotted against the NH_4-N content of fallow soil incubated for 8 wk. The green azolla contained 4.2% N and the red azolla contained 2.6% N; fertilizer and azolla additions were 30 or 60 kg N/ha. Points are experimental observations, lines are arbitrarily drawn for reference purposes (Islam et al 1984).

Slow-N

Relatively few measurements of the residual effects of green manure on a second crop were reported in the experiments reviewed. Tiwari et a1 (1980) found a green manure crop had larger residual effects than fertilizer N. Mo and Qian (1983) reported a second rice crop's uptake of ^{15}N equivalent to 17% of the residual N remaining after the first crop. Wilson et al (l980) reported uptake of ^{15}N equivalent to 2-3% of the original amount added, of the order of 6-10% of the residual N remaining after the first crop.

These results illustrate that the amount of residual N from one application of green manure is not likely to be large, which is consistent with the two-component model hypothesized initially. However, continued use of green manure could have an important effect over 10 or more years because of the accumulation of organic N (Faassen and Smilde 1985, Bouldin et a1 1984).

The following simple calculations illustrate the importance of the residual effect in the long run. Suppose that 65% of the added N mineralizes during the first crop,

14% mineralizes during the second crop, and 3.3% mineralizes during each succeeding crop. Further suppose that the green manure accumulates 100 kg N/ha. The crop sequence is green manure - crop 1 - crop 2. The effect of the green manure is calculated by assuming it operates in addition to soil organic matter and crop residues.

Based on these conditions, 65 kg N will be mineralized during the first crop. During the second crop, 14% of the residual 35 kg organic N will be mineralized, to yield 5 kg mineral N and a residue of 30 kg undecomposed residual organic N. If this system is continued, 30 kg residual N will be left at the end of each crop year and 10% of the residual N will be mineralized.

The cumulative effects of 30 kg residual N is calculated as follows:

Year	Decomposed during year	Residual at end of year
1	rM	M(l-r)
2	rM(1-r) + rM	M(l-r) + (1-r)M(l-r)
3	$rM(1-r)^2 + rM(1-r) + rM$	$M(l-r)^3 + M(1-r)^2 + M(1-r)$

r = rate of decomposition,
M = residual N left from annual green manure addition.
In general, after n years:

$$\text{Decomposition} = rM[1+(l-r)+(1-r)^2+\ldots+(1-r)^n]$$

$$\text{Residual} = M[(l-r)+(l-r)^2+\ldots(1-r)^n].$$

Using these equations, results were calculated assuming that

- 100 kg green manure/ha is added each year,
- 65% of the green manure decomposes during the first crop,
- 14% of the residual N left after the first crop decomposes during crop 2, and
- 3.3% of the residual N from the second crop decomposes during each successive crop.

The results in Table 3 illustrate that eventually total mineralization during the crop year equals annual input. However, this stabilization requires several years; thus, the full impact of the green manure is not seen for some time. If less than 65% of

Table 3. Mineral N and residual N calculated by year after beginning annual additions of green manure.

Year	Residual at beginning of war (crop 1) (%)	As % of added N	Mineral N from green manure					
			Crop 1			Crop 2		
			Residual	Current	Total	Residual	Current	Total
1	0	-	0	65	65	0	5	5
2	30	30	1	65	66	1	5	6
3	57	28	2	65	67	2	5	7
5	141	24	7	65	72	7	5	12
10	206	21	10	65	75	10	5	15
20	270	13	13	65	78	13	5	18
¥	300	-	15	63	78	15	5	20

the green manure decomposes during the first crop, then the residual effect will be larger but the immediate advantage of green manure will be reduced correspondingly.

Summary

The results demonstrate that green manure crops furnish N sufficient to replace 50 to more than 100 kg fertilizer N to a succeeding nonlegume crop. In some experiments, a green manure crop increased soil productivity and increased the effectiveness of fertilizer N, where effectiveness of fertilizer N is defined as

$$\text{N effect} = \frac{[\text{yield with X amount of fertilizer N}] - [\text{yield with no fertilizer N}]}{X}$$

These effects are extremely important and much more research is needed to identify the cause and effect relationships so that crop situations, where they would be most useful, can be targeted.

The seldom measured residual effect of one green manure crop is small, but the cumulative effects of continued use of green manure are expected to be important, not only on N supply but on soil productivity. Realistic economic analysis must go beyond the evaluation of green manure as a substitute for fertilizer N in 1 yr.

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Notes

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Nitrogen fixation by leguminous green manure and practices for its enhancement in tropical lowland rice

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Several types of leguminous green manure crops have been used as N sources for rice. *Sesbania cannabina (S. aculeata)* and *Crotalaria juncea* are outstanding N_2 fixers and are the most acceptable to Asian farmers. About 2.6 kg N/ha per day can be accumulated by a leguminous green manure crop. Incorporating such a crop at 45-65 d results in rice yields equivalent to those with 50-100 kg fertilizer N/ha. Estimates of the equivalent of more than 200 kg N/ha have been reported in 45- to 60-d-old stem-nodulating *Aeschynomene* and *Sesbania* species and nonstem-nodulating *Sesbania aculeata.* N accumulation and equivalence methods do not differentiate between the contribution of soil and biological N_2 fixation, so that reliable data on the amount of N_2 fixed and made available to the succeeding crop are not available. Information is sparse on the basics of leguminous green manure-*Rhizobium* symbiosis and our knowledge of the rhizobia of leguminous green manure lags far behind that of the grain legumes. Considerable research is needed to improve existing leguminous green manure-*Rhizobium* symbiosis and to expand the range of the crop's germplasm. Basic research is needed before the full potential of leguminous green manure crops can be exploited.

Nitrogen, the most important nutrient in rice production, is added to the crop growth system through biological and chemical means. Despite high production and use of chemical N fertilizers in modern agriculture, soil N and biological N_2 fixation (BNF) remain primary N sources for rice production in a vast area (Bouldin 1986, Herdt and Stangel 1984). For centuries, farmers in the tropics have harvested low but consistent rice yields with little or no chemical N fertilizer inputs because BNF occurs along with rice cropping (Koyama and App 1979, Ladha 1986, Roger and Watanabe 1986). Often farmers also grow and incorporate a N_2-fixing green manure crop before rice (FAO 1977,1978; Singh 1984; Vachhani and Murty 1964). Until the 1960s, several countries used a green manure crop as biofertilizer. During the last two decades, however, leguminous green manure crops have been overlooked because of crop intensification and increased availability of chemical fertilizer (FAO 1978).

Recently, interest in green manure has revived because of fertilizer prices in relation to rice prices, increased concern for maintaining long-term soil productivity, and interest in ecological sustainability. This rising interest has led to the identification of some hitherto unknown legume plants that have green manuring potential for rice (Alazard et al 1987, Rinaudo et al 1982). Attempts are being made to identify shortduration leguminous green manure crops that a farmer can insert into an intensified cropping system (Meelu et al 1985, Morris et al 1986).

Recent developments in legume-*Rhizohium* symbiosis bypass leguminous green manure problems, because research on the agronomy, ecology, and bacteriology of such plants had been phased out in the 1960s. Information on the amounts of N_2 fixed and the N available to a succeeding rice crop is not available. Knowledge on the rhizobia associated with leguminous green manure crops also lags far behind that on rhizobium of grain legume crops; information on ways to enhance their N_2 fixation is meager. This paper reviews the literature on N_2 fixation by leguminous green manure-*Rhizobium* association and explores its potential for lowland rice.

Leguminous green manure crops

An ideal leguminous green manure crop for lowland rice should possess 8 important traits: a) early establishment and high seedling vigor, b) tolerance for flooding and drying, c) early onset of BNF and its efficient sustenance, d) fast growth as well as the ability to accumulate large biomass and N in 5-7 wk, e) photoperiod insensitivity, f) ease of incorporation, g) pest resistance, and h) good yield of highly viable seeds. Many legume species have been studied and tried as green manure in different countries (FAO 1977,1978); however, none of the studies considered all the needed traits.

Vachhani and Murty (1964) extensively surveyed about 100 leguminous green manure crops in India and recommended several suitable for rice culture systems (Table 1). Sunn hemp *Crotalaria juncea* and dhaincha *Sesbania cannabina* (syn: *S. aculeata)* were most acceptable to farmers in India, and were widely grown in other countries in the tropics (FAO 1977,1978; Meelu and Morris 1986; Pandey and Morris 1983; Saono 1977; Staker 1958; Vachhani and Murty 1964). In Japan and China, the most widely used is *Astragalus sinicus* (milk vetch) (Watanabe 1984).

Recently, *Sesbania rostrata* (Rinaudo et al 1983) and species of *Aeschynomene (A. nilotica* and *A. afraspera)* (Alazard et al 1987) that grow wild in the waterlogged soils of Senegal (Africa) were reported to have potential as green manure plants. They produce nodules on both roots and stems and can grow under flooded as well as dry conditions. *S. rostrata,* unlike most other legumes, can grow well in saline and alkaline soils.

Measuring N_2 fixation

An accurate, rapid, and convenient method of estimating the amount of N_2 fixed is critical. Researchers need to identify organisms or plants with N_2 fixation capacity and to study ways to enhance their efficiency. The techniques available for

Table 1. Green manure (GM) crops for different rice ecologies (modified from Vachhani and Murty 1964).

Ecology	GM species
Short-duration rice	*Sesbania aculeata, S. sericea*
Medium- and long-duration rice	*Aeschynomene americana, Phaseolus semierectus,* and *S. speciosa*
Dry season (Nov-Jan) rice	*S. speciosa, S. sericea, Crotalaria usaramaensis,* and *C. brownei*
Sowing in standing rice just before harvest	*S. speciosa* and *Cassia leschenaultiana*
Grown on and along margin of bunds (green leaf manuring)	*Gliricidia maculata* and *S. speciosa*
Dryland	*Crotalaria juncea, Cassia leschenaultiana,* and *Tephrosia purpurea*
Flooded soil	*A. americana, P. semierectus* and all *Sesbania* spp.
Saline soil	*S. sericea* and *S. aculeata*
Low temperature	*Astragalus sinicus*

measuring N_2 fixation by field-grown plants tend to be more qualitative than quantitative. Although the methods used have provided reasonable estimates of N gain, none are entirely satisfactory.

Various methods can be used to measure N_2 fixation.

N accumulation and ^{15}N incorporation

Direct measurements of N_2 fixation are based on N accumulation or on ^{15}N incorporation. The simplest estimate is total N accumulation of a crop. This method assumes that the crop derives all of its N via N_2 fixation—which is only possible if a plant is grown in a medium completely free from combined N. It is not suitable for field studies because most lowland rice soils contain significant amounts of N.

The method using $^{15}N_2$ is a short-term measurement of N_2 reduction. However, the cost of $^{15}N_2$ and the volume required to test several times over a growing season preclude the use of this method in the field.

N balance

The N balance method involves measuring changes in soil N content to develop a N balance sheet covering a period of years. The time required to complete such studies has discouraged its use. The change in soil N content usually does not exceed the sampling and analysis error unless the study spans several years.

N difference

The N difference method is based on the total N difference between a legume and a grass or non-nodulated legume. But the problem is that the plant types generally differ in soil rooting volume and efficiency of N utilization.

Acetylene reduction

Acetylene reduction (AR) assay is based on the phenomenon that the enzyme nitrogenase also reduces C_2H_2 to C_2H_4 (Hardy et a1 1973). It is rapid, inexpensive,

and more sensitive than other methods available. AR assay has been used most widely to measure rates of N_2 fixation at specific time intervals. The calibration of AR against N_2 fixation and the nonlinearity of AR activity are the major drawbacks to using this method to obtain an integrated value for the amount of N fixed over a crop cycle.

Substrate-labeled isotope dilution

The isotope dilution ("A" value) method provides an integrated estimate of the amount of fixed N accumulated by a crop over a growing season. Isotopically labeled N fertilizer is added to plots with legume and nonfixing reference crops. The technique is based on the fact that a N_2-fixing system uses available combined ^{15}N and dilutes it with atmospheric $^{14}N_2$ in proportion to the amount of $^{14}N_2$ fixed (Legg and Sloger 1975).

The major problems with ^{15}N dilution are the assumptions that the enrichment of soil N available to the plant remains constant across time and the legume and reference crop have similar N uptake patterns. In practice, when fertilizer N is added as a single application, the enrichment of plant-available soil N declines across time. This decline varies with the test legume and the reference crop (Witty 1983). The advantages and disadvantages of ^{15}N dilution have also been argued (Chalk 1985, Danso 1986, Phillips et al 1986, Rennie 1986, Vose and Victoria 1986, and Witty 1983). In spite of the arguments, ^{15}N dilution is the only method available that can integrate N_2 fixation over time with a single sampling and permit evaluation of the separate contributions of soil, fertilizer, and atmospheric N_2 to total plant N. That has led to its widespread use.

$d^{15}N$ (natural abundance) dilution

The principle of the $d^{15}N$ (natural abundance) method is the same as for the substrate-labeled ^{15}N dilution method. Soil has higher $d^{15}N$ enrichment than the atmosphere and can serve as a naturally labeled medium. However, the experimental soil must have a reasonably high initial $d^{15}N$ value, so that test values. obtained by dilution will be reasonably precise (Vose and Victoria 1986). The potential problem here is the gradient of $d^{15}N$ within the profile of the active rooting zone, as it has been shown that $d^{15}N$ values tend to increase with soil depth. Watanabe et al (l987) have suggested that the experiment be performed with well-mixed soil in pots. Since no ^{15}N-labeled fertilizer is applied in the $d^{15}N$ method, differences in enrichment of plant-available soil N in test asnd reference plots will be much lower.

There are other constraints to using natural abundance to quantify N_2 fixation. It has been suggested that, at present, the method should be considered semi-quantitative (Rennie and Rennie 1983). Bergersen and Turner (1983) and Ledgard et al (l984) have obtained estimates of N_2 fixation by the natural abundance method very similar to estimates obtained by ^{15}N enrichment. The method was recently reviewed by Shearer and Kohl (1986).

Fertilizer equivalence

The N fertilizer equivalence method has been used most often to estimate the value of a leguminous green manure crop to a following crop. The total N added to the soil

by the legume crop gives to the succeeding crop a yield comparable to a response to levels of added N fertilizer. Although this is not really a measurement of N_2 fixation, it does provide a rough estimate of the savings of N fertilizer by using a green manure crop. The main problem with this method is that chemical N fertilizer is subject to such N losses as ammonia volatilization, denitrification, and leaching.

N solutes analysis

The kind of N compound exported by the nodules has been used to classify legumes into ureide (allantoin and allantoic acid)- and amide (asparagine and glutamine, etc.)-exporting types. In ureides-exporting legumes such as soybean, the concentration of ureides in the shoot is correlated positively with the amount of N_2 fixation (Atkins 1982). This method may have some value in comparing treatments and cultivars but cannot quantify the amount of N fixed by a crop. This aspect has yet to be studied in leguminous green manure plants.

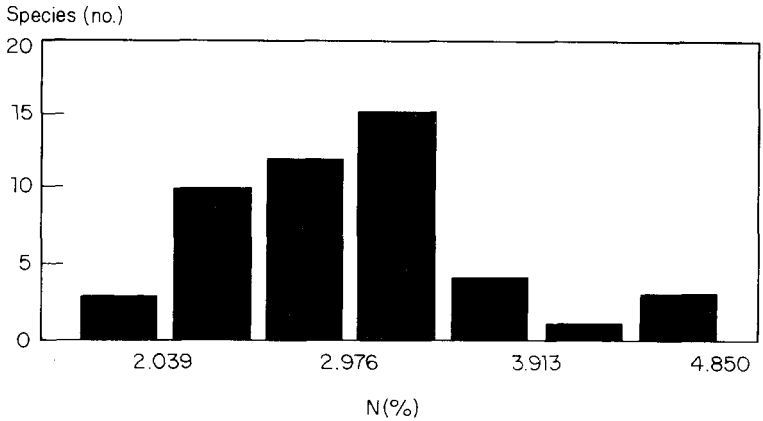
It is obvious that the availability of a reliable and simple method for field measurement of N_2 fixation is a great constraint to research. The isotope dilution of natural ^{15}N abundance or of ^{15}N enrichment is the only method that can give an accurate integrated value for N_2 fixation across time. The natural abundance method has certain advantages over the ^{15}N enrichment method (N fertilizer application is not needed and $\delta^{15}N$ enrichment of soil N available to the plant is more constant). However, widespread use of the $\delta^{15}N$ method will be restricted because of the high price of the mass spectrometer involved.

Appraisal of N_2 fixation

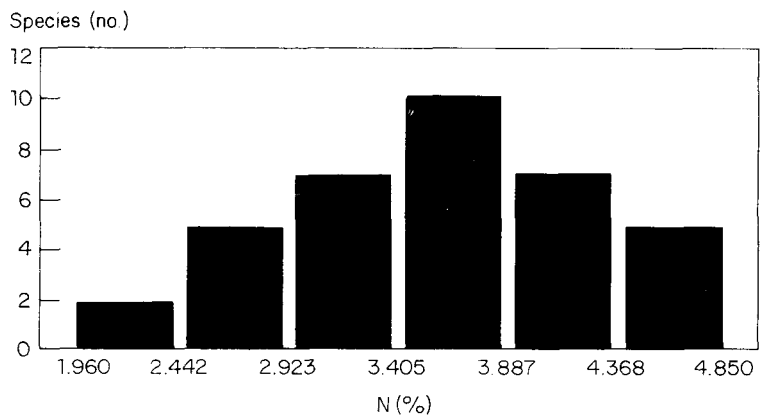
No precise quantified data are available on the amount of N_2 fixed by leguminous green manure, except in a recent report by Rinaudo et al(l983). They incorporated a 52-d crop of *S. rostrata* and quantified total N gains in the soil and in a succeeding rice crop. In their microplot experiments, 267 kg N/ha was fixed. In other studies, the N contributed by leguminous green manure crops was estimated from the total N accumulation or fertilizer N equivalence methods. But these methods do not differentiate between the contributions of soil and atmospheric N. One reason for the lack of precise data could be that most of the work was carried out before the 1960s when ^{15}N techniques were not readily available. During the last two decades, little research has been done. With the recent increase in interest, precise estimates of N_2 fixation are expected to become available.

Leguminous green manure species differ widely in N concentration and N yield. Because different authors measured N accumulation under diverse cultural, climatic, and edaphic conditions and for different durations, a valid comparison cannot be made (Table 2). In a study of 15 crops in the 1963 wet season at IRRI, N accumulation ranged from 42 to 202 kg/ha in about 75 d (IRRI 1963). The highest estimates were reported for *S. sesban.*

Vachhani and Murty (1964) evaluated 50 species in different seasons at Cuttack (Orissa, India); Ghai et a1 (1985) evaluated 36 species or varieties of *Sesbania* in the wet season at Karnal (Punjab, India). At Cuttack, N content in 56-d-old green



1. Percentage N found in 50 legume green manure species (Vachhani and Murty 1964).



2. Percentage N found in 36 species or varieties of *Sesbania* (Ghai et al 1985).

manure was 2.036 to 4.85% (Fig. 1); at Karnal, N content in 30-d-old *Sesbania* sp. was 1.96 to 4.85% (Fig. 2).

The estimates of N accumulation compiled in Table 2 show a range of 0.4 to 10.8 kg N/ha per day (av 2.6 kg N/ha per day). The highest potential values have been reported for 49-d-old *A. afraspera* (423 kg N/ha) and *A. nilotica* (523 kg N/ha) (Alazard et al 1987), 45-d-old *S. aculeata* (225 kg N/ha) (Meelu et al 1985), and 60-d-old *S. rostrata* (219 kg N/ha) (Morris et al 1987). Assuming that 50-80% of the N accumulated in the legumes originated from BNF (Fried et al 1983), it appears that the crops can provide 1.3-2.1 kg N/ha per day, or 65-105 kg N/ha in 50 d.

Table 3 shows N gains for rice from a preceding leguminous green manure crop in terms of equivalent fertilizer N. Incorporating 1 crop at about 45-65 d provides a yield equivalent to that with 50-100 kg fertilizer N/ha. If a green manure crop is

Table 2. N accumulation by green manure crop.

Country, species	Duration (d)	N accumulation (kg/ha)		Reference
		Total	Per day	
Senegal				
Aeschynomene afraspera [a]	49	423	8.63	Alazard et al 1987
Aeschynomene nilotica [a]	49	532	10.85	
India				
Sesbania aegyptica	57	39	0.68	Ghai et al 1985
S. grandiflora	57	24	0.42	
S. glabra	57	27	0.47	
Sesbania sp.	57	32	0.56	
S. aculeata #17	57	102	1.79	
S. aculeata #15	57	106	1.86	
Thailand				
S. rostrata	55	131	2.38	Crozat and Sangchyo-sawat 1985
Aeschynomene indica	55	41	0.75	
Philippines				
S. aculeata	45	225	5.00	Meelu et ai 1985
Crotalaria juncea	45	169	3.75	
Glycine max	45	115	2.55	
Vigna radiata	45	75	1.66	
Dolichos lablab	45	63	1.40	
Indigofera tinctoria	45	45	1.00	
Cajanus cajan	45	33	0.73	
S. rostrata	56	176	3.14	Furoc et al 1985
S. aculeata	56	144	2.57	
Sesbania 'China type'	56	131	2.33	
Vigna radiata	45	75	1.66	Morris et ai 1986
Vigna unguiculata	45	75	1.66	
S. rostrata	60	219	3.65	Morris et al 1987
S. cannabina #1	60	171	2.85	
S. cannabina #2	60	156	2.60	
S. rostrata	45	79	1.75	Ventura et al 1987

[a] *Experiment* conducted in replicated microplots.

combined with 40-60 kg fertilizer N/ ha, the yield obtained is equivalent to that from 120 kg fertilizer N/ha.

Data on the recovery by a succeeding rice of N fixed by a leguminous green manure crop are meager. Using N balance. Rinaudo et al (1983) reported a low recovery of about 35% in microplot experiments. Ventura et al (1987) found 80% recovery by the rice crop of the total N gained by a 50-d crop of *S. rostrata.*

Enhancing N_2 fixation

Published average and potential or highest estimates for N_2 fixation by leguminous green manure crops, obtained by N accumulation and fertilizer N equivalence

Table 3. Equivalence of GM crops to fertilizer nitrogen.

GM crop	Duration (d)	N fertilizer equivalence	Reference
S. aculeata	67	80	Dargan et al (1975)
S. aculeata + 40 kg N/ha	67	120	
S. aculeata	50	65	Tiwari et al (1980)
S. aculeata + 40 kg N/ha	50	120	
C. juncea	50	75	Bhardwaj et al (1981)
S. cannabina	50	50	
S. aculeata	60	60	Beri and Meelu (1981)
S. aculeata + 60 kg N/ha	60	120	
Vigna radiata + 60 kg N/ha	60	120	Meelu and Rekhi (1981)
S. cannabina	45	100	Bhardwaj and Dev (1985)
S. aculeata	60	60	Furoc et al (1985)
S. rostrata	60	60	
S. aculeata	65	100	Meelu et al (1985)
S. aculeata	65	50	
S. rostrata	55	80	Crozat and Sangchyo-sawat
Aeschynomeneindica	55	80	(1985)
Alysicarpusvaginalis	55	80	
S. rostrata	50	70	Ventura et al (1987)

methods, indicate that the crops' N_2-fixing potential is far from being totally exploited. Since not much basic information on crop-*Rhizobium* symbiosis is available, and not much effort is being expended to enhance N_2 fixation, much remains to be done. Possibilities and approaches to increase symbiotic N_2 fixation are briefly discussed here.

Germplasm collection, selection, and breeding

Although green manuring has a long history, most farmers throughout the tropics have used only a few species of leguminous green manure crops. This is probably because better crops have not been sought even though the need for them has often been felt (Shiping 1983). Unlike cereals, which have been improved significantly by selection and further breeding, no such attempts have been made to improve legumes. Exploration and testing of new legume plants need to be given the highest priority. Selection and breeding for short-duration, fast-growing, and efficient N_2-fixing genotypes with higher N content, photoperiod insensitivity, and tolerance for pests, flooding, and higher levels of combined N should be undertaken. Screening and selecting for these traits would directly or indirectly enhance N_2 fixation. Recent discoveries of fast-growing, stem- and root-nodulating, and flood-tolerant legumes, such as *S. rostrata* and *Aeschynomene* spp., are encouraging (Alazard et al 1987, Rinaudo et al 1983). A large number of species of *Aeschynomene* are known (Kretschmer and Bullock 1980); several produce stem nodules under waterlogged conditions. But only a few attempts have been made to adapt them for rice production. Several leguminous species tolerant of stagnant water in Indonesia have been described: *Calopogonium mucunoides, Codoriocalyx*

gyroides, Desmodium styracifolium, Pueraria phaseoloides, and *Sesbania sericea* (Anonymous 1985). Their potential as green manure for lowland rice production is yet to be determined.

Short-duration and fast-growing leguminous green manure

In present-day intensive agriculture, land and time are major constraints for many farmers in tropical Asia. If farmers insert green manure into their cropping systems. they are most likely to grow them during the 30- to 45-d transition period between the dry and wet seasons (Morris et al 1986). Efforts to identify fast-growing green manure crops that can fix and accumulate N in shorter time should be intensified. The species differ widely in N content (Fig. 1,2); this provides an opportunity to combine that trait with faster, more efficient growth.

Identifying and selecting dual-purpose legumes

It is probable that farmers may not grow legumes for green manure alone. Dual-purpose legume varieties, such as mungbean *Vigna radiata,* cowpea *V. unguiculata,* and lablab *Lablab purpureus,* could be valuable for green pods or dry grain yield and for sufficient residues to incorporate as green manure (Meelu et al 1986). Unlike *S. aculeata* or *S. rostrata,* however, those species often have reduced growth because of occasional waterlogging. The need to identify or develop more adapted germplasm for use in various rice ecologies is urgent.

Many leguminous plants, currently little known and underutilized, recently have been described as having great potential for providing food, fodder, and green manure (NAS 1979). How these would best fit into rice-based cropping systems and provide nutrients must be determined.

Sensitivity to photoperiod and pests

Sensitivities of leguminous green manure species to photoperiod and pests also are major constraints and need immediate attention. During a short-day season, vegetative growth is retarded by early flowering. As a result, biomass and N yield are poor. Germplasm collection and screening may provide genotypes with the traits of less or no photoperiod sensitivity and pest resistance.

Stem-nodulating plants with tolerance for flooding and combined N

N_2-fixing nodules on legume plants generally form on the roots. A few legume species also produce nodules on the stem, at predetermined locations identified as incipient root sites (Table 4). The sites are either an epidermal (as in *S. rostrata*) or

Table 4. Stem-nodulating legumes.

Genus	Species
Sesbania	*rostrata* and *punctata*
Neptunia	*oleracea*
Aeschynomene	*afraspera, denticulata, elaphroxylon, evenia, filosa, indica, paniculata, pfundii, pratensis, rudis, schimperi, scabra,* and *sensitiva, nilotica, crassicaulis, tambacoundensis, aspera*

subepidermal (as in *A. crassicaulis*) dome pierced by an incipient root. When infected by a specific *Rhizobium* strain, tissue at these sites proliferates into stem nodules (Dreyfus et al 1984).

In root-nodulating legumes, where nodules function in the soil, the competition between an inoculated efficient strain of *Rhizobium* and native strains of rhizobia is a great problem. Nodules are formed most often by inefficient native *Rhizobium* strains. In stem-nodulating plants, nodules are produced on an aerial portion of the plant, where competition with other rhizobia may be low or nonexistent. Stem nodulation can be effectively enhanced by an inoculated *Rhizobium* strain. This was shown when *S. rostrata* plants were sprayed with antibiotic (streptomycin and spectinomycin)-resistant *Rhizobium* strain ORS 571. All the nodules produced were due to the inoculated *Rhizobium* (Ladha et al, unpubl.).

Another significant feature of stem nodulation is its tolerance for high levels of combined N. Applying combined N reduces root nodulation and N_2 fixation. Dreyfus and Dommergues (1980) studied the effect of 3 mM NH_4NO_3 on nodulation and N_2 fixation by hydroponically grown *S. rostrata.* Root nodulation and associated N_2ase activity were significantly reduced by combined N, but nodulation and N_2 fixation by stem nodules increased. Similar results were obtained by Becker et al (1986) in *Aeschynomene afraspera* grown hydroponically. They also studied the effect of different amounts of urea on growth, nodulation, and N_2 fixation by *A. afraspera* grown in pots under field conditions. Fresh weight of root nodules and specific acetylene-reducing activity (SARA) were inhibited at higher N fertilization (100 and 200 kg/ha). Stem SARA was unaffected at 50 and 100 kg N/ ha, but was significantly decreased at 200 kg ha. Nodule fresh weight increased with up to 100 kg N/ ha, then leveled off (Table 5). The threshold level in *A. afraspera* for N fertilizer was deduced to be 200 kg N/ ha for stem nodulation and 100 kg N/ ha for N_2 fixation. The insensitivity of stem nodulation and N_2 fixation to inorganic N fertilizer was explained by nodules not being directly exposed to soil N, and the nodule functioning as an independent organ, getting its supply of carbohydrates from its own photosynthetic cortical tissues. While the first possibility may be true, the possibility that photosynthesis by cortical tissues of nodules can provide enough photosynthates for such a high N_2 fixation may be doubtful. Further research is urgently needed to clarify this.

Table 5. Effect of urea on nodule fresh weight (FW) and specific acetylene-reducing activity (SARA) by *Aeschynomene afraspera* (Becker et al 1986).

N fertilizer (kg N/ha)[a]	Root		Stem	
	Nodule FW (g)	SARA (µmol C_2H_4/h per g FW)	Nodule FW (g)	SARA (µmol C_2H_4/h per g FW)
0	0.55	29	0.91	89
50	0.53	29	1.00	87
100	0.50	20	1.52	86
200	0.38	10	1.47	69

[a] N fertilizer applied in 2 splits: 1/2 before sowing and 1/2 at 30 d after sowing.

Stem nodulation is an adaptive response to waterlogging. But botanical taxonomists not interested in N_2 fixation have rarely described this character, probably believing that the structures are insect galls (Gibson et al 1982). Nevertheless, stem nodulation was reported before the 1950s (Dreyfus et al 1984). Further development of legumes for their ability to produce stem nodules to tolerate flooding and combined N, and to adapt to lowland rice production would improve N economy of rice.

Collection and characterization of *Rhizobium* germplasm

Research on rhizobia of tropical leguminous green manure plants lags far behind that on grain legumes. Interest in studying *Rhizobium* of new crops has arisen only recently, probably because of their unique stem-nodulating ability.

Taxonomy. From limited cultural tests, Johnson and Allen (1952a) concluded that rhizobia of most *Sesbania* species belong to the fast-growing group. From a cross inoculation study. they concluded that the *Sesbania* rhizobia bear a close relationship to rhizobia of cowpea *Vigna sinensis* and bean *Phaseolus trilobus* and *Dolichos biflorus* (Johnson and Allen 1952h).

Rhizobia of stem-nodulating species range from fast-growing (generation time 3-4 h, ex.: *S. rostrata, A. indica*) to slow-growing (generation time 10 h, ex.: *A. elaphroxylon, A. crassicaulis)* types (Dreyfus et al 1984). A fast-growing *Rhizobium* of *A. indica* has been found to have biochemical characteristics of both fast- and slow-growing groups (Stowers and Eaglesham 1983). Eaglesham and Szalay (1983) and Alazard (1985) studied cross inoculations in several species of *Aeschynomene.* Alazard classified them into three groups. Group 1 comprises strains from *A. americana, A. crassicaulis, A. elaphroxylon, A. falcata, A. fluminensis, A. histrix, A. pfundii,* and *A. villosa,* and strains from *Arachis hypogaea, Stylosanthes guianensis,* and *Macroptilium atropurpureum.* Group 2 comprises strains from only two species, *A. afraspera* and *A. nilotica.* Group 3 has strains from *A. ciliata, A. denticulata, A. evenia, A. indica, A. prarensis, A. rudis, A. scabra, A. sensitiva,* and *A. tambucoundensis.*

None of the rhizobia from the *Aeschynomene* species tested cross-inoculated with strains from *S. rostrata,* or vice versa. All species in groups 2 and 3 are stem-nodulating; in group 1, only *A. elaphroxylon* bears stem nodules.

Rhizobia of stem-nodulating plants isolated from root or stem nodules could produce nodules in both stem and root (Dreyfus et al 1984, Eaglesham and Szalay 1983, Olsson and Rolfe 1985, SubbaRao et al 1980, Yatazawa and Yoshida 1979). However, root nodule-specific rhizobia of *S. rostrata* have been reported (Dreyfus et al 1984, Ladha et al, unpubl.).

Rhizobia symbiotically associated with the roots of leguminous plants recently were divided into two genera: fast-growing *Rhizobium* (which includes three species: *leguminosarum, melilotii,* and *loti*), and slow-growing *Bradyrhizobium* (which has only *japonicum* species) (Jordan 1984). In this classification, the former species *R. trifolii, R. phaseoli,* and *R. leguminosarum* are combined into one species. *R. leguminosarum; R. melilotii* remains unchanged. More recently, another species (*R. fredii*) of fast-growing rhizobia, which nodulates soybean, has been created (Scholla and Elkan 1984).

On the basis of DNA-rRNA hydridization studies, Jarvis et al (1986) found three genetically distinct groups in the genus *Rhizobium.* Group I comprises *R. melilotii, R. fredii.* and *R. leguminosarum.* Group II is represented by *R. loti.* Group III comprises rhizobia isolated from *Galega* sp. The genus *Bradyrhizobium* was found to contain rRNA cistrons, which have diverged from those of the phototrophic bacterium *Rhodopseudomonas palustris.* Jarvis et al (1986) suggested that phylogenetic classification should put these genera together.

Interestingly, Jarvis et al (l986) also reported that the stem-nodulating strain ORS 571 from *S. rostrata* belongs to *Rhodopseudomonas palustris* rRNA branch, quite distinct from *B. japonicum* and *Rhodopseudomonas palustris* On the other hand, *Rhizobium* strains that nodulate roots of *S. rostrata* belong to the fast-growing rhizobia group. Chakrabarti et al (1986) studied nutrition and carbohydrate utilization patterns and DNA homologies of rhizobia of *A. aspera* and of other known species. They concluded that the rhizobia of *A. aspera* cannot be categorized under any known species.

Such results seem to suggest that rhizobia strains of stem-nodulating plants belong to a highly complex and heterogeneous group. Further investigations on more rhizobia1 strains of stem and nonstem-nodulating plants are needed to determine their exact taxonomic positions.

Nitrogen fixation. Several reports now show N_2 fixation by rhizobia under free-living or host-free condition (Gibson et al 1977). This is possible only when a wide range of nutritional factors and a source of combined N are supplied. Most of the fixed N_2 was not actually assimilated by the rhizobia (O'Gara and Shanmugam 1976). It was exciting when Dreyfus et al (1983) reported very high N_2 fixation and nitrogenase activity by *Rhizobium* strain ORS 571 from stem nodules of *S. rostrata* under completely N_2-free conditions. Later Gebhardt et al (1984) quantified the nitrogenase activity of 2 µmol C_2H_4/mg dry weight per h under an optimum O_2 tension (9 µmol). Dreyfus and Rinaudo (1985) reported nitrogenase activity of about 600 µmol C_2H_4/h per plant by *S. rostrata* grown in the field. Nitrogenase activities by *S. rostrata-Rhizobium* under free-living and symbiotic conditions are the highest ever reported for any legume-*Rhizobium* symbiosis.

Another characteristic feature of free-living N_2 fixation by stem-nodulating Rhizobium is high tolerance for O_2 (up to 9 µmol) (Gebhardt et al 1984). This is understandable, because the stem nodules also function photosynthetically. The exact mechanism for an apparent greater respiratory efficiency of N_2 fixation is not known. Substantially higher amounts of Lbå, one of the two components (Lbå and Lbß) of leghaemoglobin, were found in stem nodules than in root nodules (Legocki et al 1983). Whether the increased level of Lbå in stem nodules is due to elevated amounts of O_2 in the photosynthetic tissue is not clearly known.

Selection and inoculation of *Rhizobium*

Selection. Isolation and characterization of rhizobia of leguminous green manure crops was neglected until recently. This could be why information on rhizobia selection and inoculation to crops is not found.

Strains to be used for inoculation should be preselected to ensure that they are capable of forming fully effective N_2-fixing nodules on the target legume species

(Halliday 1984). Rhizobia also should be selected for their ability to be cultured in bulk and to develop high populations in the carrier material, to survive distribution and application, and to multiply in the soil. Other characteristics that should be examined are tolerance for stresses such as drying, flooding, salinity, soil acidity, and alkalinity. Halliday (1984) described a multistage screening approach for selecting rhizobia to use as legume inoculants. The stages involve 1) large-scale screening for ability to nodulate under semisterile and controlled environments, 2) screening infective strains from stage 1 for potential N_2 fixation effectiveness under more realistic growth conditions (sand jar assemblies) in the greenhouse, 3) screening several potentially effective strains for effectiveness under physical and biological stresses of soils, 4) evaluating selected strains from stage 3 with inoculation methodology for nodulation and N_2 fixation in the field, and 5) testing a promising strain at many sites.

Recently, we isolated about 75 strains of *Rhizobium* from stems and root nodules of *S. rostrata* grown in wetland rice soils. All strains were screened for nodulation in agar tubes. Selected strains and a reference strain (ORS 571) were compared for nodulation, N_2 fixation, and plant dry weight in Leonard jars. Significant differences among strains were found (Table 6). Most strains isolated from root and stem nodules produced both types of nodules; three isolates from root nodules of plants grown in Lalao and Pangil soils produced only root nodules. Plant dry weight was correlated with AR activity, and can be used as a relative measure of N_2 fixation.

Table 6. Isolation and selection of rhizobia strains from root (R) and stem (S) nodules of *S. rostrata* (Leonard jar method) (Ladha et al, unpublished).

Soil	Rhizobium strain no.	Inoculated to root		Inoculated to stem	
		Nodules (no.)	μ mol C_2H_4/g nodule dry wt/h	Nodules (no.)	μ mol C_2H_4/g nodule dry wt/h
Cotabato	R2	32	43	47	71
	S1	23	66	44	30
Lalao	R6	19	65	0	0
	R4	30	39	0	0
Luisiana	R3	25	57	60	66
	S3	26	36	57	43
Maahas	R4	31	64	32	55
	S5	29	44	68	37
Maligaya	R1	18	48	80	54
	S5	25	35	63	55
Tiaong	R2	23	55	42	65
	S4	23	59	40	112
Pangil	R6	26	50	0	0
	R6	4	27	0	0
Senegal	ORS571	32	52	34	97
Standard error of mean		4	8	9	12

Inoculation. The question of whether the inoculation of rhizobia to leguminous green manure crops is really needed can always be raised. Three categories of tropical legumes have recently been recognized: 1) promiscuous-effective (PE) group, where nodulation occurs with a wide array of rhizobia isolated from many legume genera and where the resultant symbiosis is predominantly effective in N_2 fixation; 2) promiscuous-ineffective (PI) group, where nodulation occurs with an array of strains of rhizobia isolated from many legume genera, but where fully effective symbiosis forms with only a few of those strains; 3) specific (S) group, where those strains from the same genus form effective symbiosis. Whether rhizobia of leguminous green manure plants belong to the PE, PI, or S group has not clearly been defined.

In general, inoculation is required when a legume is grown in a particular soil for the first time. It is not known, however, if rhizobia survive in intermittent flooding and drying, a situation common to tropical lowland rice. On the other hand, growing and plowing back a green manure crop may build up the population of *Rhizobium.* In Japan, Tuzimura and Watanabe (1959) reported survival and maintenance of rhizobia of *Astragalus sinicus* (fast-grower) under flooded conditions. They also reported that continuous cropping of *A. sinicus* led to the establishment of a rhizobia population of about 10^5/ g soil.

When no information is available, a simple preliminary trial can signal the need for inoculation. Inoculation should enhance the onset and number (and biomass) of effective nodules and of N_2 fixation. Another way would be to count the population of native rhizobia using the most probable number plant infection method. If the population of native rhizobia is low and ineffective, inoculation should be done.

Several reviews have described preparation of inoculum and methods of inoculation for root-nodulating rhizobia (Date and Roughley 1977, Thompson 1980, Brockwell 1982), and that process will not be discussed here. Methods of inoculating for stem nodulation are briefly discussed.

Inoculation of stem-nodulating plants. Rhizobium of *S. rostrata* has been reported to be specific (Gibson et a1 1982); therefore, inoculation is recommended (Dreyfus et al 1985). In the Philippines, nodulation was usually observed in the field without inoculation in *S. rostrata* introduced from Senegal about 5 yr ago (Saint Macary, pers. comm.). This was surprising, because *S. rostrata* is not a plant native to the Philippines.

We counted the *Rhizobium* population in some Philippine rice soils, using the plant infection method (Ladha and Daroy, unpubl.). Soil samples were collected during the dry season from fields left fallow for 1 or 2 seasons. Rhizobia were less than 50/g dry soil at 5 locations and 137/g dry soil at 1 location, not enough to account for spontaneous nodulation.

Recently we found that many seeds of *S. rostrata* harbor the rhizobia. Rubbing with sandpaper 15-30 min, concentrated sulfuric acid treatment, and soaking in water, a commonly used method to break seed dormancy, did not completely eliminate rhizobia1 cells. It is possible that at *S. rostrata* flowering, some stem nodules senesce and release rhizobia. Because nodules inhabit the part of the stem where flowering and seed formation occur, seed may become contaminated with

aerial-borne rhizobia. This phenomenon of natural seed inoculation could be responsible for spontaneous nodulation (Ladha and Miyan, unpubl.).

Dreyfus et al (1985) reported that, without inoculation, nodulation in *S. rostrata* will be irregular. We also found that spontaneous nodulation was infrequent, and sometimes delayed. Nodules mostly were produced in roots and the lower or submerged portion of the stem. Plants exhibit better nodulation during the wet season than the dry season.

If flooding prevails, *Rhizobium* inoculation to seeds produces nodules in roots and the basal portion of stems. Under nonflooded conditions, only root nodules are formed. Sometimes a pair of stem nodules formed at the first node results from rhizobia carried through the seed coat.

The advantage of stem nodulation is its certain response to spray inoculation of a specific *Rhizobium.* Unlike root nodules, where an inoculated *Rhizobium* has to compete with native rhizobia, stem nodules are probably formed without any or with very low competition.

We studied the effect of stem-spray inoculation of *S. rostrata-Rhizobium* (using gum arabic as a sticking agent, soil, and crushed nodule suspension) on nodulation, N_2 fixation, and plant biomass of *S. rostrata* grown in flooded and nonflooded soils in the greenhouse.

At 30 d after emergence, plants in the gum arabic treatment received gum arabic-*Rhizobium* suspension containing 10^8 plate count cells/ml at the rate of 5 ml/plant. Plants in the soil and nodule suspension treatments received 5 ml/plant of suspensions containing 10^6 or 10^8 MPN (most probable number) rhizobia/ml.

Treated plants differed significantly in nodule number, N_2-fixing activity (ARA), and plant dry weight. *Rhizobium*-inoculated plants grown under non-flooded condition had higher numbers of nodules and ARA than plants grown under flooded condition. Total biomass was higher in plants grown under flooding; this could be because they utilized more soil N than plants grown under the nonflooded condition (which probably utilized more fixed N). Flooding inhibits root nodulation; that also may be a reason for the lower ARA. Stem-spray inoculation with a 30 or 40% suspension of gum arabic produced the highest number of stem nodules, ARA, and plant biomass. Several uninoculated plants also produced delayed and infrequent nodules. Almost all the stem nodules in control plants contained antibiotic-resistant *Rhizobium,* suggesting natural infestation from inoculated plants (Ladha and Miyan, unpubl.). The exact mechanism causing this is not known, but infestation might occur through wind, humidity, or insect activity (Dreyfus and Rinaudo 1985).

Soil amendments

Application of inorganic fertilizers, P, N, and organic matter have been reported to stimulate nodulation and N_2 fixation by legume crops (Gibson et al 1982). P required for efficient N_2 fixation is often a limiting nutrient in tropical lowland soils. In a number of long-term experiments. green manure has responded significantly to fertilizer P, exhibiting increased biomass and N content. Mycorrhizal fungi have been used for green manure legumes in China. The fungi are applied to

the field every 4 or 5 yr (FAO 1977). It is not known whether mycorrhiza can survive in lowland soils with intermittent flooding and drying. A low level of N as a starter dose was found to promote nodulation and N_2 fixation by grain legume crops. In lowland soils, this may not be needed because their natural fertility is higher. The positive effect of organic matter application could be due to increased plant growth and better survival and growth of rhizobia (Gibson et al 1982).

Biotechnological approaches

Although most popular green manure species, such as *S. aculeata,* withstand temporary waterlogging, their nodulation and N_2 fixation may be impaired. Introducing stem-nodulating ability to nonstem-nodulating green manure and to grain legumes may increase their adaptability to different ecological niches of rice.

Conclusion

Symbiotic N_2 fixation by leguminous green manure crops can provide a substantial portion of the N required by rice. Its role in achieving and maintaining ecological sustainability in rice farming systems is expected to increase. Green manure for rice production could be a viable component of integrated nutrient management to maintain higher agronomic yields.

Recent work has shown the possibility of increasing N_2 fixation by the plants. Considerable research into methods for improving existing plant- *Rhizobium* symbiosis and for expanding the range of the plants' germplasm is needed. Accurate estimates of N_2 fixation by selected species and N availability to the succeeding rice crop under different environments also are needed. Short-duration and efficient N_2-fixing genotypes with high N content, photoperiod insensitivity, and tolerance for drying and flooding should be selected and bred. Immediate attention should be given to eliminating photoperiod sensitivity in stem-nodulating and other green manure species. Rhizobia should be collected, selected, and inoculated to promising species. Germplasm collection and selection is a lengthy and expensive undertaking. International institutes should assume that responsibility.

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Notes

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Role of green manure in low-input farming in the humid tropics

J. van der Heide

Field experiments under humid tropical conditions in southeastern Nigeria for several years studied N requirement and utilization of upland cropping systems, with and without legumes and with low-input management on acid, low-activity clay soils. Total N utilization over several cropping systems was assessed. Quantities of N removed from the soil and left behind as crop residues after harvest and residual effects of N fertilizers and legumes included in the cropping systems were determined. Sustained food crop production could be obtained at low rates of fertilizer application. Including a green manure crop such as mucuna in the minor season did not result in better performance of maize than of second season cowpea, but did have a pronounced residual effect on the succeeding maize crop.

Shifting cultivation—still the traditional type of farming in nonirrigated agricultural areas in the humid tropics (Okigbo 1984)—is a stable agricultural system, provided a sufficiently long fallow period can be applied (Greenland 1975). However, reduced availability of land due to rapid population growth has resulted in overexploitation, rapid soil degradation. and declining crop yields, particularly in the humid tropics (Ruthenberg 1980). More effective corrective measures have to be implemented to maintain productivity (Swift 1986).

Loss of soil fertility must be compensated for in prolonged or continuous cropping. However, the fact that most shifting cultivators are subsistence farmers limits the possibilities of using chemical fertilizers on a large scale. Furthermore, fertilizer efficiency is generally low in nonirrigated agriculture in the humid tropics.

A (leguminous) planted fallow plus a more efficient use of crop residues, combined with small quantities of chemical inputs when necessary or possible, appears to be a good alternative for maintaining crop productivity on low-activity clay soils, at least as far as N supply is concerned. An adequate and timely N supply is even more relevant to sustained plant production, as N is readily leached under high rainfall conditions (Pleysier and Juo 1981). Maintaining an adequate level of soil organic matter is essential, and maintaining and increasing biomass production are an integral part of management strategies for sustained yields (Gliessman et al 1982).

Among the various ways to add organic material to the soil, the use of *in situ* mulch and green manure appears to be a practical proposition (Mulongoy and

Akobundu 1985). Using annual or perennial fallow leguminous species has the additional advantage of adding biologically fixed N to the system.

We studied the direct and residual contribution of green manure to food crop production in low-input agriculture in southeastern Nigeria.

Methods

The experiment was conducted at the International Institute of Tropical Agriculture's high rainfall substation at Onne (04° 45' N, 07° 01' E) in southeastern Nigeria, with a pseudobimodal annual rainfall of 2,400 mm/yr. Average monthly temperature ranges from 25 to 27 °C. Solar radiation is generally low, averaging about 4.2 h/d during the rainy season (van der Heide et al 1985). The soils, developed on a plio-Pleistocene sedimentary coastal plain, are classified as Typic Paleudults (USDA 1975) with sandy loam texture, strongly leached and acidic, and a low base saturation (Table 1).

The experimental area had been under bush fallow for more than 12 yr. The dominant species were *Anthonata macrophylla* and *Alchornea cordifolia.* After manual bush-clearing and field preparation according to local farmer practice, an experiment in a split-plot design with four replications was laid out in 1981.

Five N levels (0, 45, 90, 135, and 180 kg N/ ha annually) in the main plots were combined with 4 cropping systems in the subplots:

- CS- 1 = intercropped maize (first season) and cassava (whole year)
- CS-2 = maize (first season) followed by cowpea (second season)
- CS-3 = maize (first season) followed by *Stylosanthes guiunensis* (1982) or *Mucuna pruriens* var. *utilis* (1983 onward)
- CS-4 = intercropped maize (first season) and cassava with tree-type pigeonpea *Cajanus cajan* (whole year)

Table 1. Soil properties of a Typic Paleudult at Onne, Nigeria, after 12 yr of bush fallow.

Property	Depth of				
	0-10 cm	10-20 cm	20-30 cm	60-70 cm	140-150 cm
Mechanical analysis					
Sand (%)	82	76	71	62	62
Silt (%)	8	7	6	4	6
Clay (%)	10	17	23	34	32
Chemical analysis					
pH-H_2O	4.8	4.6	4.6	4.5	4.5
Organic C (%)	1.18	0.77	0.62	0.55	0.37
Total N (%)	0.165	0.088	0.082	0.079	0.062
1n NH_3 acetate exchangeable cations (meq/100 g)					
Ca	1.05	0.30	0.30	0.22	0.22
Mg	0.12	0.03	0.03	0.01	0.0 1
K	0.31	0.04	0.03	0.03	0.03
Na	0.10	0.16	0.18	0.12	0.13
Total acidity	0.84	1.82	2.11	2.20	1.46
EC (meq/100 g)	2.51	2.35	2.65	2.59	1.85
Extractable Bray P (mg/kg)	56.4	16.6	44.6	50.5	21.2

Maize TZPB was planted at 25 × 100 cm spacing, cassava TMS30572 at 100 × 100 cm, and pigeonpea (loca1 cultivar from Sierra Leone) at 100 × 400 cm. *M. utilis* was planted at 0.5 × 25 cm and *S. guianensis* was drilled in rows spaced 50 cm apart. During the 1984 and 1985 growing seasons, plant populations in CS-4 were reduced by 50% to 20,000 for maize, and 5,000 for cassava/ha. In 1986, all plots were planted to maize at 40,000 plants/ ha to assess the residual effect of fertilizer or green manure on maize performance.

Fertilizer N as urea was applied in the first season annually, in 3 equal split doses: at planting (broadcast), 4 wk after sowing (WAS), and 8 WAS (banded). In the 1986 season, no N fertilizer was applied.

Annual basal dressings were applied throughout the experiment. The first season crop received 40 kg P (as single superphosphate), 80 kg K (as muriate of potash), 20 kg Mg as magnesium sulfate, and 2 kg Zn as zinc sulfate at planting. Plant samples were taken periodically for analysis. Total N in plant samples was determined using the micro-Kjeldahl method.

Results

Yield effects, N uptake, and N content of harvest residues

Crop response to fertilizer application, fertilizer efficiency, and N uptake were reported in detail in earlier publications (van der Heide et al 1985,1986). Even in the first year after bush clearing, both monocropped and intercropped maize showed a significant response to fertilizer N application. With continuous cropping, maize yields could be maintained at about 1.5 t/ ha with a fertilizer application of 45 kg N/ha. Cassava showed no response to N the first year, but a moderate response the second year.

Maize as a single crop after cowpea or a cover crop (CS-2 and CS-3) did not show a significant difference in grain yield. Table 2 shows that after the first cropping year after bush clearing, total N uptake by maize on the plots without N application stabilized at a low level. Monocropped maize (CS-2 and CS-3) followed by a second season green manure crop had a higher N uptake than intercropped maize, which

Table 2. N uptake at harvest of maize with and without N application. Onne, Nigeria, 198284.

Cropping system	N uptake (kg/ha)											
	No N						90 kg N/ha					
	Plant			Grain			Plant			Grain		
	1982	1983	1984	1982	1983	1984	1982	1983	1984	1982	1983	1984
CS-1	12.5	10.1	11.5	12.9	6.7	6.2	17.8	22.7	29.0	36.4	22.0	29.8
CS-2	16.4	11.7	14.7	29.5	11.8	8.1	22.3	23.6	20.1	50.1	32.0	29.1
CS-3	13.6	17.1	15.3	23.2	14.6	9.4	25.6	26.2	26.8	57.7	36.6	37.7
CS-4	12.1	11.4	8.6	16.5	8.6	8.8	21.8	22.6	15.1	43.6	23.2	22.3
Combined LSD (0.05) between cropping systems										1982 = 4.3 1983 = 2.8 1984 = 2.3		

can be attributed to the competition for soil N. Including pigeonpea in a mixed crop of maize and cassava did not increase N uptake by maize. If only the maize grain was removed from the field, about 60% of the N extracted was restored to the soil (Table 3).

N uptake by maize in plots receiving 90 kg N/ha per year was significantly higher than in unfertilized plots in all cropping systems. Grain production, particularly in a second season cover crop, benefited most from supplementary N. Although about 40% of the extracted N was returned to the soil with residual maize stems and leaves after harvest, total N returned as plant residue was considerably higher than in the unfertilized plots.

Cassava stores considerable N in its aboveground parts, particularly the stems (Table 4). However, a major part of the N stored in the cassava plant is removed after harvest as most stems are removed to provide cuttings for the next season or to prevent regrowth in the field. On the other hand, substantial quantities of N are returned to the soil through leaf fall during cassava growth.

Table 3. Total N in harvest products and crop residue of cropping systems at various fertilizer N levels.[a] Onne, Nigeria, 1982-83.

Cropping system	Total N (kg/ha)									
	0 kg N/ha		45 kg N/ha		90 kg N/ha		135 kg N/ha		180 kg N/ha	
	R	H	R	H	R	H	R	H	R	H
CS-1, 1982	29.5	154.1	30.1	157.0	31.7	177.4	38.4	182.0	33.3	176.1
CS-1, 1983	20.8	88.6	34.0	141.2	39.2	127.6	39.7	152.4	40.3	157.7
CS-2, 1982	34.4	54.1	31.7	61.3	33.5	72.5	38.9	79.3	43.6	91.5
CS-2, 1983	24.0	32.2	40.5	48.0	36.3	54.3	36.7	60.5	43.8	61.7
CS-3, 1982	164.4	23.2	151.8	43.4	160.1	57.7	150.1	57.0	176.7	62.6
CS-3, 1983	75.1	14.6	75.6	26.0	80.2	36.6	76.4	43.4	93.9	49.1
CS-4, 1982	29.2	143.9	34.9	153.01	38.5	202.8	34.3	217.1	32.2	194.4
CS-4, 1983	22.9	117.1	31.7	107.0	38.9	141.1	39.5	150.3	40.1	178.3

[a]R = aboveground residue at harvest, H = harvested. Data for CS-3, 1983 are tentative, Equivalents for each cropping system follow. CS-1: R = maize stems + leaves, cassava leaves; H = maize grain, cassava tubers + stems. CS-2: R = maize stems + leaves, cowpea stover; H = maize and cowpea grains. CS-3: R = maize stems + leaves, stylosanthes (1982) or mucuna (1983) stover; H = maize grain. CS-4: R = maize stems + leaves, cassava leaves, pigeonpea stover; H = maize grain, cassava tubers + stems.

Table 4. N uptake at harvest of cassava. Onne, Nigeria, 1982-83.

N level (kg/ha)	N uptake (kg/ha)							
	Leaves		Stems		Tubers		Total	
	1982	1983	1982	1983	1982	1983	1982	1983
No N	17.0	10.7	97.9	59.7	43.3	22.2	158.2	92.6
45	12.8	15.6	90.6	98.2	31.2	27.4	134.7	114.2
90	13.9	16.5	102.1	76.9	38.9	28.7	154.9	122.2
135	15.3	14.6	96.6	91.4	44.2	29.9	156.1	135.9
180	9.7	13.4	105.3	94.1	33.4	30.9	148.4	138.4
LSD (0.05)					1982 = 38.7		1983 = 26.8	

Cowpea yields, as well as total N of the crop residues after harvest, were generally low (van der Heide et al 1986).

The N accumulated in harvest products and plant residue was calculated for each cropping system. The inclusion of stylosanthes or mucuna added considerable N to the cropping system, mostly returned to the soil as plant residue. Table 3 shows that at all N levels applied with a green manure as second season crop, more N is returned to the field as crop residue than is removed as harvest product. In the three other cropping systems studied, more N was removed from the plot in harvest products than was returned with crop residue. This may have a direct effect on the buildup and maintenance of soil organic matter, as well as on the N balance of the soil.

Residual effects of cover crops

In 1986, the sixth year of the experiment, a single maize crop was planted, at 40,000 plants/ ha, in all experimental plots to study the residual effects of N fertilizer applications or legumes. Early stage maize performance, indicated by plant height at 5 wk after sowing, illustrates the dramatic impact of an organic matter source in a cropping system (Table 5). Maize plants were tallest after CS-3 (with mucuna as second season crop), followed by maize after CS-4 (with pigeonpea as the intercrop).

Maize yield in 1986 was also strongly affected by the previous cropping systems. Without any N application, maize yields after mucuna were about three times the yields of maize after cowpea (Fig. 1). A single maize crop yielded one and a half times more after a maize/ cassava/ pigeonpea intercrop than after a mixed maize/ cassava crop at double the plant population.

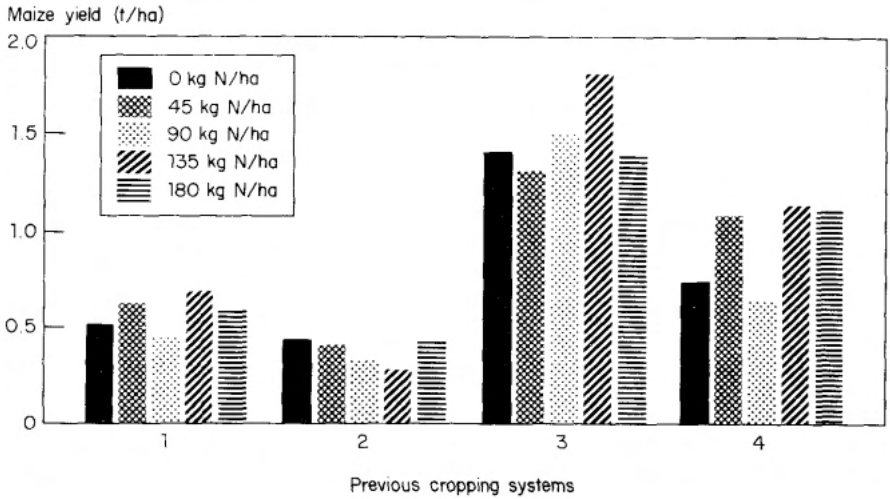
Table 5 and Figure 1 show no appreciable residual effect of applied fertilizer N under the prevailing soil and climatic conditions. However, soil productivity was preserved best in the cropping systems that included a legume in the rotation, particularly if a green manure was a second-season crop.

Discussion and conclusion

Although the data presented were obtained in the first years of a long-term experiment, the results indicate that, from the first year after clearing, considerable

Table 5. influence of cropping history on monocropped maize growth, expressed as plant height at 5 wk after sowing, following different cropping patterns and fertilizer N applications in 1982-85. Onne, Nigeria, 1986.

Annual fertilizer (kg N/ha)	Plant height (cm)				
	CS-1	CS-2	CS-3	CS-4	Mean
0	116	114	151	141	131
45	126	113	150	149	135
90	113	106	141	143	126
135	110	108	151	149	130
180	125	115	159	150	137
Mean	118	111	150	146	



1. Residual effect of previous cropping systems and fertilizer applications (1981-85) on monocropped maize without application of N fertilizer (1986).

differences occur in N use and conservation of intercropped or sequentially cropped systems of nonirrigated agriculture in the humid tropics. In three of the four systems studied, more N was removed by harvest products than was returned after harvest with the crop residue, even at the high N fertilizer levels applied in the experiment. This also occurred if pigeonpea or cowpea were included in the cropping system.

Although a green manure planted after monocropped maize in the second season did not have a significant effect on yield of the following maize crop compared to cowpea, substantially more nitrogen was returned to the plot than was removed by harvest products.

After continuous cropping for 4 yr, the inclusion of a legume in the crop rotation, in particular as a second season cover crop, showed an important residual effect on N supply to monocropped maize. No residual effects were observed from N fertilizer applications. The possible effect of a second-season legume in a cropping system was confounded by the effects of monocropping and intercropping in the experiment discussed here. That is being evaluated in other field trials.

The efficiency of the N which is returned to the plot in crop residue is the focus of further study, in which such key elements as the breakdown of plant residues, supply and demand of N from plant residues, and the influence of crop rooting depth of crops are being studied.

Cassava utilizes substantial amounts of fertilizer N. Removal of stems from the field after harvest removes large quantities of N from the cropping system. After the basic requirement of cuttings has been satisfied, ways should be found to restore the N in the stems to the soil without harmful side effects. Including a green manure in traditional cropping systems appears to be the best alternative to attain sustained crop production in low-input agriculture, as far as the supply of N is concerned. Detailed studies on the relationship between the inclusion of cover crops and the

buildup and maintenance of soil organic matter, and the processes that control the availability of plant nutrients in the low-activity clay soils in the humid tropics are needed.

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Notes

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Transformation of green manure nitrogen in lowland rice soils

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In lowland rice soils, green manure N undergoes transformation into NH_4^+-N and is rapidly partitioned into exchangeable NH_4^+-N and soil solution NH_4^+-N. Increases in exchangeable and soil solution NH_4^--N after green manure application have been used as measures of N released. In laboratory and greenhouse studies, NH_4^+ -N concentration in soils after green manure incorporation increased rapidly, then tended to level off; in a few instances, a decline in NH_4^+-N concentration followed the initial increase, possibly because of losses. When rice plants were grown in the soil, NH_4^+-N concentration peaked, then declined to very low levels due to plant assimilation. Similar patterns of N release from applied azolla and sesbania were obtained recently in experiments on IRRI fields. Green manure N release has been found to be influenced by soil type, submergence period, soil temperature, quantity and quality of green manure crop, applied mineral N, application method, and water management after incorporation. In some soils, substantial amounts of N released from green manure are lost to NH_3 volatilization and denitrification. More information on green manure N release, its availability, and losses under different soil and environmental conditions is needed if green manure crops are to be used efficiently in lowland rice.

Before the advent of modern agriculture technology in countries like China, India, and Japan, green manure was recognized as an important source of N for lowland rice (Bin 1983, Singh 1984, Watanabe 1984). But during the last few decades, the low cost and ready availability of inorganic fertilizers have pushed green manuring into a decline in all rice-growing countries except China. Now, in the face of a continuing energy crisis and higher fertilizer prices, interest in green manure is being renewed.

Green manure, unlike inorganic N fertilizers, must undergo decomposition and mineralization before its N becomes available to the rice plant. Understanding the N transformation processes after incorporation and the factors that govern them is essential in developing management practices that can lead to more efficient use of organic fertilizers in lowland rice.

Green manure use in lowland rice

Green manure refers to "a plant material incorporated with the soil while green or soon after maturity, for improving the soil"(Soi1 Science Society of America 1978). Green manure crops can be grown *in situ* or brought from outside. Applying green matter brought from outside is also called green leaf manuring.

Green manure crops can be leguminous as well as nonleguminous. Crops commonly used in ricefields are the N_2-fixing legumes *Astragalus sinicus* (milk vetch), *Sesbania aculeata* (dhaincha), *Crotalaria juncea* (sunn hemp), and *Aeschynomene americana* (joint vetch). They are suitable for growing *in situ,* with incorporation 4-6 wk after sowing (Patnaik and Rao 1979, Watanabe 1984). The most efficient green leaf manure brought from outside are loppings from *Gliricidia maculata, Crotalaria brownei, C. striata, C. usaramoenis,* and *Cassia leschenaultiana* (Nagarajah and Amarasiri 1977, Patnaik and Rao 1979). Leaves and tender stems of nonleguminous shrubs such as *Tithonia diversifolia* also are used as green manure in ricefields (Nagarajah and Nizar 1982). Azolla, an aquatic N_2-fixing fern, has been used as green manure in northern Vietnam and southern China (Chu 1979, Tuan and Thuyet 1979). *Sesbania rostrata,* a tropical legume that thrives in the waterlogged soils of the Senegal valley in Africa, forms N_2-fixing nodules on both roots and stem. With profuse stem nodulation, it has 5 to 10 times more nodules than most legumes (Dreyfus and Dommergues 1981).

Because of their high N_2-fixing ability in standing water, azolla and *S. rostrata* are considered two of the most promising green manure crops for lowland rice.

Chemical composition of green manure crops

Decomposition of added plant material depends on its chemicalconstituents and the physical and chemical conditions in the surrounding environment (Alexander 1977). The organic constituents in plant materials are commonly divided into six broad categories: cellulose, hemicelluloses, lignin, water-soluble fraction (includes simple sugars, amino acids, and aliphatic acids), ether- and alcohol-soluble constituents (containing fats, oils, waxes, resins, and a number of pigments), and proteins (Alexander 1977). The water-soluble fraction containing the least resistant plant components is the first to be metabolized. Cellulose and hemicelluloses do not decompose as fast as the water-soluble substances, but their persistence usually is not too great. The lignins are the most resistant to decomposition, and consequently become abundant in residual decaying organic matter (Alexander 1977).

Tissue content of these constituents varies with the age of the plant. As the plant matures, the amount of nitrogen, proteins, and water-soluble constituents decreases while that of cellulose, hemicelluloses, and lignin increases. Different parts of a green manure plant also vary in N and lignin content, as well as in C-to-N ratio. Leaves have higher N but lower lignin and C:N than stems or roots (Watanabe 1984; S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1987, unpubl.). The plant materials also contain mineral constituents (Na, K, Ca, Mg, and microelements).

Decomposition and nitrogen transformation

Decomposition of plant materials in a flooded soil is carried out by anaerobic and facultative bacteria. The rate is slower in flooded than in well-drained soils, irrespective of the type of plant material used or its constituents (Tenny and Waksman 1930). The organic N compounds, mainly proteins and their derivatives, undergo anaerobic decomposition to yield simpler forms, such as amino acids. Deamination of the simpler forms results in the release of NH_4^+-N, a stable end product in the reduced layer. The process of the release of inorganic N from organic N is known as nitrogen mineralization. Because this conversion of organic N to inorganic N proceeds only up to the ammonia stage, it is also called ammonification. The reverse process, with inorganic N converted to organic N through consumption by microorganisms, is nitrogen immobilization. These two processes proceed continuously and simultaneously. Depending on their relative dominance, there is a net increase or a net decrease in NH_4^+-N concentration.

The NH_4^+-N released from green manure is adsorbed rapidly onto the cation exchange complex of the soil, with the balance of unadsorbed NH_4^+-N in the soil solution. The two forms of NH_4^+-N are in equilibrium and can be represented by

$$NH_4^+(\text{exchangeable}) \rightleftharpoons NH_4^+(\text{solution})$$

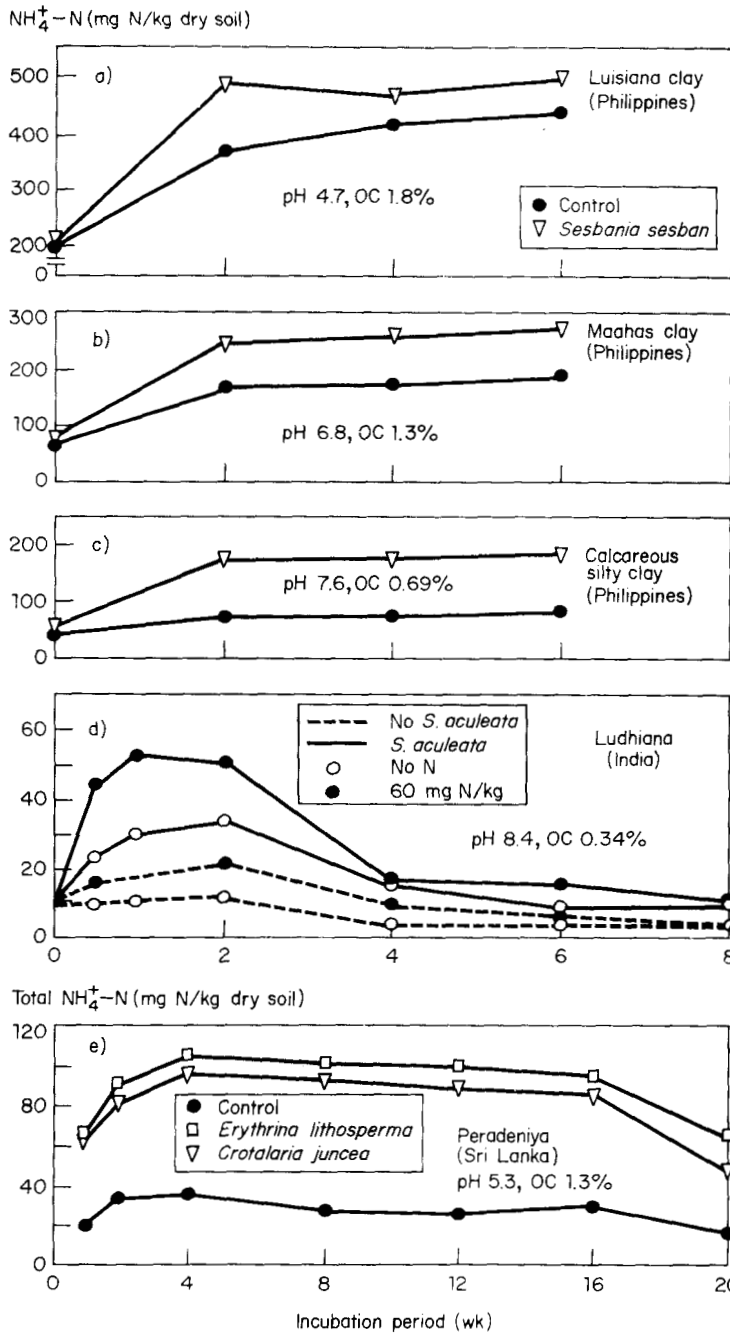
The relative proportions of the two forms are largely governed by the cation exchange capacity (CEC) of the soil and the nature of the cation exchange complex. In flooded soils, the ratio of NH_4^+-N in soil solution to total NH_4^+-N may vary from 3 to 50% (Ponnamperuma 1965; Reddy and Patrick 1986; S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.). Some of the NH_4^+-N may also be transferred from exchangeable into nonexchangeable (fixed) form in soils containing significant amounts of vermiculite and illite (Broadbent 1978, Keerthisinghe et al 1985). Withdrawal of NH_4^+N from soil solution by plant absorption, incorporation into microbial tissue, nitrification, and volatilization loss causes movement of NH_4^+-N from exchange sites into soil solution. Ammonium N released from plant materials may be partly lost to leaching, denitrification, and NH_3 volatilization, similar to losses of applied fertilizer N. But the magnitude of such losses may be lower than that from fertilizer N, especially in the presence of a rice crop, because of the relatively slower rate of N release from plant materials.

Patterns of N release

Laboratory and greenhouse studies

Most studies of green manure N release studies have been conducted under laboratory and greenhouse conditions. These indicate that, in the absence of rice plants, N release increases rapidly and reaches a plateau. In the presence of plants, it peaks, then declines.

In his study of 3 Philippine soils, Aapiras (1966) found that soil NH_4^+-N increased rapidly after the addition of *S. sesban* up to 2 wk of incubation, then

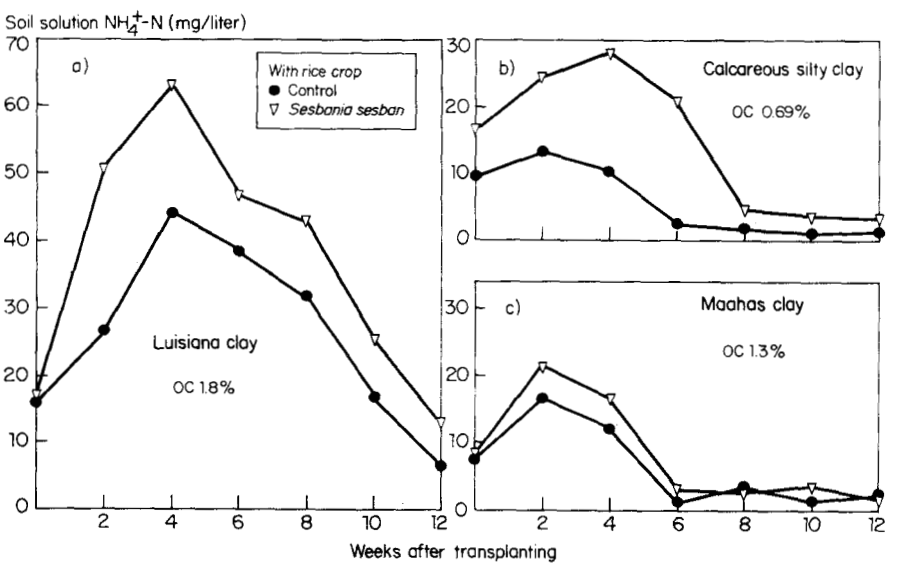


1. Effect of green manure incorporation on NH_4^+-N kinetics in flooded rice soils in the absence of a rice crop. Laboratory experiment. Source: (a), (b) and (c) from Aspiras 1966, (d) from Khind et al 1985, (e) from Joachim and Kandiah 1929. OC = organic carbon.

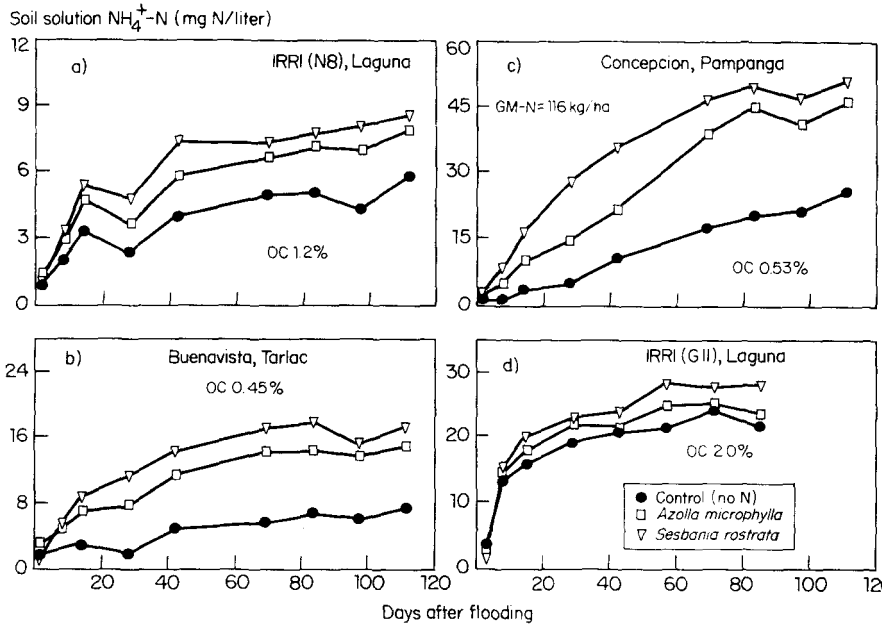
remained nearly constant (Fig. 1a,b,c). With rice plants, the soil solution NH_4^--N kinetics peaked at 2 wk in 1 soil and at 4 wk in 2 others (Fig. 2). After flooding, NH_4^+-N declined to very low levels at 6 wk in Maahas clay, at 8 wk in calcareous silty clay, and at 12 wk in Luisiana clay.

The same N equivalent of *S. rostrata* and *Azolla microphylla* increased soil solution and exchangeable NH_4^+-N in several flooded rice soils of the Philippines (Nagarajah et al 1986; S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.). In the absence of rice plants, soil solution NH_4^+-N showed an initial increase up to 40-80 d after flooding (DF), then leveled off in all but one soil, where it continued to increase slowly (Fig. 3). This was similar to the NH_4^+-N release pattern of flooded soils obtained by Ponnamperuma (1965). Exchangeable NH_4^--N followed a similar pattern, but the plateau started at 40 DF (Fig. 4). In the presence of rice plants, soil solution NH_4^+-N peaked around 15 to 30 DF and was almost exhausted by 55 DF (Fig. 5). The decline was attributed largely to plant uptake.

Only a few studies have shown a decline in NH_4^+-N release in the absence of rice plants. Joachim and Kandiah (1929) found that ammonium N release from *Crotalaria* and *Erythrina lithosperma* applied to a rice soil from Sri Lanka remained nearly constant between4 and 16 wk of incubation, but declined thereafter (Fig. ld). Khind et al (1985) reported a decline in exchangeable NH_4^+-N in soil from India 2 wk after the addition of *S. aculeata,* with and without fertilizer N (Fig. le). The decline could be due to N losses. In India, it was attributed to denitrification loss (C. S. Khind 1987, Punjab Agricultural University, pers. comm.). However, NH_3 volatilization loss cannot be overruled, especially in view of the high soil pH (8.4).



2. Effect of sesbania incorporation on soil solution NH_4^+-N kinetics in 3 flooded Philippine rice soils in the presence of a rice crop. Greenhouse experiment (adapted from Aspiras 1966).



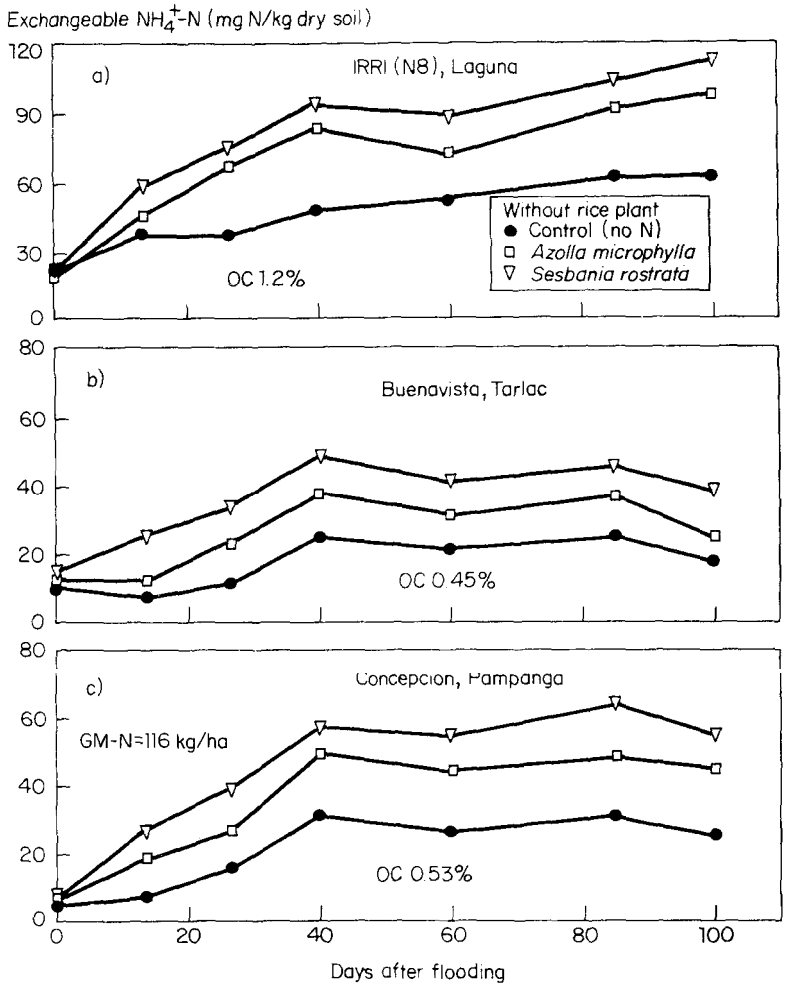
3. Effect of sesbania and azolla incorporation on soil solution NH_4^+-N kinetics in four flooded rice soils in the absence of a rice crop. Greenhouse experiment (S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.) GM-N = green manure nitrogen.

Field studies

Recently the kinetics of NH_4^+-N release from sesbania and azolla grown *in situ* and incorporated was studied in several field experiments (flooded conditions) at IRRI (S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.). A 60-d crop of *Sesbania cannabina* was incorporated in the 1985 wet season. In the absence of a rice crop, exchangeable soil NH_4^+-N increased up to about 20 d after transplanting (DT), then stabilized (Fig. 6). In the presence of a rice crop, NH_4^+-N values peaked at about 20 DT, then gradually declined to very low levels 25 d later. In green manure combined with fertilizer N treatment, trends were similar but NH_4^+-N values were much higher.

In an Oct 1985-Feb 1986 experiment, *S. rostrata* (N equivalent 64 kg/ ha) and *A. microphylla* (N equivalent 96 kg/ ha) were incorporated and exchangeable soil and soil solution NH_4^+-N monitored. Peak exchangeable NH_4^+-N values occurred around 10 DT for sesbania and 20 DT for azolla. Ammonium N was almost completely depleted by about 45 DT for sesbania and 70 DT for azolla (Fig. 7). Soil solution NH_4^+-N followed the same pattern, but peak values occurred at about 20 DT for both green manure crops.

The experiment was repeated during the 1986 wet season, but only exchangeable NH_4^+-N in the presence and absence of a rice crop was determined. Sesbania at N equivalent of 79 kg/ ha and azolla at 89 kg/ ha were added. In the absence of a rice crop, exchangeable NH_4^+-N increased rapidly to 15 DT, then remained nearly

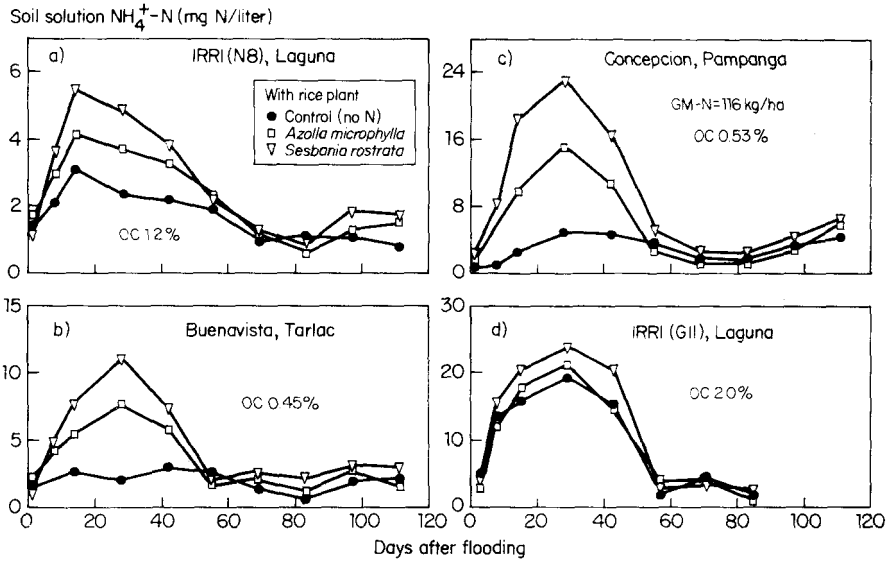


4. Effect of sesbania and azolla incorporation on exchangeable NH_4^+-N in 3 flooded Philippine rice soils in the absence of a rice crop. Greenhouse experiment (S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.)

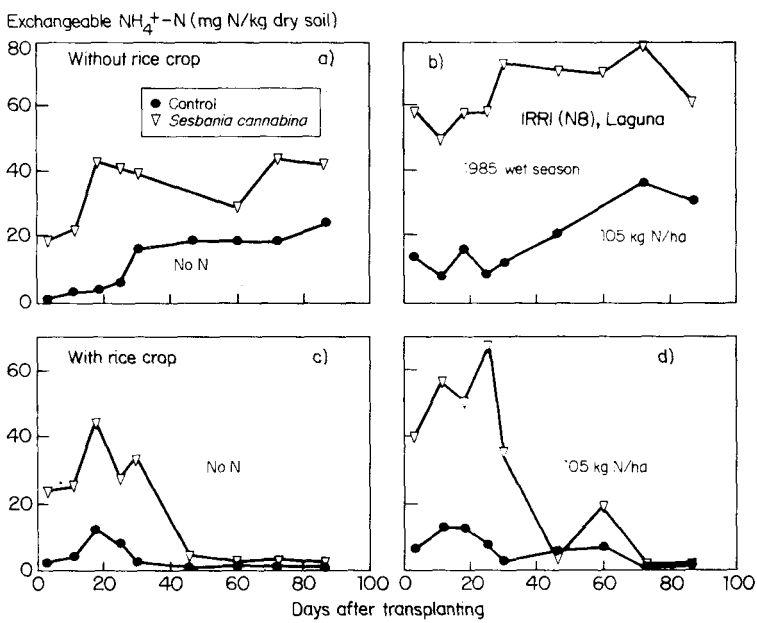
constant for both green manure crops. With a rice crop, exchangeable NH_4^+-N increased to 15 DT, then decreased to a very low level by 40 DT. The low level was maintained even after harvest.

The N release patterns from green manure under field conditions were similar to those obtained in laboratory and greenhouse experiments. The main features follow:

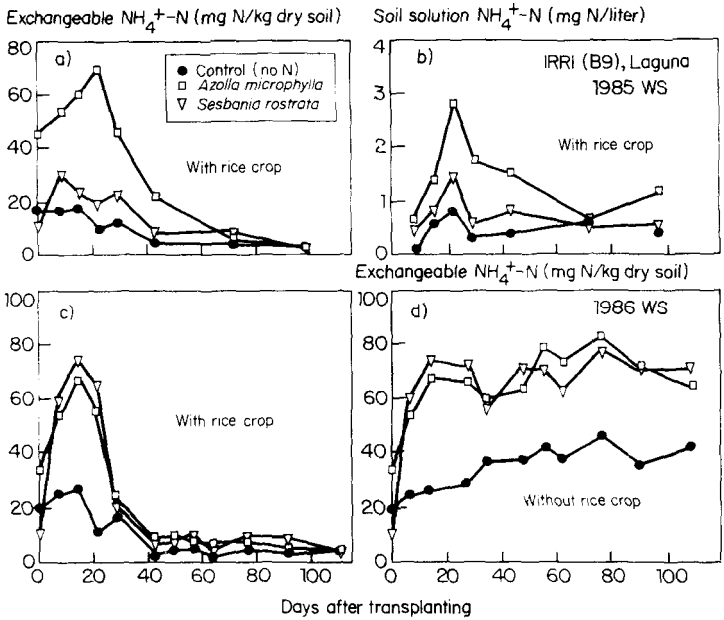
- In the absence of rice plants, NH_4^+-N concentration in soil or soil solution following green manure incorporation reached a plateau after an initial rapid increase. In some soils, a decline occurred after the peak, perhaps because of loss of N released from the green manure.



5. Effect of sesbania and azolla incorporation on soil solution NH_4^+ -N kinetics in four flooded Philippine rice soils in the presence of a rice crop. Greenhouse experiment (S. Sagarajah. H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.)



6. Effect of sesbania incorporation, with 105 kg N/ha or without fertilizer N on exchangeable NH_4^+-N in a flooded Philippine rice soil, 1985 wet season (S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.)



7. Effect of *sesbania* and azolla incorporation on NH_4^+-N kinetics in a flooded Philippine rice soil, 1985 and 1986 wet season (WS) (S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl).

- In the presence of rice plants, NH_4^+-N reached a peak, then declined to low levels at 6-8 wk, largely because of plant uptake.
- Time of occurrence of the maximum or peak NH_4^+-N value varied in the different studies.

It appears that under flooded conditions, N released from green manure generally can be maintained without serious losses. With green manure application, especially at lower rates, N topdressing 6-8 wk after transplanting could be beneficial to the rice crop.

Factors affecting N release

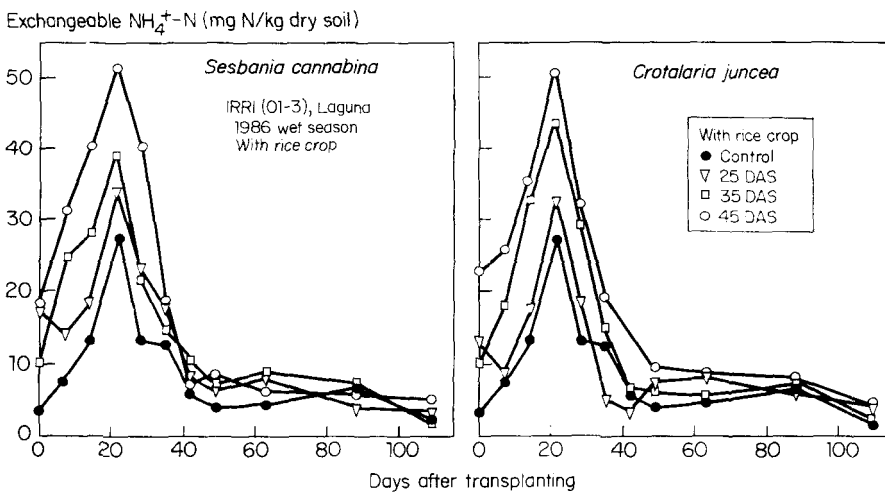
Ammonium N release from green manure has been reported to be influenced by soil type, submergence period, soil temperature, the green manure species (its nature, amount, N content or C:N, and lignin content), applied mineral N, method of application, and water management after incorporation.

The addition of the same rate of green manure N to different soils did not release equal amounts of NH_4^+-N, indicating that N release from green manure depends on the soil type (Aspiras 1966; S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.). N release from green manure also varied with duration of submergence up to a certain time (in some soils, 80 d). Thereafter, it did not vary much.

Aspiras (1966) reported that NH_4^+ -N release from *S. sesban* increased when the temperature increased from 20 to 40 °C. In one soil (Luisiana clay - Philippines), however, it declined at temperatures higher than 30 °C. He also noted an increase in NH_4^+ -N release when the rates of *S. sesban* added were increased. In a recent study (S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1986, unpubl.), *Sesbania cannabina* and *Crotalaria juncea* were incorporated in a lowland ricefield at 25, 35, and 45 d after sowing (DAS). The released NH_4^--N was highest for the 45-d-old plants and lowest for the 35-d-old; however, their release patterns were similar (Fig. 8) because the total N added by a green manure crop (a product of its N content and total biomass) increases with increasing age. It must be noted that as a green manure matures, its C:N, fiber, and lignin contents also increase (Watanabe 1984; S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1987, unpubl.). That adversely affects its decomposition and mineralization.

Ito and Watanabe (1985) compared the N released from several species of fresh azolla. Ammonium N release was rapid during the first week, but slowed after the third week. *Azolla pinnata,* with a high (4.88%) N content, released more NH_4^+-N at a faster rate than *A. mexicana,* which had the lowest (3.46%) N content. NH_4^+-N released from *A. filiculoides* (N 4.54%) was between that released from *A. pinnata* and *A. mexicana.* Maximum N release from several species of azolla added to an alluvial soil from Cuttack (India) were 88% from *A. pinnata* (India), 77% from *A.* pinnata (Vietnam), 79% from *A. filiculoides,* and 55% from *A. mexicana* (Singh et a1 1981). The differences were in spite of the comparable (5%) N content of the different species.

Chemical components other than N also may affect availability of azolla N. In four Philippine rice soils, S. Nagarajah, H. U. Neue, and M. C. R. Alberto (IRRI,

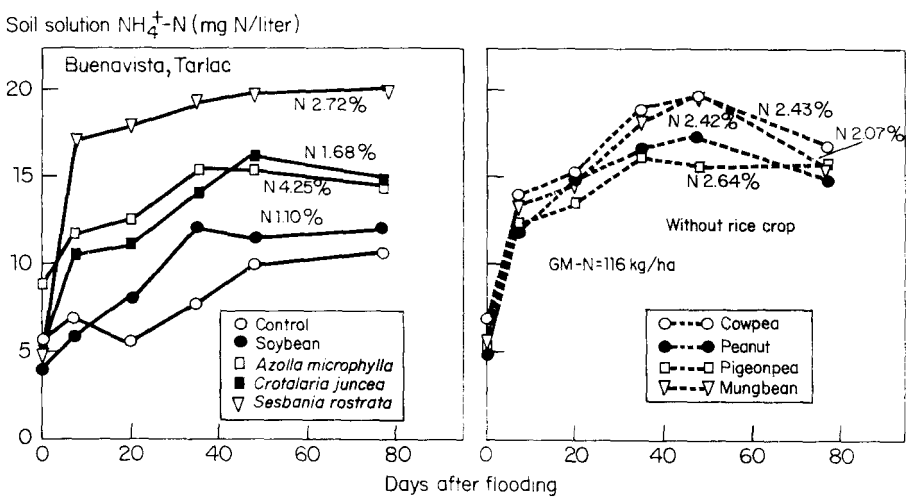


8. Effect of sesbania and crotalaria incorporation at different ages on exchangeable NH_4^+ -N in a flooded Philippine rice soil, 1986 wet season (S. Nagarajah, H. U Neue, and M. C. R Alberto, IRRI, 1986, unpubl.). DAS = days after seeding of green manure crop.

1986, unpubl.) found that at the same N equivalents, NH_4^+-N release from *A. microphylla* was slower and lower than that from *S. rostrata,* despite its lower C:N (Fig. 3, 4, 5). This difference was attributed to the much higher lignin content of *A. microphylla* (20% vs 9%), which is known to retard degradation of organic constituents of plant materials (Alexander 1977). Higher lignin content had been considered the reason for lower N availability in azolla than in milk vetch (Shi et al 1980).

In another study, S. Nagarajah, H. U. Neue, and M. C. R. Alberto (IRRI, 1987, unpubl.) found that N release from several green manure and crop residues, determined by an increase in soil solution NH_4^+-N, was related to the N and lignin content of the green manure crop. Sesbania, cowpea, pigeonpea, mungbean, and peanut with similar N content and C:N released almost similar amounts of NH_4^+-N; the initial rate of N release was fastest in sesbania (Fig. 9). Soybean, which had a very low N content, also had the lowest amount of released N. Azolla released less N than sesbania, cowpea, pigeonpea, mungbean, and peanut despite its much higher N content. This was attributed to its higher lignin content (20% vs 6-13%).

Drying green manure before incorporation seems to reduce the rate and amount of N release. Ito and Watanabe (1985) found that fresh *A. pinnata* released up to 2.5 times more NH_4^+-N than dry azolla. The NH_4^+-N release from fresh azolla reached a plateau after 16 d. In dry azolla, mineralization was rapid up to 4 d of incubation, then leveled off. The initial rapid mineralization was attributed to easily decomposable organic forms of N; the slow mineralization, to less easily decomposable forms. Thus drying is believed to result in a decrease in easily decomposable organic forms of N. According to Joachim (1931), drying green manure converts soluble hemicelluloses into less soluble forms; this retards its



9. Effect of incorporation of different kinds of green manure on soil solution NH_4^+-N kinetics in a flooded Philippine rice soil. Greenhouse experiment (S. Nagarajah, H. U. Neue, and M. C. R. Alberto, IRRI, 1987, unpubl.).

decomposition. To achieve speedy decomposition, he recommended that leafy material be buried green, not dry.

Using ^{15}N-labeled crotalaria, Huang et al (1981) found that adding ammonium sulfate promoted mineralization of crotalaria N; immobilization of fertilizer N was increased by the presence of crotalaria.

In studies using ^{15}N-labeled azolla, azolla N release was highest when azolla was incorporated (Ito and Watanabe 1985). Only a small amount of exchangeable NH_4^+-N originated from azolla grown on water. N release was intermediate when azolla was placed on the soil.

Water management following green manure incorporation is important in utilizing released N. Joachim and Kandiah (1929) monitored total NH_4^+-N and NO_3^--N after incorporating green manure *Tithonia diversifolia* under semidry and flooded conditions. When it was applied under semidry conditions and flooded 6 wk later, NH_4^+-N concentration peaked 2 wk after incorporation, then declined to a very low level that continued even after 12 wk of submergence (Fig. 10). On the other hand, flooding immediately after incorporation resulted in an NH_4^+-N concentration peak at 4 wk after flooding. That level was maintained in the greenhouse experiment but declined slowly under field conditions. Total NO_3^--N determined in the greenhouse experiment for the early application peaked around the puddling stage. After flooding, NO_3^--N declined rapidly, to very low levels by 4 wk, perhaps because of denitrification losses.

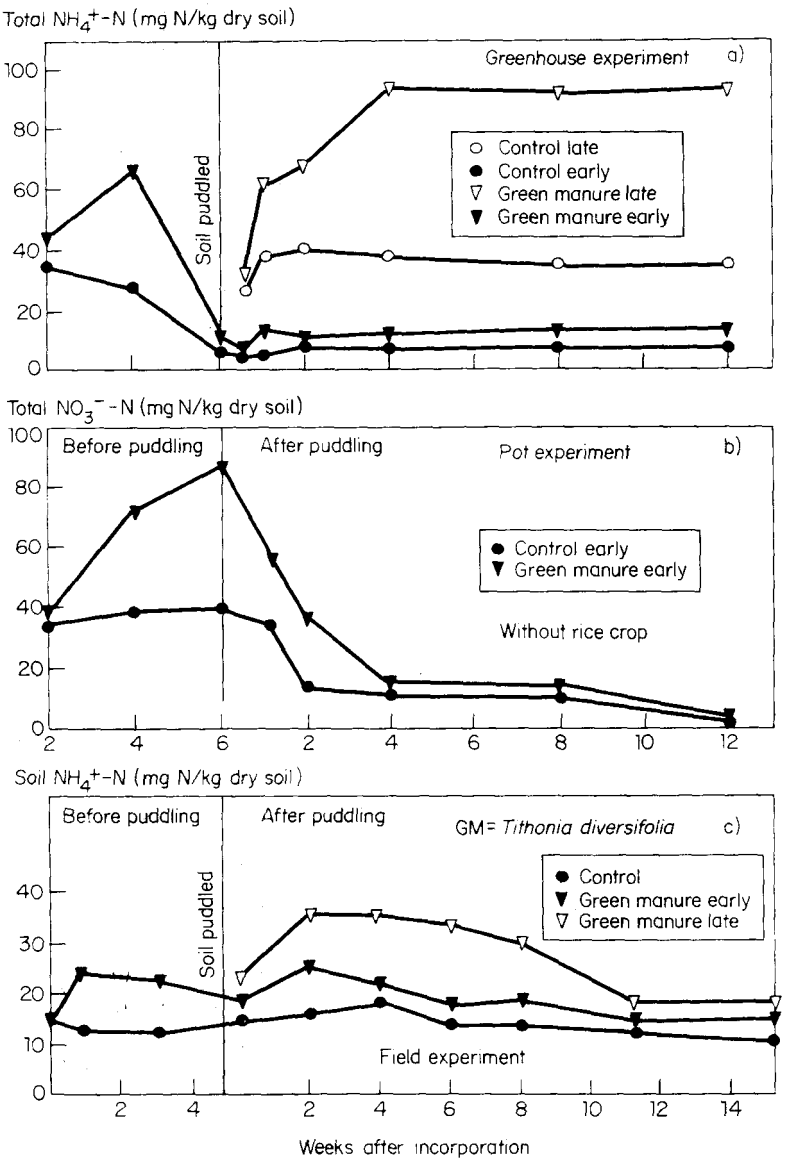
In a recent study, S. Nagarajah, H. U. Neue, and M. C. R. Alberto (IRRI, 1986, unpubl.) found that after incorporation of sesbania and azolla under flooded conditions, both exchangeable and soil solution NH_4^+-N initially increased, then remained nearly constant (Fig. 3, 4, 6, 7). It appears that maximum benefits from green manure can be achieved by maintaining flooded conditions immediately after incorporation.

Availability of green manure N to rice

Studies using ^{15}N-labeled azolla have indicated that availability of azolla N to rice depends on the method and time of its application (Ito and Watanabe 1985). In pot experiments, 50% of the N from incorporated azolla was absorbed by the rice plant by 42 d after transplanting (DT); this value remained constant to 123 DT. Only about 10% of the azolla N floated on the water was absorbed. In the field, about 25% of the N from azolla incorporated at 30 to 53 DT was absorbed by rice; that was reduced to 14% when azolla was incorporated at 78 DT. When azolla was kept on the soil surface or grown on water, only about 15% was taken up by the plant. N availability decreased when azolla was applied at later stages of growth.

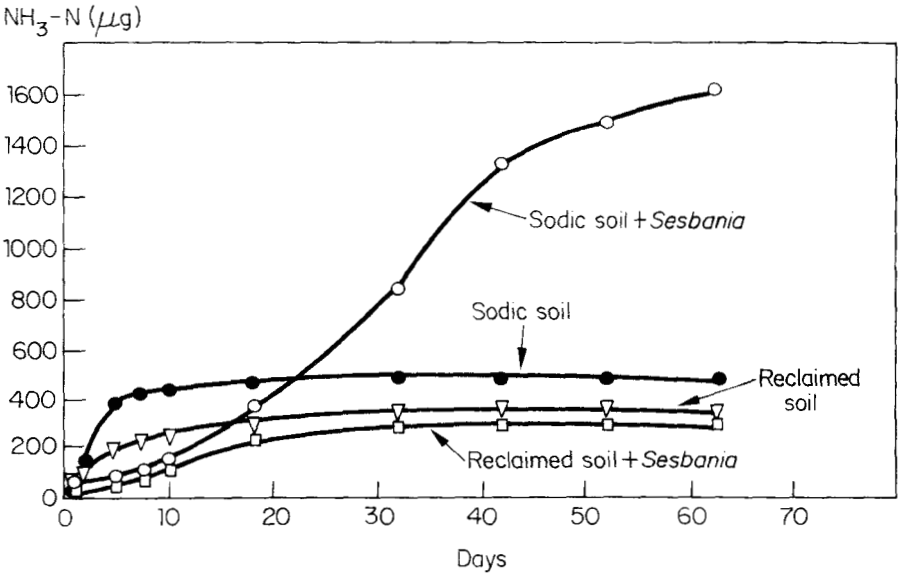
Losses of N released from green manure

Like fertilizer N, ammonium N released from green manure is subject to losses by denitrification, NH_3 volatilization, and leaching. Losses amounting to more than 60% in 6 wk were noted when ^{15}N-labeled azolla was placed on the soil surface (Ito



10. Changes in NH_4^+-N and NO_3^--N in a soil after addition of green manure under 2 water management practices (adapted from Joachim and Kandiah 1929). Early: green manure added under semidry conditions and puddled 5-6 wk later; late: green manure added under flooded conditions and puddled immediately.

and Watanabe 1985). When floated on water, losses were 50% in 6 wk. With incorporation, only about 30% was lost. The mechanism of N losses was not identified.



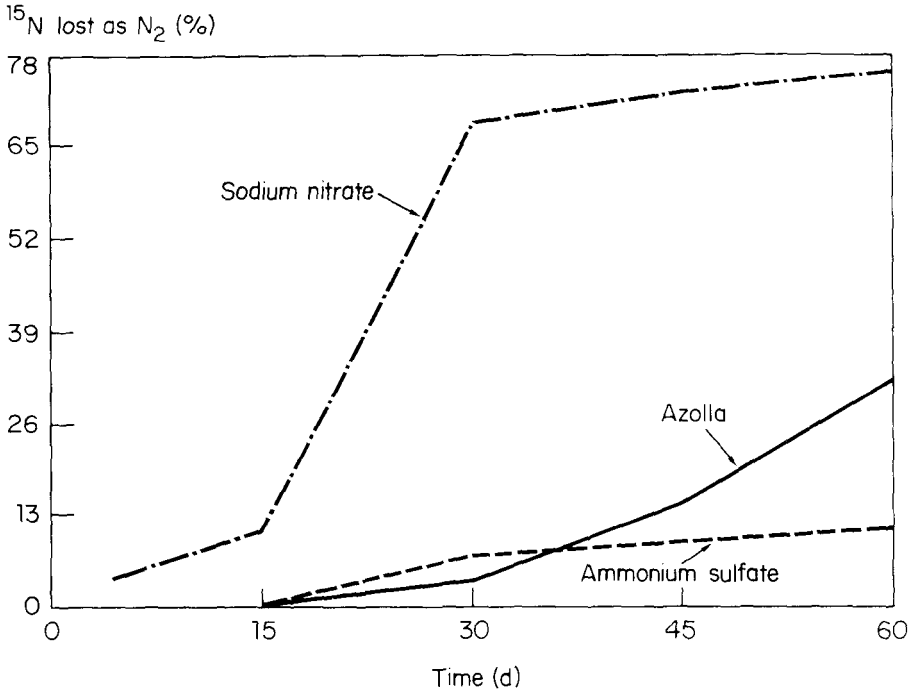
11. Ammonia volatilized from flooded sodic and reclaimed soils after addition of *Sesbania aculeata* (Venkatakrishnan 1980).

Loss of NH_4^+-N released from green manure also depends on the soil type. In a laboratory incubation study, *S. aculeata* N added to a sodic sandy loam soil (pH 10.3, organic C 0.14%) showed extensive NH_3 loss through volatilization 10 d after application; that loss continued to 9 wk, when the experiment was concluded (Fig. 11). Loss in a reclaimed soil (pH 8.3) was much lower (Venkatakrishnan 1980).

Denitrification losses of N released from azolla also have been reported (Mian 1985). In a laboratory incubation study of a flooded loamy soil from Bangladesh (pH 7.2. organic C 0.56%), 32% of the total azolla N was released as NH_4^+-N in 60 d; 96% of this was lost as gaseous N_2. Denitrification did not occur in *A. caroliniana* or ammonium sulfate-treated soil until after 30 d incubation. In sodium nitrate-treated soil, denitrification started within 3 d (Fig. 12). The 30-d delay was attributed to the time required for the development of a surface-oxidized layer where nitrification could occur. In the presence of rice plants, denitrification loss of released N was only 25-28% in 60 d. It was concluded that severe denitrification loss of released azolla N may be avoided by planting the rice crop within 3 wk of azolla incorporation in a flooded soil.

Conclusions

It is apparent that the limited information on mineralization of green manure under flooded conditions has come mostly from laboratory and pot incubation studies carried out in the absence of rice plants. These may not fully reflect field conditions. The few field experiments at IRRI did give patterns of N release from green manure



12. Denitrification loss of N released from *Azolla caroliniana.* ammonium sulfate, and sodium nitrate in a flooded soil (Mian 1985).

similar to those obtained from *in vitro* and greenhouse studies, but that is unlikely to be universal. There is a need to conduct such studies under different soil and climatic conditions. To use green manure N efficiently, more research on its availability and losses under field conditions using ^{15}N-labeled green manure is needed.

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Notes

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Green manure management in rice-based cropping systems

O. P. Meelu and R. A. Morris

When green manure crops are used in rice-based farming systems, the green manure commonly is applied to the rice crop. Green manure species vary in their environmental adaptation, and therefore in their ability to accumulate N in different agroecological niches. In several environments, some green manure species accumulated more than 150 kg N/ha in less than 2 mo. The response of rice to green manure is associated primarily with increased N availability. Green manure has substituted for more than 100 kg N/ha to rice crops. Rice yields also respond to residues from early-maturing grain legumes such as mungbean. Because most green manure N is mineralized within 4 wk of incorporation, N may become limiting after rice panicle initiation. Residual effects in second crops have been low and variable. When green manure is incorporated annually, soil organic carbon and total N increase. The effects of these increases on other soil parameters and on crop yields in selected agroecologies need documentation. That information will enable scientists to judge the potential contributions of green manure to sustained production from rice-based farming systems. More data also are needed on the green manure potentials of lesser-known species, such as *Sesbania rostrata.*

The vast majority of soils in South and Southeast Asia, where rice is the staple food, are deficient in N and organic matter (Kawaguchi and Kyuma 1977). Consequently, rice is a major consumer of fertilizer N. However, N fertilizer efficiency on rice is low compared to its efficiency on upland crops (Vlek and Byrnes 1986).

The production of inorganic fertilizer requires considerable energy. It is estimated that fertilizer production accounts for about 45% of the energy used in agriculture worldwide; 73% of that is used to manufacture N fertilizer (McCune 1984). Chinese agriculturists have placed heavy emphasis on organic fertilizers (farmyard manure, compost, green manure, azolla) to meet crop nutrient needs while keeping cash inputs low. But agriculturists in other countries have paid little attention to devising management techniques that maintain soil productivity while reducing dependency on nonrenewable resources. Notable and encouraging developments in this direction are cropping systems for tropical Alfisols in West Africa (Kang et al 1981) and Ultisols in the Amazon Basin (Wade and Sanchez 1983). These systems include legumes that maintain soil productivity and produce food.

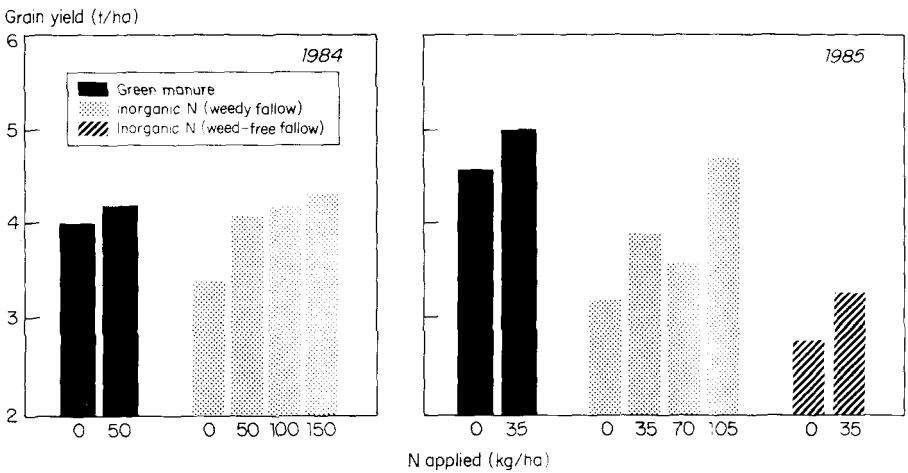
Integrated management of organic manure and inorganic fertilizer and including legumes in rice-based cropping systems can contribute to the maintenance of a sustainable system while increasing farm income to above a subsistence level. Supplies of farmyard manure and compost are limited, however, and usually are low in nutrient concentration. Recent research suggests that some leguminous green manure crops potentially could be abundant sources of N. Those crops should be reevaluated under current economic conditions.

Nitrogen accumulation and rice grain yield

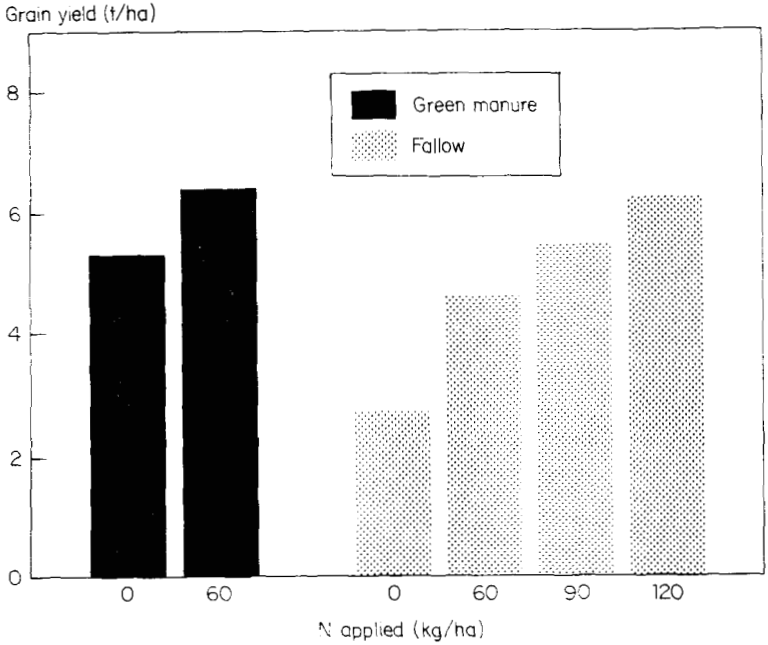
Although green manure has been reported to benefit crops in rice-based systems through several mechanisms, the quantity of N in the green manure largely determines its fertilizer value (Morris et a1 1986, Meelu et a1 1987b). Morris et a1 (1986) reported that with up to 85 kg green manure N/ ha, rice yields increased an average 23 kg grain/ kg green manure N. More data have been reported on the value of single-level substitutions of green manure N than on responses to a range of green manure N levels.

Those data demonstrate the wide variation in the substitution value of green manure N for inorganic fertilizer N. Meelu et a1 (1987b) obtained substitution for 50-105 kg inorganic N/ha (Fig. 1). Beri and Meelu (1981) reported substitution for 60 kg inorganic N/ha with sesbania green manure (Fig. 2). Substitutions of 45-120 kg N/ ha were reported by Williams et a1 (1972), Tiwari et a1 (1980), Bhardwaj and Dev (1985), and Morris et a1 (1986).

Differences in N accumulation by green manure crops, and in the recovery and utilization of incorporated N due to differences in crop management, cultivars, soils, and weather, may explain the wide range of inorganic N equivalencies in green



1. N equivalent supplied by green manure in rice. IRRI, 1984-85 wet ,season.



2. Nitrogen accumulation in green manure crops at 30, 45, and 60 d growth.

manure crops. Furthermore, responses to inorganic N are not constant (Craswell and Godwin 1984); that could account for some of the variability.

The wide range in green manure N accumulation found in some recent experiments is shown in Table 1. In a comparison of eight tropical green manure crops (Meelu et a1 1987b), biomass production and N accumulation varied widely among species grown in the same environment (Table 2). Sesbania *Sesbania aculeata* and sunn hemp *Crotalaria juncea* accumulated the most N.

Table 1. N accumulation in green manure crops.

Age (g)	Green manure N (kg/ha)				Reference
	Sesbania cannabina	*Crotalaria juncea*	*Cowpea*	*Ipomoea*	
45	79	-	32	-	Rajbhandari (1984)
56	57	78		28	Bhardwaj et al (1981)
57	102[a]	-	-	-	Ghai et al (1985)
60	105[a]	-	-	-	Beri and Meelu (1981)
65	165	-	-	-	Bhardwaj and Dev (1985)
40	-	-	86[b]	-	Morris et al (1986)

[a] *S. aculeata.* [b] Mungbean (mean of 3 yr).

Table 2. Nitrogen accumulation in green manure crops at 30, 45, and 60 days growth. 1984 and 1985.

Species	N accumulation[a] (kg N/ha)		
	30	45	60
Sesbania aculeata	77	182	199
Crotalaria juncea	72	140	143
Soybean	31	107	138
Mungbean	39	90	93
Indigofera tinctoria	8	33	84
Lablab purpureus	30	67	80
Cowpea	18	62	75
Pigeonpea[b]	9	30	76

[a]Mean of 1984 and 1985. [b]1984 only.

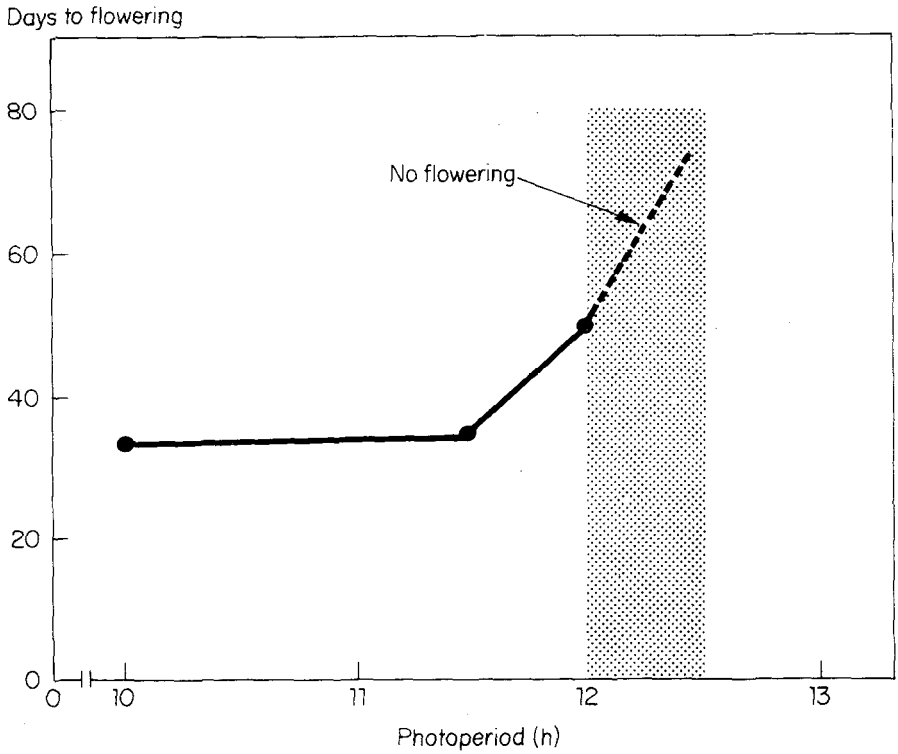
Although use of green manure has a long history, the practice was abandoned in favor of the inorganic fertilizers that came with modern rice, wheat, and maize cultivars. In the context of intensive Asian agriculture, a farmer may not be willing to use green manure in the traditional manner. Intensive crop schedules do not permit 10 to 12 wk for green manure cultivation. But some recent experiments have demonstrated that N accumulation by some green manure species can exceed 150 kg/ha in less than 8 wk. Such species should receive more consideration in future research for their N contributions as well as for other possible beneficial effects.

Environmental effects

Species vary in their adaptation to environmental factors. In a comparison of sesbania *S, aculeata,* sunn hemp *C. juncea,* and clusterbean *Cyamopsis tetragonoloba* (Uppal 1955), sesbania was the best green manure for rice on alkali soils. Even on normal soils, sesbania is often superior to other green manure crops because of its ability to withstand prolonged moisture.

Meelu et al (1987b) and Morris et al (1987) found that cowpea *Vigna unguiculata* was sensitive to excess moisture. At Ludhiana, India, Singh et al (1981) found that sesbania was less tolerant of drought than was cowpea. Water use efficiency and N accumulation by cowpea were higher than those of clusterbean and sesbania at irrigation:evaporation (open pan) ratios of 1.0, 0.7, and 0.5.

Green manure species (and cultivars within species) differ in their responses to photoperiod. Photoperiod responses of common commercial species, such as cowpea and soybean, have been extensively explored. *Sesbania rostrata* and others are short-day plants (Fig. 3) (Visperas et al 1987). Limited experience indicates that this short-day habit may restrict green manure for wet season rice to the more productive species, such as *S. rostrata* (IRRI 1986). For use as a green manure for a dry season rice crop, *S. rostrata* must be planted before the vernal equinox; then it flowers in 30 d. Vegetative growth and N accumulation during those 30 d are limited.



3. Effect of photoperiod on sowing-to-heading days of *Sesbania rostrata* (R. M. Visperas, G. Pateña, and R. S. Vergara, IRRI, 1987 unpubl. data).

The contribution of green manure N to rice yields, the importance of the effect of environment on N accumulation by green manure species, and the time constraint in Asian rice-based farming systems imply that green manure species must be adapted to the physical environment they will experience during growth and that rates of N accumulation during the first 6 wk of growth must be relatively high and reliable.

Green manure management

Management practices that influence the rate of N accumulation by a green manure crop must be given special consideration in rice-based cropping systems.

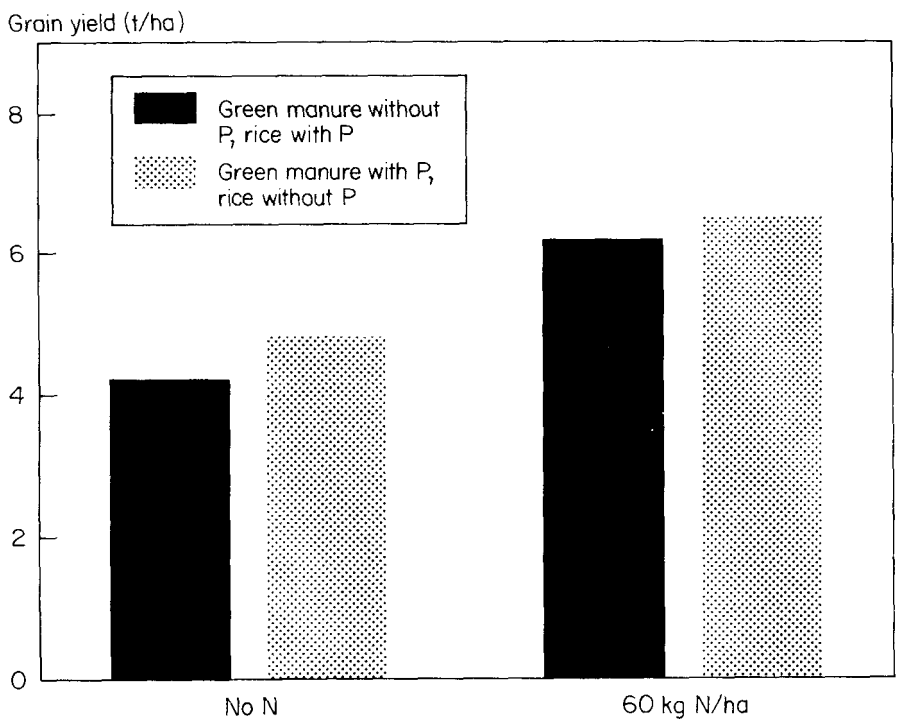
If N accumulation is limited by a nutrient deficiency, application of that nutrient to the green manure crop will increase N available to the rice crop. On a soil testing low in available P in Ludhiana, India, applying P to the green manure crop was beneficial to N accumulation (Table 3) and increased rice yield more than did P applied directly to rice (Fig. 4) (Beri and Meelu 1980). On a soil testing high in available P in the Philippines, however, 199 kg N/ ha was obtained in *S. aculeata* without P application (Meelu et al 1987b).

Table 3. Effect of P application on green matter and N added to soil.

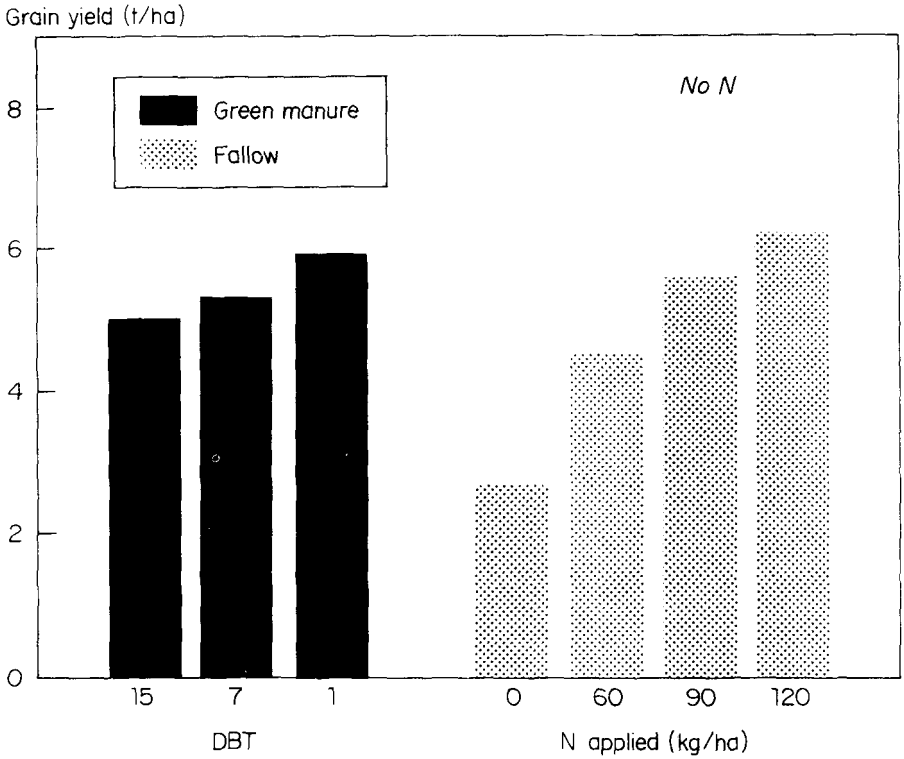
Treatment	Green matter weight (t/ha)	Dry weight (t/ha)	N added (kg/ha)
Green manure without P	17.9	4.0	88
Green manure with P	20.8	4.2	104

The availability of P and other nutrients must be considered in choosing green manure species. Green manure crops should not have critical soil test levels that greatly exceed those for rice. Research with azolla suggests that farmers are not willing to apply large quantities of P to produce N if the application does not substitute for a comparable P application to rice (Kikuchi et al 1984). In practice, flooding increases the availability of soil P and K, suggesting that green manure species may be limited by P or K more frequently than is rice. Empirical studies have shown that critical P and K soil test levels of legumes are above those for rice (PCARR 1978).

Seeding at rates to achieve high plant densities will conceivably increase N accumulation rates prior to canopy closure. IRRI (1986) reported that N accumulation in *S. rostrata* earlier than 35 d after emergence was increased by higher seeding rates. At older ages, the advantage of increased seeding density was not



4. Rice yields with P applied to the green manure crop or to the rice crop.



5. Effect on rice grain yield of days between green manure incorporation and transplanting. DBT = days before transplanting.

apparent. On the other hand, Morris et a1 (1986) reported that doubling mungbean seeding rate (from 300,000 to 600,000 plants/ha) did not significantly increase N accumulation rate in a 30-d crop, nor rice yield response to its incorporation as a green manure.

Shortening the time between green manure incorporation and rice transplanting effectively shortens the cycle. Beri and Meelu (1981) showed that the 2-wk delay between incorporation and transplanting recommended in temperate climates was not necessary in the tropics. Yields from green manure incorporated 1 d before transplanting exceeded yields from green manure incorporated 1 or 2 wk before transplanting (Fig. 5). Bhardwaj et a1 (1981) reported similar results.

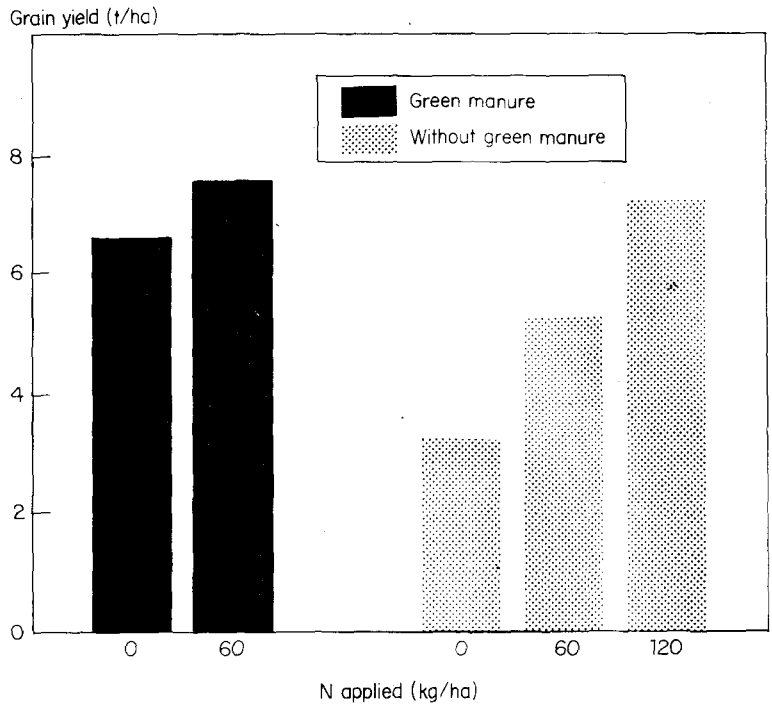
Mungbean for grain and green manure

With the introduction of high-yielding cereal cultivars, cereal hectarage increased at the cost of pulse hectarage. An effective way to increase pulse production is to insert mungbean or cowpea (which matures in 60-70 d) as a summer crop between wheat or maize and rice. In a wheat - mungbean - rice rotation in Ludhiana, India, mungbean produced 0.9 t grain/ha and the crop residue effectively substituted for 60 kg inorganic N/ha (Table 4, Fig. 6) (Meelu and Rekhi 1983). In an experiment at IRRI,

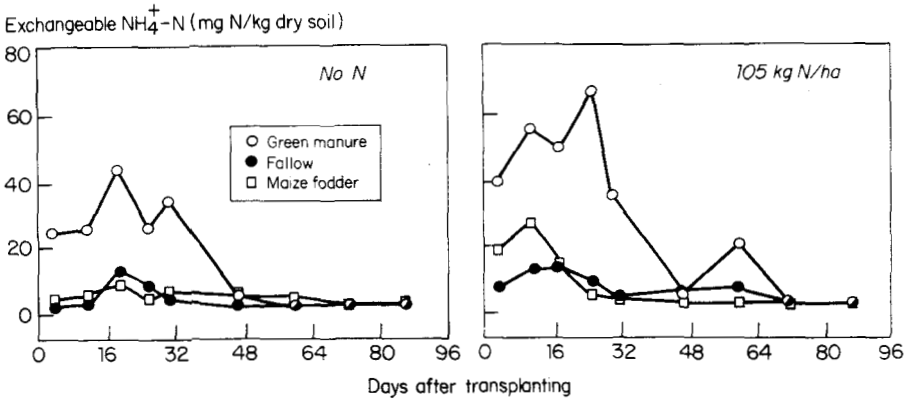
Table 4. Grain and straw yield of mungbean, with N added to soil.

Year	Grain			Straw				
	Yield (t/ha)	N content (%)	N removed (kg/ha)	Fresh wt (t/ha)	Dry wt (t/ha)	N content (%)	C-to-N ratio	N added through straw (kg/ha)
1980	0.84	3.84	32.3	7.5	4.6	2.16	16.1	99.4
1981	0.85	3.92	33.4	7.6	4.6	2.21	16.1	101.7
1982	0.89	3.64	32.4	7.5	4.5	2.26	15.1	101.7
Mean	0.86	3.80	32.1	7.6	4.6	2.21	16.1	100.7

Meelu et al (1987b) also obtained 0.9 t mungbean grain/ha and substitution for 25 kg inorganic N/ha from crop residue incorporation. These results suggest that in fields unlikely to be intermittently flooded during the 60 d before land preparation for rice cultivation, mungbean or a similar shortduration crop is an alternative to green manure. In this case, a farmer should consider growing a leguminous crop that would produce a cash income. The crop residue would be incorporated for its contribution of N and other nutrients. If necessary, fertilizer could be purchased to meet additional crop needs.



6. Effect on rice yield of green manuring with summer mungbean after one picking.



7. Effects of sesbania green manure, fallow, and maize fodder on soil NH_4^+-N during growth of fertilized and unfertilized rice. 1985.

Table 5. Rice yields after incorporation of mungbean at 40, 60, and 67 d after emergence (DE) at 3 inorganic N (50 kg/ha) timing treatments.

Time of N application	Rice yield (t/ha)			
	40 DE	60 DE	67 DE	Mean
All at panicle initiation (PI)	3.35	3.21	2.46	2.80
½ at planting + ½ at PI	3.19	3.01	2.20	2.59
All at planting	3.07	2.96	2.13	2.51

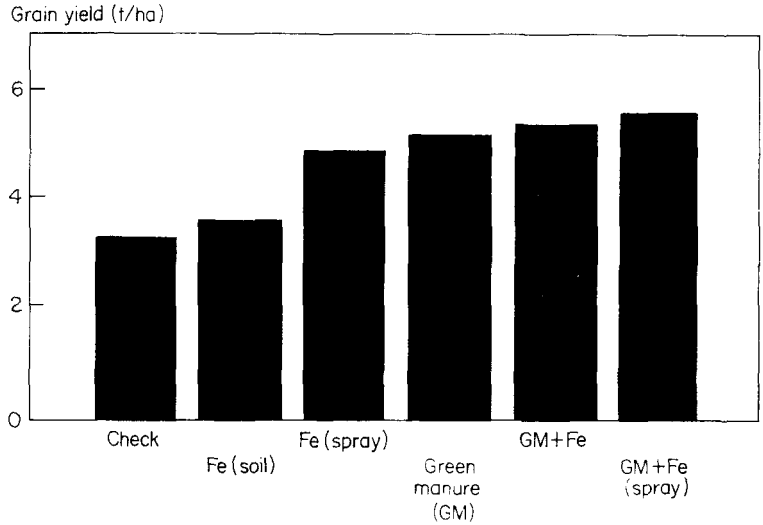
[a]Unfertilized control yield was 1.4 t/ha. Yield with 50 kg N/ha (2 splits) without green manure was 2.0 t/ha.

Green manure and time of N application to rice

Meelu et al (1987a) monitored the mineralization of *S. aculeata* green manure in rice (Fig. 7). After incorporation, soil NH_4-N increased steadily to a peak at 3-4 wk, then gradually declined to a minimum about 3 wk later. This suggests that green manure has an effect similar to that of basal N application. Inorganic N topdressed at 40-50 d after transplanting (DT) might be beneficial. Morris et al (1985) reported the effects of single and split application of N with green manure. N applied at panicle initiation increased rice yield more than did split-applied N (Table 5). In a study at Ludhiana, India, Khind et al (1985) obtained higher yield from green manure before rice and all inorganic N topdressed 42 DT or 1/2 21 DT + 1/2 42 DT, rather than from all N topdressed 21 DT. Results of these 1-yr studies need to be confirmed.

Green manure and iron and manganese availability

In a 2-yr field experiment on a coarse-textured soil at Ludhiana, Fe was more effectively corrected by green manuring with sesbania alone or in combination with soil-applied Fe than by soil-applied Fe alone (Fig. 8) (Takkar and Nayyar 1986).



8. Rice grain yield as influenced by soil and foliar application of Fe alone and in conjunction with green manure.

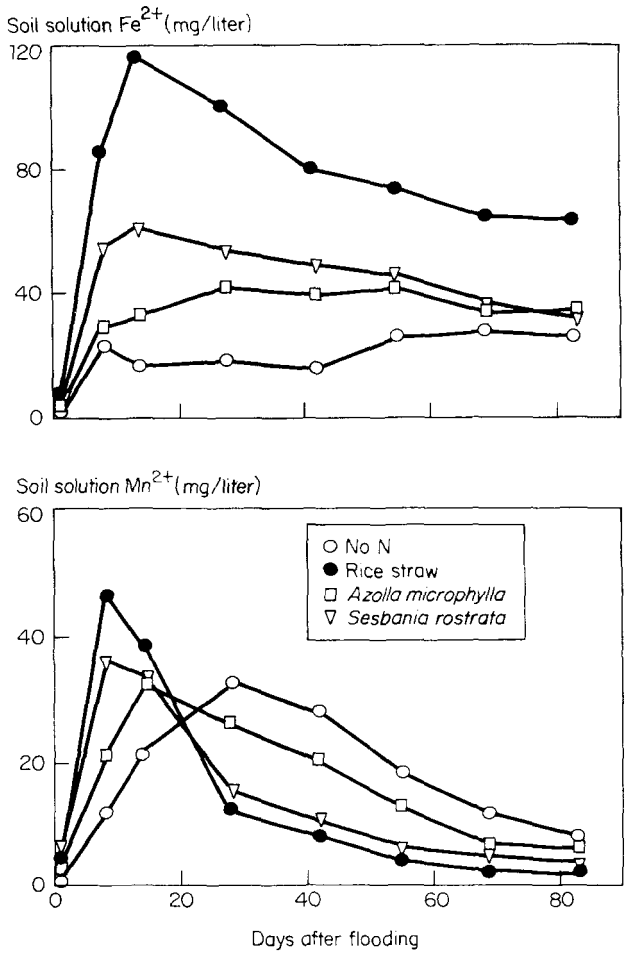
Gopala Rao (1956) reported a pot experiment in which green manuring with *Gliricidia maculata* increased Fe and Mn availability and rice shoot weight.

In a greenhouse experiment, Nagarajah et a1 (1986) monitored N mineralization of *S. rostrata,* azolla, and rice straw applied at 116 kg N/ha. They determined soil solution Fe and Mn changes and rice grain yield. After an initial increase, NH_4-N declined to level off 8 wk after flooding. Initial Fe and Mn in solution decreased in this order: rice straw > sesbania > azolla > control (Fig. 9). Rice grain yield and NH_4-N concentration in the soil during crop growth increased in this order: control < rice straw < azolla < sesbania. Those results indicate that green manuring with sesbania increased soil Fe and Mn availability as well as N.

Residual effects

The green manure N levels in Tables 1 and 2 include several observations that exceeded 120 kg N/ ha. Those N levels are in excess of inorganic N fertilizer recommendations for wet season rice in many countries. Because the green manure N quantities are often high and because the form of N is organic, occasional residual effects might be expected on second crops.

Sethi et a1 (1952) reviewed green manure research in India and concluded that the residual value of green manure applied to rice was low. Singh et a1 (1981) did not obtain residual effects from green manure incorporated before rice in a rice - wheat rotation. However, Tiwari et a1 (1980) and Singh (1971) reported residual effects from green manure on rice in succeeding wheat crops. Meelu et a1 (1987b) obtained no significant residual effect in the first year of a 2-yr evaluation of 8 green manure crops. But in the second year, *S. aculeata,* the most productive among the species,



9. Change, in Fe^{2+} and Mn^{2+} concentrations in soil solution of flooded IRRI N8 soil with incorporation of sesbania, azolla, and rice straw. IRRI greenhouse, 1986.

significantly increased yield of the succeeding dry season rice. Morris et al (1987) also reported small (0.5 t ha) but significant residual effects on second rice crops from sesbania incorporation. In those experiments, green manure N averaged 123 kg/ha in many treatments. In an earlier study, in which green manure N levels averaged 85 kg/ ha, Morris et al (1986) did not detect residual N effects after 4 yr.

These results suggest that residual effects of green manure are related to the N in the green manure and, presumably, to the quantity of N recovered by the first crop.

Green manure has been observed to affect soil fertility parameters. Sahu and Nayak (1971) studied the effect of fertilizers alone and in combinations with farmyard manure (FYM) and green manure. FYM and green manure improved soil fertility relative to control and fertilizer treatments (Table 6). Green manure

Table 6. Effect of organic and inorganic fertilizers on nutrient status of soil.

Treatment	Organic C (%)	Total N (%)	Available P_2O_5 (ppm)	Available K_2O (ppm)
At start of trial, 1956	0.66	0.029	30	150
At the end of 10th yr, 1965				
No manure (control)	0.58	0.021	20	103
Organic manure (45 kg N/ha)				
Farmyard manure	0.78	0.058	34	166
Green manure	0.67	0.054	33	130
Ammonium sulfate				
22.5 kg N/ha	0.60	0.032	24	130
45.0 kg N/ha	0.61	0.037	30	123
67.5 kg N/ha	0.62	0.045	26	103
90.0 kg N/ha	0.65	0.054	24	103

increased total soil N and maintained organic C and available P. Available K, however, declined slightly. Meelu et al (1986) reported that soil organic C and total N increased when sesbania and crotalaria, the most productive green manure crops in the experiment, preceded rice for two wet seasons. In an experiment in a subtropical humid climate, Bhardwaj and Dev (1985) obtained soil organic C and total N increases from sesbania incorporation.

Potentials and problems

The potential of green manure to substitute for inorganic fertilizers has been demonstrated. The major factor derived from green manure that promotes rice yield appears to be its N contribution. Green manure species capable of accumulating in less than 2 mo sufficient N to substitute for most of the inorganic N applied to rice are the most likely to find farmer acceptance. Species that require significantly longer growth will not fit well into the rice-based cropping systems that predominate in Asia.

Fortunately, a number of species are capable of accumulating more than 100 kg N/ha in less than 2 mo. Additional research is needed. however, to evaluate their adaptation to specific soil conditions (aerobic, intermittent aerobic, continuously aerobic) and their acceptance by farmers. Studies needed to improve green manure management practices include green manure decomposition rates and responses by rice to green manure-inorganic N combinations (rates and time of inorganic N application) for soils differing in available N. *S. rostrata* warrants special efforts on germplasm collection and comparisons of accessions for N accumulation, adaptation, and response to management practices.

Residual responses of the second crop after incorporation have been low and variable. Tagged-N studies show that only 3-5% of the N incorporated is recovered by the second crop. That variability possibly is associated with the quantity of N

incorporated, the quantity removed by the first crop, soil properties, and soil management between crops.

The potential of green manure to maintain or even improve soil properties and productivity is less well documented than its potential to substitute for inorganic N. With regard to long-term soil productivity maintenance or improvement, logic and evidence from a few long-term green manure studies and in other cropping sequences suggest that annual incorporation of 3-6 t dry matter/ ha will increase soil organic C, thereby influencing soil physical properties when dry and, presumably, puddling ability when wet.

Chemical properties such as cation exchange capacity and absolute as well as relative quantities of cations are likely to be altered by annual green manure incorporation of this magnitude. Studies of chemical processes (including the possible promotion of ferrolysis) and changes in nutrient availabilities as well as physical properties in selected soils are needed to compare green manure effects after three or more annual applications. Such studies will enable scientists to more accurately predict changes in soil productivity caused by sustained green manure application.

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Notes

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Measurement of nitrogen fixation in crop and shrub legumes

M. B. Peoples, D. F. Herridge, and F. J. Bergersen

Biological fixation of atmospheric N_2 is difficult to measure, although progress in developing field-based methodologies has been rapid over the last decade. In practice, such measurements could contribute to more N-efficient farming systems, germplasm improvement, and elimination of nodulation problems associated with *Rhizobium* inoculation and inoculants. Methodologies for measuring biological N_2 fixation in nodulated legumes provide either short-term or time-averaged determinations. Short-term estimates of symbiotic activity may be obtained from acetylene reduction assays or by analyzing the N solutes transported in the xylem stream leaving the roots of legumes. N-difference methods or dilution of isotopically enriched (naturally or by addition of ^{15}N-labeled N)soil N by N_2 fixed from air has been used to calculate time-averaged values for the proportion of plant N derived from atmospheric N_2.

Legumes are important features in the traditional agriculture of Africa, Asia, and South America and in systems where large-field agriculture is practiced. While N_2-fixing components are commonly utilized in the production of food, fiber, and fuel, their potential benefits have often gone unrecognized. The efficiency of such systems is predominantly assessed in terms of production and quality of products. Ultimately, the role played by legumes in sustaining productivity and maintaining soil N status will need to be known. Measuring N_2 fixation is important in the study of many aspects of agricultural research. Aspects were identified by Bergersen (1987a):

- Inputs for systems of agricultural production are usually measured in kg N/ ha per yr, and that is the way N_2 fixation is commonly expressed. More properly, it should be kg N/ ha per crop period. For forest or natural systems, it should be g N/fixing unit per growth period.
- Ecological considerations for conserving landscapes demand an understanding of the relative importance of N_2-fixing components in the maintenance of N balance.
- Development of farming systems requires that nutrient balance be preserved. In terms of N_2 fixation, it is necessary to know the relationships between legumes and other crops. Understanding the amount of N_2 fixed by legumes allows the

development of more efficient systems for maintaining N balance, by careful use of legumes in the cropping sequence, in a pasture or fallow phase, or as a green manure.

- Once the user is satisfied that nodule development is adequate. measurement of N_2 fixation establishes whether or not a legume is achieving its potential. N_2 fixation becomes an additional means of identifying such constraints as nutrient limitations.
- Measurement allows more reliable assessment of whether N_2 fixation rates actually achieved in the field are adequate or limiting for crop yield.
- Residual effects on the crops that follow legumes are frequently attributed to N_2 fixation. Improvements in soil structure or control of pests and diseases may be additional benefits. Measuring N_2 fixation allows appropriate assessment of the benefits from fixed N input.

Measuring N_2 fixation in the field

Acetylene reduction assay

The enzyme nitrogenase not only reduces atmospheric N_2 to NH_3, but also can catalyze the reduction of acetylene to ethylene. The acetylene reduction assay (ARA) commonly involves enclosing detached nodules, detopped root systems, or whole plants in a closed vessel containing 10% acetylene. Accumulation of ethylene in the gas phase is determined by gas chromatography (Hardy et al 1968, Turner and Gibson 1980). The ARA essentially provides an instantaneous determination of nitrogenase activity under the conditions prevailing during assay. Long-term estimates require a series of measurements to cover diurnal, daily, and seasonal changes. However, variation in activity due to light intensity, temperature, and moisture levels in the field can make it extremely difficult to meaningfully integrate a series of short-term assays (Turner and Gibson 1980).

The ARA is a particularly useful diagnostic tool for detecting nitrogenase activity. It has been used widely in legume research because of its high sensitivity, simplicity, and relatively low cost. Nonetheless, other limitations to the technique, apart from the disadvantages of using short-term assays to assess overall activity, limit its accuracy in quantifying N_2 fixation in the field.

Inherent problems. A major limitation of ARA is the need to calibrate the rates of ethylene production with the actual rates of N_2 fixation. The theoretical acetylene-to-N_2 conversion ratio is 3:1 (provided all electrons transferred are allocated to these substrates). Although some estimates of the conversion ratio have been close to this value, other measurements have shown it to range from 1.5:1 to 25:1 in pasture and food legumes and 1.6:1 to 4.8:1 in shrub legumes (Hansen et al 1987a, Hopmans et al 1983, Turner and Gibson 1980, van Kessel et al 1983). Since acetylene reduction does not relate directly to N_2 fixation, but only measures electron flux through nitrogenase, the electrons used in H_2 production will influence the acetylene reduction measurements obtained. Various factors have been reported to affect electron allocation to H_2. A simple ranking of treatments (e.g., *Rhizobium* strains) based on their ability to reduce acetylene may be invalid if appropriate conversion ratios are not determined (Witty and Minchin 1987).

Another source of error important in some nodulated legumes is the substantial decline in nitrogenase activity which occurs within a few minutes of the commencement of assay (Minchin et al 1983). Such nonlinear rates of ethylene accumulation, attributed to acetylene-induced changes in nodule gas exchange, could underestimate nitrogenase activity by as much as 50% (Witty and Minchin 1987).

Procedural limitations. Apart from the need to recover the entire population of nodules to estimate N_2 fixation per plant, removal of the shoot and washing or shaking the root system to separate soil can have a detrimental effect on nitrogenase activity (Minchin et a1 1986). Nodule detachment also is detrimental (Witty and Minchin 1987). To overcome these problems, *in situ* methods have been devised. Open-ended chambers are placed in the soil at the beginning of a growing season or driven into the ground around established plants. A flow-through gas system is used to introduce acetylene for assay (Denison et a1 1983).

Notwithstanding the effects that these technical limitations may have on the interpretation of experimental data, and despite the difficulties of recovering root systems and nodules of tree and shrub species, ARA has been the method most widely used to measure fixation by woody legumes. Estimates of seasonal fixation of N_2 have ranged from 0-2 kg N/ha per yr in the dry sclerophyll forests of temperate and tropical Australia(Hansen et a1 1987b, Langkamp et al 1981) to 13-45 kgN/ ha per yr by leguminous trees in agro-ecosystems of Mexico (Roskoski et a1 1982, Roskoski and van Kessel 1985) and 110 kg N/ha per yr in pure stands of leucaena growing in the humid tropics (Högberg and Kvarnstdröm 1982).

One must conclude, however, that the problems encountered in the use of ARA, coupled with the large degree of variation in plant and nodule density commonly found in shrub legumes, make quantitative interpretation difficult. Witty and Minchin (1987) suggested that the ARA procedure is incapable of even comparative estimates of nitrogenase activity in field-grown legumes. Nonetheless, studies with leguminous trees could still be useful. If nothing else, they could provide an estimate of the level of N_2 fixation achieved by these woody species under field conditions.

Analysis of N solutes in xylem exudate

In a legume growing in the field, sap ascending in the xylem from the roots carries N-containing compounds originating from the root nodules that are assimilation products from N_2 fixation and from inorganic soil N. Many legumes of tropical origin transport the bulk of their fixed N from nodules in the form of the ureides allantoin and allantoic acid (Table 1). Ureides have also been detected as minor components of xylem sap in some species. But since some sap samples were collected from field-grown plants (e.g., *Bossiaea, Desmodium,* and *Leucaena* species), the significance of ureides to the plants' N economy remains unknown. In most other legumes studied, nodule products are exported predominantly as the amides asparagine and glutamine (Pate and Atkins 1983, Peoples et a1 1986, 1987b). In agricultural soils, nitrate is the most available form of N for plant growth; the solutes derived from soil mineral N will be transported primarily as free nitrate or as organic products of nitrate reduction in the root (Fig. 1).

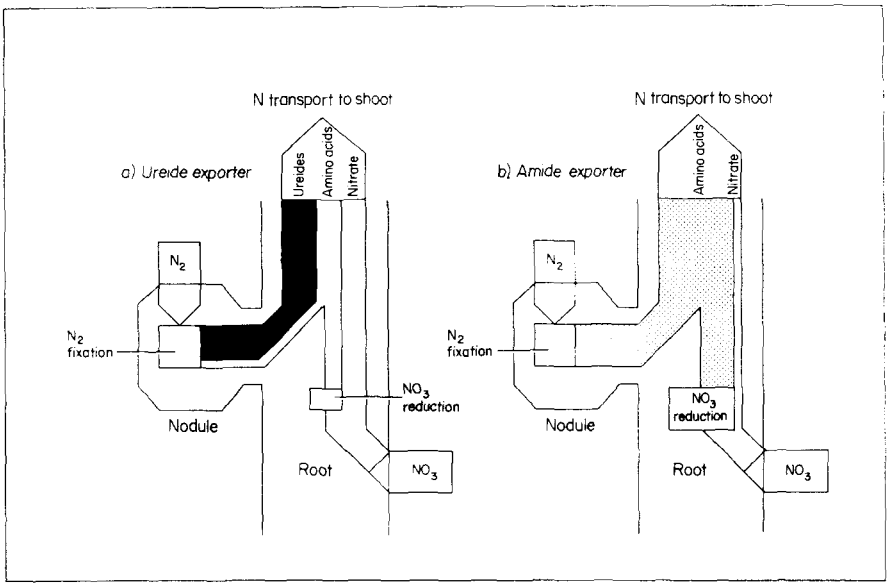
Table 1. Occurrence of ureides in xylem sap of nodulated legumes.[a]

Species in which ureides are major components of solute N[b]	Species in which ureides have been detected as a minor component[c]	Species in which ureides have not been detected
Albizia lophantha	*Bossiaea aquifolium*	*Acacia alata*
	Desmodium spp.	
Cajanus cajan	*Erythrina variegata*	*A. auriculaformis*
Calopogonium caeruleum	*Leucaena* spp.	*A. extensa*
Cyamopsis tetragonoloba	*Lens esculenta*	*A. insauvis*
Glycine max	*Pisum arvense*	*A. pulchella*
Hardenbergia spp.	*Sesbania rostrata*	*Arachis hypogaea*
Kennedya spp.	*Vicia ervilia*	*Bauhinia* spp.
Lablab purpureus	*V. sativa*	*Caesalpinia* spp.
Macroptilium atropurpureum	*Virminaria juncea*	*Cicer arietinum*
Macrotyloma uniflorum		*Derris elliptica*
		Desmodium spp.
Pueraria javanica		*Gliricidia* spp.
P. phaseoloides		*Lathyrus cicera*
Phaseolus vulgaris		*L. sativus*
P. lunatus		*Lens culinaris*
Phosphocarpus tetragonolobus		*Lotus corniculatus*
Vigna angularis		*Lupinus albus*
V. mungo		*L. angustifolius*
V. radiata		*L. cosentinii*
V. triloba		*L. mutabilis*
V. unguiculata		*Medicago minima*
V. umbellata		*M. sativa*
Voandzeia subterranea		*Mimosa pigra*
		Pisum sativum
		Stylosanthes spp.
		Trifolium pratense
		T. subterraneum
		T. repens
		Vicia culacarata
		V. faba
		Zornia spp.

[a] Information from Hansen and Pate 1987; Pate and Atkins 1983; Peoples et al 1986, 1987b; M. B. Peoples and D. F. Herridge, unpubl.; F. Dakora, C. A. Atkins and J. S. Pate, unpubi. [b] 50% or more total N of xylem sap. [c] 25% or less total N of xylem sap collected from glasshouse or field-grown plants.

Because most of the nitrogenous compounds in the xylem stream are likely to represent current products of N uptake and assimilation, it is possible to devise a sap analyses system to assess the extent to which plants rely on N_2 fixation in the presence of soil N. However, differences in the sap composition of fully symbiotic plants and of non-nodulated plants totally dependent upon soil mineral N must be well established.

Crop legumes. With ureide-exporting species, nitrate reductase activity in the roots characteristically assumes a minor role in assimilating incoming nitrate (Peoples et al 1987b), so that much of the nitrate taken up is transported to the shoot in an unreduced form. The composition of the xylem exudate of nodulated plants changes progressively, from one dominated by ureides to one dominated by nitrate

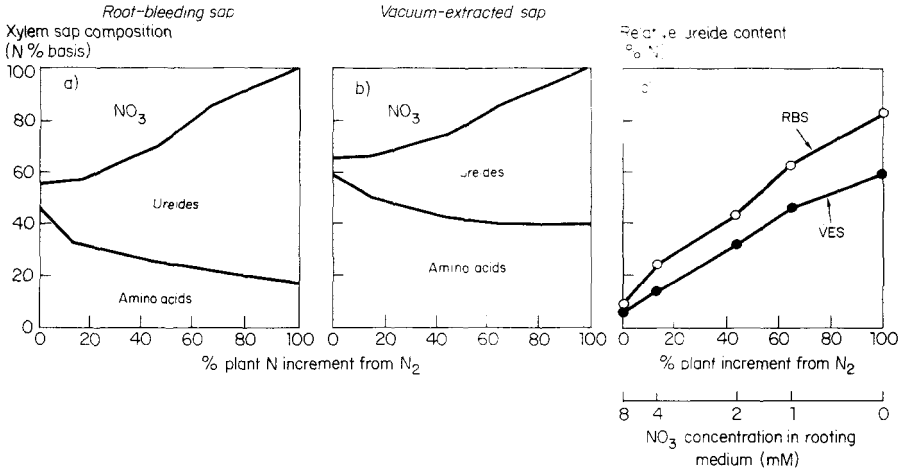


1. Pathways of nitrogen transport from the nodulated root systems of a) ureide-exporting, and b) amide-exporting legumes relying on both symbiotic N_2 fixation and nitrate uptake from the soil. The areas indicating nitrate reduction are proportional to the relative extent of nitrate metabolism occurring within the roots of species from each class of legume

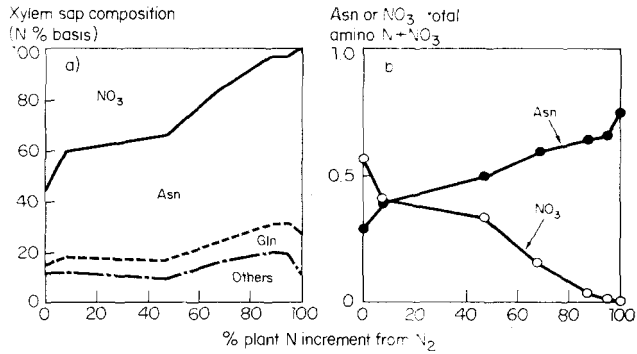
and amino compounds, as the plant's dependence upon fixation declines in response to increasing uptake of nitrate by the roots (Fig. 2). These changes in xylem composition are so predictable that the relative abundance of ureides (the proportion of total sap N as ureides) in xylem exudate can be used as a quantitative measure of the N_2-fixing status of many legumes within this broad group of plant species.

The response of the amide-exporting legumes is less well defined because the products of N_2 fixation and nitrate assimilation are essentially the same. In species such as white lupin *Lupinus albus* and faba bean *Vicia faba,* which have a high capacity for nitrate reduction in their roots, the spectrum of products exported from the roots does not change greatly with altered N nutrition. Only small amounts of nitrate are detected in the xylem exudate (Peoples et al 1987b). On the other hand, when the proportion of nitrate reduced in the roots is low, the relative proportions of nitrate and organic N vary sufficiently with changing proportions of N_2 and nitrate assimilation to allow assessment of N_2 fixation activity (Fig. 3).

Compositional relationships based on nitrate are not as useful as those that rely on the products of N_2 fixation, since the presence of nitrate in the exudate depends upon a correlation between its concentration, rate of uptake, and the extent of storage and reduction in the root. Nonetheless, the proportion of N solutes as nitrate appears to be a reasonable index of the dependence on soil N in nodulated peanut *Arachis hypogaea,* pea *Pisum sativum,* lentil *Lens culinaris,* and chickpea *Cicer arietinum* (Peoples et al 1986, 1987b).



2. Changes in the composition of xylem sap collected as a) root-bleeding exudate, or b) vacuum-extracted from stems of nodulated soybean fed a range of constantly maintained levels of nitrate, and c) the relationship between the abundance of ureides and plant dependence upon N_2 fixation. Relative ureide contents of root-bleeding sap (RBS) and vacuum-extracted sap (VES) are expressed as a proportion of total sap N (urcide-N α.+ -amino-N+nitrate-N). The N contents of solutes were calculated from the soybean *Glycine max* (L.) Merrill data of Herridge (1984) as described by Peoples et al (1987a).



3. Changes in a) the xylem exudate composition of nodulated peanut *Arachis hypogaea* L. fed a range of constantly maintained levels of nitrate, and b) the relationship between compositional features (N:N) and plant dependence on N_2 fixation. Data derived from Peoples et al (1986). Asn = asparagine, Gln = glutamine, others = amino acids listed in Peoples et al (1986)

In the humid tropics, it is relatively easy to collect the xylem exudate bleeding spontaneously from intact root stumps of crop legumes after decapitation of the shoot (Peoples et al 1987a). It may be difficult, however, to collect root-bleeding exudate from field-grown plants in some other environments (Herridge 1982).

Prewatering field plots may assist plants to bleed, but this is not always convenient. nor does it guarantee success.

Alternative methods for collecting xylem exudate have been examined. One useful technique for sampling N solutes involves preparing aqueous extracts from ground plant tissue. Relationships between the composition of the soluble-N components of aqueous extracts and plant reliance on N_2 fixation or nitrate uptake have been successfully prepared for both ureide-exporting (Herridge 1982) and amide-exporting species (Peoples et al 1987b).

In a recently developed technique, a mild vacuum is applied to the lower end of a detached shoot and small lengths are cut successively from the top to allow the xylem contents to be drawn through. The xylem exudate is trapped in a vacutainer connected in series to the source of the vacuum and the shoot (Herridge 1984).

Although there may be quantitative differences in concentration and relative composition of vacuum-extracted sap and root-bleeding exudate, strong correlations between the proportion of N solutes and symbiotic dependence have been found in soybean *Glycine max* and other legumes (Herridge 1984; Herridge and Peoples, unpubl.; Peoples et al 1987b).

The ureide method using root-bleeding exudate, extracts from plant parts, and vacuum-extracted exudate has been used in field studies of N_2 fixation for several years (Herridge and Peoples 1986). In most studies, the technique has provided an index of fixation activity, rather than a quantitative estimate of N fixed. Where estimates of seasonal fixation were made, agreement between those and the estimates using other procedures (e.g., soil nitrate depletion, N difference method) was reasonable (Herridge et al 1984). Calibration of the technique against ^{15}N methods under field conditions (in progress, Herridge, Peoples, and Bergersen, unpubl.) should provide a more quantitative basis for widespread applications. The use of N-solute analysis in amide-exporting species has been restricted to recent field studies on groundnut in Australia and Malaysia (Peoples and Bergersen, unpubl.). The field potential of N-solute analysis in non-ureide legumes has yet to be assessed in detail.

Tree and shrub legumes. There are obvious advantages to the solute method that may overcome the problems of measuring N_2 fixation by the woody perennial legumes. The near-impossible task of recovering all of the nodular tissue for analysis will be eliminated and sampling will be confined to the more accessible aerial parts of the plant. We have found that xylem exudate is easily vacuumextracted from stem and branch segments of almost all of the woody species examined so far, with the exception of N_2-fixing nonlegume *Casuarina* (Herridge and Peoples, unpubl.).

Some preliminary studies also have examined the forms of N transported by the woody species (Table 1) (Hansen and Pate 1987; van Kessel and Roskoski, unpubl.: Peoples and Herridge, unpubl.). Hansen and Pate suggest that the technique would have little application for the predominantly amide-exporting acacias in the West Australian eucalypt forests. The forest legumes *Bossiaea, Kennedya,* and *Hardenbergia* were found to export ureides.

A comprehensive survey of tree and shrub legumes to identify the principal N transport compounds for both N_2-fixing and mineral-N dependent plants is needed.

Once these compounds are known, the next step is to calibrate the relationship between symbiotic dependence and solute composition. Unfortunately, this probably will be a long-term exercise, given the perennial nature of the majority of the woody species.

Advantages of N solute analysis. Technically, the collection of xylem contents is very simple. The analysis of the N-components of sap (i.e., ureides, total a -amino N, and nitrate) can be done by colorimetric assays in a test tube; expensive, sophisticated equipment is not needed. Many analyses can be performed daily. It is not necessary to dig out legume roots and recover nodules to obtain measures of N_2 fixation (a totally destructive technique). Sufficient sap for analysis can be collected from stem segments and laterals of mature plants, so that destructive harvest of whole plants is unnecessary.

Possible difficulties. Apart from interspecific differences in the forms of transport N, consideration of the effect of physiological, environmental, and nutritional variables is needed before glasshouse-derived relationships can be legitimately applied to field-grown crops. Potential sources of error with the ureide bioassay have been considered in soybean (Table 2). The effect of plant age and time delays in sampling xylem contents by vacuum-extraction were the most serious. It

Table 2. Potential sources of error in the ureide analysis technique for soybean.[a]

Variable	Comments
Plant age	Multiple standard curves have been produced to cover all stages of growth.
Part of stem extracted	Gradients in composition of N solutes occurred prior to R_2. Composition the same whether sap extracted from top or bottom 1/2 of stem or from laterals after R_2.
Vacuum strength	Unaffected between 50 and 80 kPa.
Diurnal effects	Relative ureide index constant between 1000 and 1600 h.
Time delay from plant harvest to exudate extraction from stem	Extraction should be done immediately. Ureide index rises dramatically with time.
Host plant or *Rhizobium* strain effects	Probably insignificant although further testing required.
Varietal differences in location of nitrate reductase	Unlikely to greatly affect ureide index – only nitrate and amino acid components will change.
Storage of exudate	Stable for 4 h at 25 °C, stable in 50% ethanol for 14 d at 25°C. Preferable to keep samples as cold as possible until they can be frozen for long-term storage.
Effect of N stress	Ureide relationships appear to be invalid in N-deficient plants (exudate N contents of less than 45 to 50 µg/ml). Since sap collection should be taken in conjunction with periodic harvests, severe N stress should become apparent from total plant N increments.

[a] From Peoples et al 1987a.

appears that in soybean, the xylem ureide content is dependent upon the stage of physiological development. This has been overcome by calculating age-development correlations (Herridge 1984). Time-related changes in N solutes during sampling can be avoided by vacuum-extracting sap within 5 min of stem decapitation.

The major disadvantage of the N-solute technique is that it is a point rather than a time-integrated assay. If an estimate of seasonal fixation is required, repeated measurements must be combined with sequential sampling for dry matter and total N content. Only then can total inputs of N be determined and partitioned between symbiotic and soil-derived N, according to the estimates of symbiotic dependence.

N difference method

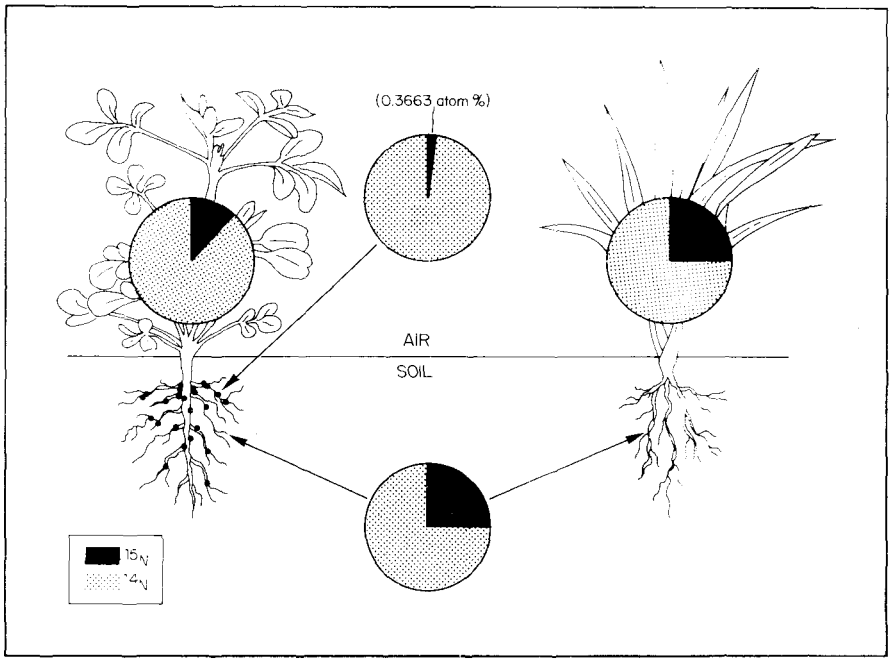
With the N-difference method, the amount of N fixed by a legume is estimated from the difference in N yield between the legume and a non-N_2-fixing reference plant grown in the same soil. The relatively simple procedure commonly is used when only total N analysis is available. A major assumption is that the legume and the reference plant assimilate the same amount of soil N. Various studies comparing several other procedures for measuring N_2 fixation indicate that erroneous estimates may be obtained using N-difference (Ruschel et al 1979). Even when the supposed ideal reference plant (a non-nodulating isoline of the legume) is used, results may be incorrect because of differences in root morphologies (Boddey et al 1984).

An adaptation of the N-difference technique has been used in assessing the potential for N_2 fixation in tree species. Increments of soil N under trees and increments of N immobilized in the plant biomass were evaluated over time (Dommergues 1982). Results using this simple procedure should be treated with caution, since the observed increments cannot be attributed solely to N_2 fixation. Other processes, such as the extraction by roots of N from deep soil horizons or from the water table, could contribute to N accumulation in the soil under the canopy.

^{15}N isotope dilution techniques

The stable isotope ^{15}N occurs in atmospheric N_2 at a constant 0.3663 atom % ^{15}N. If ^{15}N abundance in available soil N is different from that in atmospheric N_2, the proportion of legume N derived from each source can be measured by the isotopic abundances in the nodulated legume and in non-N_2-fixing reference plants totally dependent on the same soil N (Fig. 4). In many cases, the very small differences in natural abundance of ^{15}N between soil N and N_2 can be used, provided the samples can be analyzed with a precise mass spectrometer. More usually, the difference between soil N and N_2 is changed by incorporation in the soil of ^{15}N-enriched or depleted nitrogenous compounds.

Use of ^{15}N-labeled material. The use of methods involving artificial adjustment of soil ^{15}N enrichments with added ^{15}N-labeled material has greatly increased over the past decade, and the principal methodology of ^{15}N labeling techniques has been discussed in a number of reviews (Bergersen 1987a, Chalk 1985, Ledgard and Peoples 1987). The major assumption inherent in ^{15}N methodology is that the legume and reference plant absorb the same relative amounts of N from added ^{15}N and soil N. Its main advantage is that it provides a time-averaged estimate of the



4. Principles involved in the ^{15}N isotope dilution technique. Dillution of soil N by atmospheric N_2 is represented as a reduced area in the ^{15}N sector of the leguminous plant.

proportion of legume N fixed from atmospheric N_2 *(P),* which is the integral of any changes in plant reliance on the symbiosis that may occur during the measurement period.

The estimate of *P* is often considered to be independent of yield, although it is necessary to measure dry matter and N yield to obtain a measure of the amount of N fixed. The choice of reference plant is the most important single factor affecting accuracy in estimating *P*. A number of studies have shown different estimates of *P* when different reference plants were examined (Ledgard et al 1985b,c; Witty 1983). The differences occur because the legume and reference plant differ in the ratio (*R*) of N assimilated from added ^{15}N-labeled N to N assimilated from indigenous soil N. Differences in *R* may be due to differences in plant uptake of N from different soil depths, where there are differences in the isotopic composition of available soil N, or to differences in patterns of N assimilation over time, in association with time-related changes in the isotopic composition of available N.

Depth and time variations in the ^{15}N concentration of soil N probably occur in most field experiments. Where the legume and reference plant are imperfectly matched, the magnitude of the error in estimating *P* will depend on the rate of change in the ^{15}N concentration of available soil N over time. This is largely affected by the form of ^{15}N used (Ledgard and Peoples 1987).

Field experiments with ^{15}N-enriched materials include studies of pasture and food legumes (Table 3) (Chalk 1985) and a description of the role played by legume

Table 3. Estimates of percentage (*P*) of N fixed by field-grown pasture and crop legumes using natural ^{15}N abundance and ^{15}N enrichment methods.

Legume	Reference plant	Natural ^{15}N abundance		^{15}N enrichment		Reference
		P	SE	*P*	SE	
Pasturelegumes						
Subclover	Ryegrass	93	3	95	1	Bergersen and Turner 1983
Subclover	Ryegrass	85	3	70	4	Ledgard et al 1985b
Subclover	Phalaris	86	4	50	5	Ledgard et al 1985b
Lucerne	Ryegrass	81	7	88	3	Ledgard et al 1985b
Lucerne	Phalaris	64	6	70	5	Ledgard et al 1985b
Crop legumes						
Soybean	Ryegrass	64	-	58	-	Domenach et al 1979
Soybean	Non-nodulating soybean	65	-	62	-	Domenach et al 1979
Field bean	Uninoculated field bean	56	8	50	8	Rennie 1986
Lupin	Wheat	81	4	85	4	Evans et al 1987

green manure crops in a rice rotation (Chapman and Myers 1987). Although ^{15}N-enriched and -depleted materials have been used to estimate N_2 fixation in pot culture (Hansen et al 1987a, Hopmans et al 1983, van Kessel and Nakao 1986), the technique has seldom been used for leguminous trees in the field, presumably because of the difficulty of choosing an appropriate reference plant for woody legumes. Uninoculated treatments have been used with acacia when the soil is devoid of appropriate *Rhizobium* (Cornet et al 1985).

Natural ^{15}N abundance. Almost all N transformations in the soil result in isotopic fractionation. The net effect is a small increase in ^{15}N abundance in soil N compared with atmospheric N_2 (Shearer and Kohl 1986). The small difference in ^{15}N concentration (expressed in terms of parts per thousand or d ^{15}N) has been used to estimate N_2 fixation by legumes in both agricultural systems and natural ecosystems. The technique recently was described in detail (Bergersen 1987b, Ledgard and Peoples 1987, Shearer and Kohl 1986).

Several studies have shown results similar to those obtained with ^{15}N enrichment techniques, with similar precision (Table 3). The technique has demonstrated the effects of soil moisture stress, rhizobia1 strain, inoculation rate, and paddock history on N_2 fixation by crop legumes (Bergersen et al 1985, Ledgard and Peoples 1987, Rennie and Kemp 1983).

The natural ^{15}N abundance method gives an average estimate of changes in *P* over time. It has the advantage that it can be applied to already established experiments; no pretreatment is necessary, as with ^{15}N enrichment methods.

Although the principles of the techniques are similar to those of ^{15}N enrichment, the major limitations are different. An isotope ratio mass spectrometer capable of accurately measuring differences of 0.1 part per thousand (about 0.00004 atoms % ^{15}N) is needed. Great care is needed in sample preparation to avoid isotopic fractionation; contamination by ^{15}N-enriched material must be rigorously avoided.

Table 4. Advantages and limitations of methods for estimating N_2 fixation by legumes in the field (Ledgard and Peoples 1987).

Advantages	Limitations
Acetylene reduction method	
Relatively inexpensive Simple Rapid Very sensitive	Indirect (must establish conversion factor for N_2 fixation, which may vary) Acetylene may inhibit nitrogenase activity. Short-term estimate Unless using an in situ assay, incomplete recovery or damage of nodules can cause considerable error.
N-solute method	
Inexpensive Simple Analyses done by simple colorimetric assays Need not be totally destructive May be done on an individual plant basis Assesses plant dependence on atmospheric N_2 and soil N	Indirect (must establish calibration with plant N_2-fixing status) Cannot be used for interspecific comparisons without calibrating each species. Calibrations may be influenced by development stage of some species. Cannot be used on some amide-producers. Short-term estimate
N difference method	
Direct Relatively simple Adjusts for soil-derived N	Requires suitable non-N_2-fixing reference plant Legume and reference plant must absorb the same amount of soil N.
Isotope dilution techniques	
Direct Can get time-integrated Estimate of % N fixed	Requires suitable non-N_2-fixing reference plant.
^{15}N enrichment method	
Potentially accurate	Expensive Requires addition of ^{15}N-labeled compound Legume and reference plant must absorb the same relative amounts of N from the soil and added N. ^{15}N enrichment of plant-available soil N can change with depth and time. Reference plant must derive all its N from soil.
Natural ^{15}N abundance method	
No N addition required d ^{15}N of plant-available soil N is relatively constant with depth and time	Relatively expensive Insensitive if d^{15}N of soil nears d ^{15}N of air. Field variability may be large in some cases. May have to allow for isotopic fractionation.

A d ^{15}N of available soil N above 6 parts per thousand is preferable; accuracy in estimating *P* decreases markedly at lower values (Ledgard and Peoples 1987). Low soil ^{15}N abundances have been detected in intensively grazed pastures (Steele 1983).

Considerable spatial variability was found in soil mineral N $\delta^{15}N$ values in a study on shrub legumes in a dry forest environment (Hansen and Pate 1987). However, it is more usual to find relatively uniform enrichments (Shearer and Kohl 1986), with $\delta^{15}N$ values for soil-derived N commonly above 8 parts per thousand in cropping soils (Bergersen et al 1985, Rennie and Kemp 1983). These enable reliable and accurate estimates of *P* to be made.

In studies by Domenach et al (1979) and Ledpard et al (1985a), use of different reference plants did not greatly affect *P* estimates by the natural ^{15}N abundance method. The ^{15}N abundance of available soil N is generally uniform with soil depth (Ledpard et al 1984) and may show little lateral or temporal variation (Bergersen et al 1985, Ledgard et al 1985b). The major limitation of ^{15}N enrichment techniques, choice of reference plant, appears to be relatively unimportant with the natural ^{15}N abundance method.

Conclusion

Advances in the methodology of measuring N_2 fixation in recent years have been considerable, particularly in establishing a better knowledge of the limitations of the various techniques in current use (Table 4). To obtain accurate estimates of N_2 fixation in the field, these limitations must be recognized and procedures used either to reduce their effect or to establish their relative importance in calculating symbiotic activity. This is especially important when the choice of method is restricted by technical, environmental, or cultural factors.

Ideally, two or more methods should be used, and the results related to soil N measurements and plant nodulation. If an overall estimate of the value of fixed N_2 is to be obtained, studies on N_2 fixation also should be associated with research on N transfer or effects on subsequent crops.

The methodology should be chosen in relation to the overall objectives of the study. Sophisticated and elaborate techniques may not be appropriate when only quantitative or comparative determination is needed.

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Notes

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ACIAR-sponsored legume research

E. S. Wallis and D. E. Byth

The research activities of the Australian Centre for International Agricultural Research on crop and forage legumes in Asia, plus related research projects in plant nutrition, rhizobiology, and soil science are summarized. The food legume program currently centers on soybean, mungbean, peanut, and pigeonpea. A project involving cowpea was completed recently. The countries now involved in the program are Indonesia, Thailand, India, and Fiji. Activity in the forage program is still in development. Support for several new projects is being considered. Current projects include studies on multipurpose shrub legumes and an umbrella project for liaison among forage researchers in Asia.

The Australian Centre for International Agricultural Research (ACIAR) supports a wide range of collaborative research projects in the general area of food and fodder legume adaptation and productivity. ACIAR gives preference to areas in which Australia has a comparative scientific advantage; this is clearly the case in legume research.

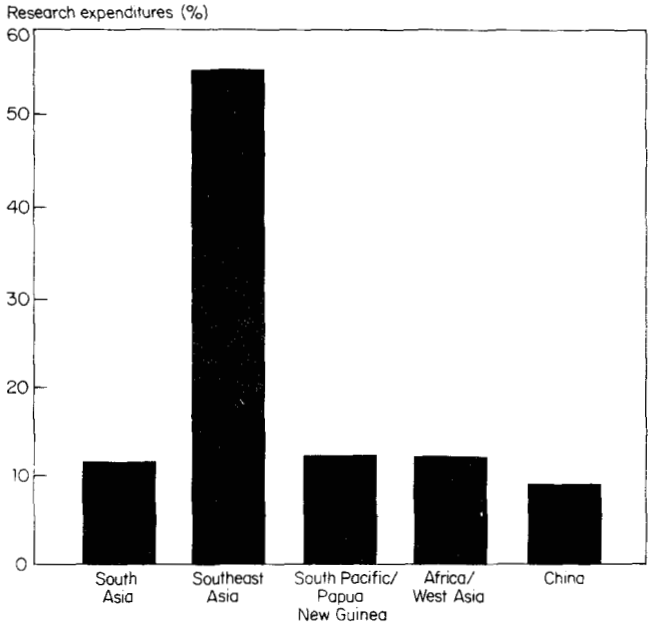
More than half of ACIAR's projects are in Southeast Asia; the remainder are divided among South Asia, South Pacific/Papua New Guinea, Africa/ West Asia, and China (Fig. 1). Distribution of research projects within the various research programs of ACIAR (Fig. 2) and among commodities (Fig. 3) indicates that legumes attract about one-fifth of ACIAR's total research resources. This reflects Australia's scientific competence and the priorities of the collaborating institutions.

This paper outlines the current program, with a brief description of each project. The projects within the overall program are described in Figure 4, which also outlines the interactions possible among the individual projects. A project based at Khon Kaen University, which was completed in August 1986, is included because it is relevant to the objectives of this symposium.

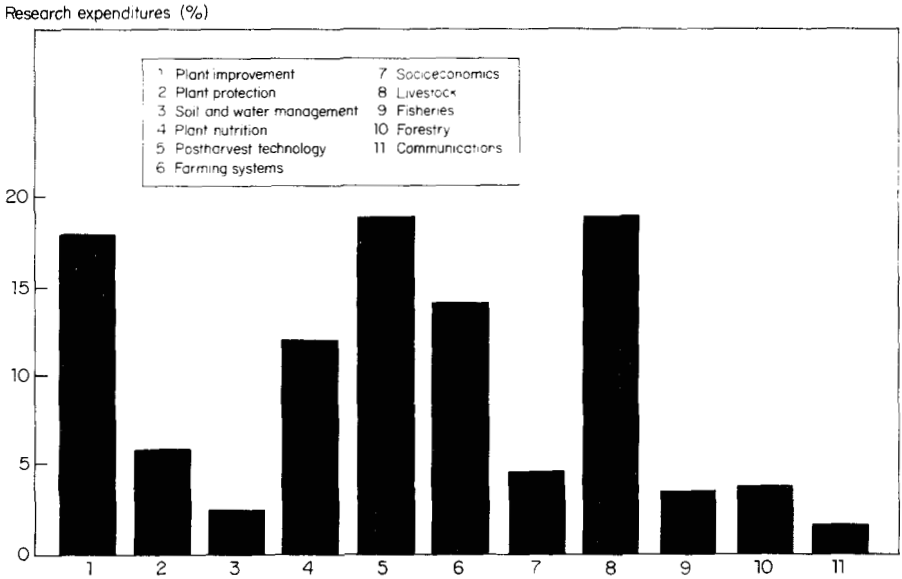
The food legume improvement program

Legumes in Farming Systems in Northeast Thailand (Aug 1983 - Aug 1986)

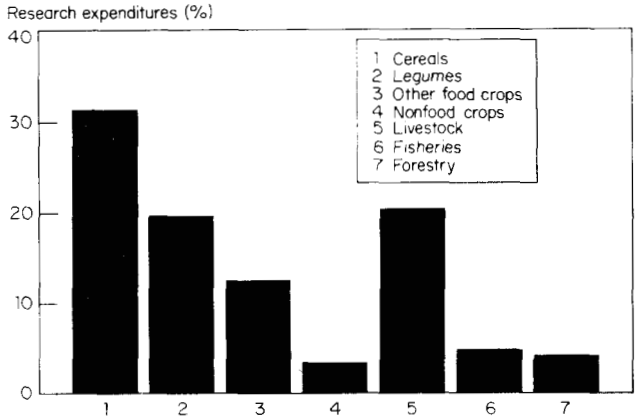
Objective. To facilitate the introduction of legumes into the farming systems of northeast Thailand via research on cowpea improvement, forage and pasture



1. Distribution of the Australian Centre for International Agricultural Research (ACIAR) research expenditures by region, March 1986.



2. Distribution of ACIAR research expenditures by program, March 1986.



3. Distribution of ACIAR research expenditures among commodity groups, March 1986.

legume improvement, and seed production systems for pasture legumes. Complementary studies on legume plant protection and plant nutrition, and integration of legumes into the cropping systems of northeast Thailand were included.

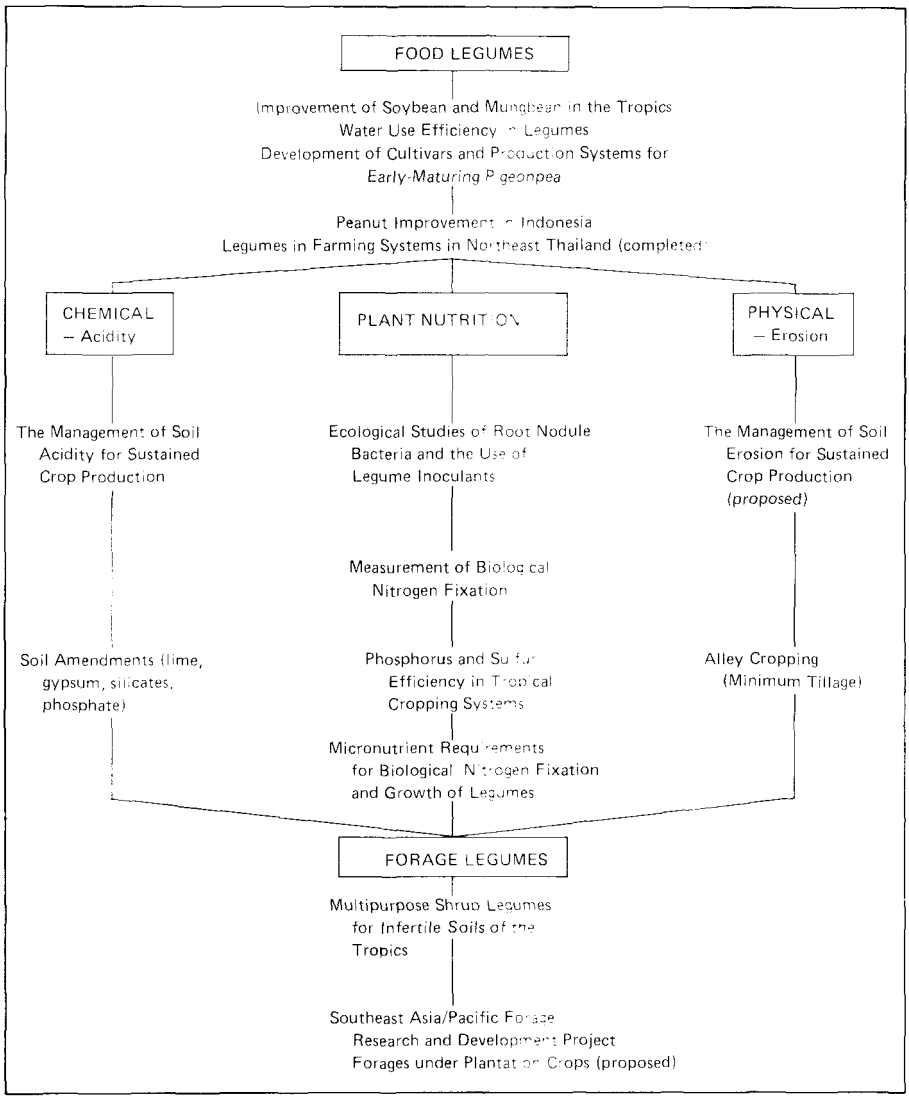
Description. Many uplands with tropical savanna climates in Thailand and elsewhere are producing progressively less food because continued cropping reduces soil fertility. Scientists at Khon Kaen University in northeastern Thailand had begun research on legumes to increase soil nitrogen content, using both high-protein food crops (such as cowpea) and fodder legumes to improve output from the large population of farm animals.

The project sought to assemble or expand collections of cowpea *Vigna unguiculata, Stylosanthes* species, and *Leucaena leucocephala,* to identify genetically elite material, and to develop locally applicable seed production systems. It included supporting studies on the limits imposed by mineral nutrition on legume performance, together with some aspects of systems integrating fodder legumes with kenaf and cassava crops.

Cowpea, at present not a major crop in Thailand, performs well as a short-season crop, with better drought resistance than mungbean or soybean for the uncertain period before the monsoon (opening rains). Its seed has satisfactory flour-milling quality, and Khon Kaen University staff have developed recipes with good local acceptance.

A large collection of cowpea genotypes was gathered from sources such as the International Institute of Tropical Agriculture in Nigeria and Australia. Selection criteria included pod and seed yields, milling quality and acceptability, maturity type, resistance to pests and diseases, nodulation type, nitrogen yield, and nutritive value. After primary evaluation at Khon Kaen, the Thai Department of Agriculture (TDA) assisted in district evaluation trials of elite material and in seed multiplication.

Fodder legume improvement studies were directed primarily at shrub legumes and the genus *Stylosanthes.* At the time, *S. hamata* cv. Verano, *S. humilis* CPI



4. Research on legumes with ACIAR.

161674, and *S. scabra* cv. Seca showed field resistance to anthracnose in Thailand. This plant disease—a major problem in Thailand-devastated *S. guianensis* cv. Schofield in 1982; the relatively newly released cultivar Graham had lost its early resistance. The Commonwealth Scientific and Industrial Research Organization (CSIRO) Division of Tropical Crops and Pastures provided elite breeding material of Graham/Tardio crosses for evaluation (additional Tardio material had been obtained from Brazil and elsewhere).

Shrub legumes have great potential as a source of high-protein fodder (especially in the dry season) and fuel, and as a means of soil nitrogen accretion. In early evaluation trials, leucaena *L. leucocephala* gave the best yields and showed the best survival. The leucaena collection in Thailand was expanded and exploited, using such selection criteria as branching habit, adaptation to low-fertility soils, ease of nodulation, fodder yield, nitrogen production, and, especially, seedling vigor. Slow initial growth is a major constraint to more widespread use of leucaena.

A newly established Thai seed production Industry achieved considerable success with *Stylosanthes hamata* cv. Verano and *S. humilis.* Research on *S. guianensis* at the University of Queensland had identified a long day short day response (plants require long days before short days for flowering) that has many field implications. This has been further investigated, primarily at the University of Queensland, St. Lucia. *Macroptilium atropurpureum* cv. Siratro also has potential as a seed crop. The project included further research on this and other possible seed crops.

Supporting studies covered mineral nutrition of legumes, with special reference to soil fertility and agronomic constraints limiting the integration of legumes and field crops in farming systems.

Soybean and Mungbean Improvement in Thailand (Jan 1986-Dec 1988)

Objective. To increase soybean and mungbean production in Thailand through higher yields and performance stability.

Collaborating institutions. In Australia, the Division of Tropical Crops and Pastures (DTCP), CSIRO, St. Lucia, Brisbane; in Thailand, the Field Crops Research Institute (FCRI), Department of Agriculture, and Kasetsart, Khon Kaen, Chiang Mai, and Prince of Songkla Universities.

Leaders. Dr. R. J. Lawn and Dr. B. C. Imrie, DTCP, CSIRO, in Australia, and Dr. Vichitr Benjasil, FCRI, in Thailand.

Description. This project arose from a request of TDA to ACIAR for a collaborative project on improvement of tropical food legumes in Thailand. At a planning meeting in Bangkok (ACIAR Proceedings No. 8), soybean and mungbean were identified as the food legumes of highest priority. Both are important components of Thailand's agricultural production, but both field well below their potential, with large seasonal and regional variability.

Both crops are grown mainly as a source of high quality vegetable protein, although soybean *Glycine max* is also a valuable source of vegetable oil. Mungbean, of which two species are grown—green gram *Vigna radiata* and black gram *V. mungo*—is widely used as a sprouting bean and is a much-valued source of starch for noodles. Soybean meal is used extensively in the production of concentrated animal feeds.

Thailand exports substantial quantities of both green gram and black gram, but imports part of its soybean consumption. Soybean and mungbean are grown over a range of latitudes and seasons in Thailand. Both fix nitrogen, and therefore are important components of crop rotations.

Research focuses on increasing soybean and mungbean production through higher yields and performance stability. It proposes collaborative research in two complementary areas—manipulating germplasm (breeding/genetic/physiological studies to develop better-adapted cultivars with higher yield potential) and manipulating the environment (agronomic/physiological studies to develop, in the context of Thai agriculture, appropriate management strategies to minimize environmental constraints thus permitting better performance of current germplasm).

The basic philosophy is that applied breeding and agronomic studies should be supplemented with more basic research designed to improve understanding of the factors contributing to crop adaptation and performance, if the implications of the applied studies are to be fully understood. This project provides a vehicle through which applied work of TDA can be supplemented with Australian expertise and research in a coordinated program with contributions by TDA, several universities, and CSIRO.

The emphasis is on improving climatic adaptation, although other yield-limiting factors, such as disease, will be addressed.

Many of the problems in improving the performance of the crops in Thailand are similar to those in northern Australia. The project will provide the opportunity to draw on Australian research experience and technology for the benefit of the Thai programs. Specifically, through collaborative research, the project will facilitate the development and exchange of improved germplasm and the sharing of research concepts and experience. Collaborative research will be conducted in both Thailand and Australia, with regular exchange of scientists in both directions.

Studies on adaptation, breeding, and agronomy will be conducted in Thailand, with supporting research in Australia on the genetics and physiology of adaptation.

Aspects of climatic adaptation that will receive research emphasis are sensitivity to photoperiod and temperature—which influence adaptation to latitude and season of sowing—and tolerance for or resistance to such environmental stresses as temperature extremes, weather damage, drought, and waterlogging, which influence performance in specific environments. Material wil1 be evaluated to identify differential responses to those factors. Studies will investigate the physiological and genetic bases of those differences and evaluate their implications for breeding and agronomy.

On the breeding side, emphasis will be on breeding varieties more tolerant of the major constraints to yield. Lines showing promising response for the various factors will be used as parents in the breeding programs. Information generated in the adaptation studies will be used to design efficient screening methods to readily identify and select breeding lines with improved performance.

In addition to climatic factors, other constraints to be considered in the breeding studies are diseases, such as bacterial pustule and anthracnose in soybean and *Cercospora* leaf spot and powdery mildew in mungbean. Known sources of resistance will be included in the breeding program.

On the agronomic side, studies will evaluate appropriate management strategies for target regions, seasons, sowing times, spatial arrangement, and water management to optimize performance and minimize constraints.

Soybean research within TDA will center at the Mae Jo Field Crops Research Centre (FCRC) in Chiang Mai, with additional sites for adaptation studies at Sukothai and Nakhon Sawan FCRC. Studies on cool temperature tolerance will be conducted by Chiang Mai University, Khun Pae. Studies to exploit the adaptation of soybean to saturated soil will be conducted at Chainat and at Kasetsart University, Kampangsang. Coordinated studies on disease will be conducted at Lop Buri, Mae Jo, and Sukothai FCRC; Khon Kaen University; and Kasetsart University.

Mungbean research within TDA will center at Chainat FCRC, with additional sites for adaptation studies at Phitsanulok FCRC and in cooperation with Prince of Songkla University at Hat Yai.

In Australia, research on both crops will be based at laboratories in Townsville and Brisbane, with field testing at tropical and subtropical sites accessible from these laboratories and at sites in Northwest Australia. Collectively, the field sites in Thailand and Australia sample a 7-28 degree latitude range.

The results of the proposed work are expected to improve performance of both soybean and mungbean and to increase reliability of obtaining economic yields under the different seasonal conditions of the regions and production systems in which these crops are grown. Although the focus of the project is primarily in Thailand, the research should produce results and germplasm relevant to other Southeast Asian countries that share similar problems on these crops and to Australian crop production. The benefits are expected to be more productive varieties and more efficient production systems, based on better knowledge of crop adaptation and agronomy and on carefully targeted breeding and selection work.

Peanut Improvement in Indonesia
(Oct 1985-Sep 1988)

Objective. To improve peanut yield in Indonesia via research into genetic adaptation and breeding, crop agronomy, and plant pathology.

Collaborating institutions. In Australia, the Queensland Department of Primary Industries (QDPI): Department of Agriculture, University of Queensland: in Indonesia, the Agency for Agricultural Research and Development, through the Central Research Institute for Food Crops (CRIFC), Bogor.

Leaders. In Australia, Dr. V. E. Mungomery, QDPI: in Indonesia, the Director of CRIFC.

Description. The peanut is a major food legume in Indonesia and is used almost entirely for human consumption. Annual production is about 0.5 million t unshelled nuts from 550,000 ha, with yields ranging from 0.9 to 1.6 t/ha. In the current 5-yr plan, the Government of Indonesia is emphasizing research on peanut as one of the major secondary (nonrice) crops. Production is projected to expand at about 5% yr. The project is intended to assist Indonesia in raising production, both in the major production areas in Java (60% of current production) and in relatively newer areas outside Java.

In discussions between Indonesian and Australian scientists, it was agreed that collaborative research will be undertaken in both countries on three main areas: genetic adaptation and breeding, crop agronomy and crop water use, and plant

pathology. The ACIAR project for peanut improvement in Indonesia will assist with identifiable components of the Indonesian program on peanut research.

Research will be conducted by institutes under CRIFC. The genetic adaptation, breeding, and crop agronomy sections will be based at the Malang Research Institute for Food Crops (MARIF), and the pathology component will be at the Bogor Research Institute for Food Crops (BORIF).

Applied field studies of cultivar adaptation and crop agronomy (including the effects of moisture stress) will be conducted initially in East Java, and in subsequent years at other sites throughout Indonesia. Simple preliminary factorial experiments in each area will assess factors limiting peanut yields during the wet and dry seasons. Knowledge of the potential growth and development under relatively nonlimiting conditions of a wide range of indigenous and international germplasm is important; yield reductions caused by various constraints can then be assessed.

Studies in fertilized, irrigated, and (in as far as possible) disease-free situations will assess the yield potential of both local and introduced germplasm in 4 sowings during the first 12 mo. Subsequently, more detailed experiments will investigate cultivar × density × arrangement interactions at appropriate sowing dates and other yield-limiting factors identified in the preliminary studies.

The importance of diseases as factors limiting peanut production will be assessed initially in disease survey plots established in the wet and dry seasons at several sites throughout Indonesia. Subsequent characterization of the causal agents will be carried out as necessary. Appropriate disease control practices compatible with Indonesian cultural conditions will be developed.

Local and introduced germplasm will be screened for resistance to important diseases, particularly bacterial wilt. Breeding populations will be developed to combine disease resistance with other desirable traits and to determine the inheritance of bacterial wilt resistance.

The Indonesian program will be supported by research in Australia on ecophysiological adaptation (particularly with regard to temperature, photoperiod, and water relations), water stress physiology, and foliar diseases. Research in both countries will contribute to the development of a peanut yield prediction model. The Australian program will be conducted by QDPI scientists and by scientists at the University of Queensland. The project will collaborate with the ACIAR project "Water Use Efficiency in Tropical Legumes" at the Australian National University.

The project is expected to provide a sound basis for breeding improved peanut cultivars and for developing appropriate agronomic and disease management systems in Indonesia and Australia. Central to these objectives is the development of an improved understanding of the adaptation of peanut to the tropics and subtropics.

Water Use Efficiency in Food Legumes
(Jun 1985-May 1988)

Objective. To assess the potential for using measurements of the relative abundance of carbon isotopes in plant tissues in determining the water use efficiency (WUE) of a range of legumes.

Collaborating institutions. In Australia, the Research School of Biological Sciences (RSBS), Australian National University; overseas, via the Peanut Improvement Project.

Leader. Dr. G. D. Farquhar, RSBS, Australian National University.

Description. Shortage of soil moisture often limits legume yields in semiarid areas of the tropics and subtropics. This is an active area of research internationally. In 1984, ACIAR funded a preliminary study to evaluate a method, developed at RSBS, of estimating variability in WUE of tropical legumes. This preliminary phase led to the development of a second, 3-yr phase beginning 4 Jun 1985.

The technique developed by Farquhar and others measures the relative abundance of stable isotopes of carbon (C-12 and C-13) in plant tissues and uses this measure to screen for improved WUE by crops. It is based on the principle that the enzyme in the chloroplast, which catalyzes the fixation of CO_2 by photosynthesis, discriminates against heavier molecules containing C-13 by reacting 3% more slowly than with molecules containing C-12.

This discrimination is measured (using a ratio mass-spectrometer) as a depletion of C-13 in plant material compared with that in the atmosphere. Stomatal closure ensures that discrimination has more nearly the value associated with diffusion through pores, thought to be about 0.4%. Carbon isotope composition of plant material thus reflects the degree of closure of stomata in relation to the capacity for photosynthesis.

The vast majority of the water used by plants during growth is evaporated through the stomata because the air spaces inside the leaf have a much higher humidity than the atmosphere. Because stomatal closure reduces water loss and increases the proportion of 13-CO_2 molecules fixed, measurement of isotopic composition enables assessment of the efficiency with which water has been used by the plant for growth.

The technique was tested on a number of plant species in the laboratory and on parasitic mistletoes and their host trees over a large area of arid Australia. It reflected differences in WUE among wheat genotypes in the glasshouse.

With ACIAR support, the technique is being applied to assess variability in WUE in tropical food legumes. Species tested so far include peanut, mungbean, pigeonpea, and cowpea.

In the case of peanut and some related species, considerable variation in isotopic composition was observed, corresponding theoretically to a range of WUE greater than 50%. A selection of peanut lines w as grown in pots in the glasshouse and WUE measured directly. The range did exceed 50%, and WUE was closely correlated with carbon isotope composition. Genotypes with contrasting WUE are now being crossed to assess the nature of its inheritance.

Problems with the techniques are related to the speed of sample processing. More rapid methods of analyses are currently being investigated.

The results to date have been most encouraging; it is hoped that the measurement of carbon isotope composition can be used in the ACIAR Food Legume Program soon, to assist in selecting genotypes of some food legumes for increased WUE.

Pigeonpea Improvement (Dec 1985-Nov 1988)

Objective. To define the scientific bases of high seed yield potential of short-season pigeonpea, and the factors limiting productivity and adaptation in Fiji, Indonesia, India, Thailand, and Australia.

Collaborating institutions. In Australia, the Department of Agriculture, University of Queensland; overseas, the Ministry of Primary Industries (MPI), Fiji; the Agency for Agricultural Research and Development through CRIFC, Indonesia; Directorate of Pulses Research (DPR), Indian Council for Agricultural Research (ICAR), and FCRI, Thailand.

Leaders. In Australia, Dr. D. E. Byth and E. S. Wallis, University of Queensland; overseas, P. Sivan, MPI, Fiji; the Director, CRIFC, Indonesia; Dr. J. N. Sachan, DPR, India; and Dr. Vichitr Benjasil, FCRI, Thailand.

Description. Phase I was completed 30 Nov 1985. In September 1985, a review team recommended a second 3-yr program on pigeonpea improvement. This second phase now incorporates the recommendations of the Phase I Review. Collaborative research on pigeonpea improvement will continue in Indonesia. Fiji, Thailand, and Australia, with close collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Phase I showed that pigeonpea has potential in those countries. The extension will address the problems that remain to be solved, with collaborative research extended to include India, where pigeonpea occupies 2 million ha. Early-flowering, photoperiod-insensitive, high-density monoculture comprises only a small part of current production there, but is expanding rapidly.

In Fiji, research to determine the factors causing flower drop and subsequent poor pod retention in some genotypes will continue. Genetic studies will include identifying germplasm resistant to a disease complex that includes a stem canker caused by *Botryosphaeria santhocephala* and *Xanthomonas* sp., the mode of inheritance of this disease, and incorporation of resistance into adapted genotypes. Management of the crop and of its adaptation and productivity on acid, low-fertility soils with high aluminum saturation will be emphasized.

In Indonesia, Phase I revealed considerable potential for pigeonpea production. Phase II will continue the research into adaptation and productivity, particularly on the outer islands where acid soils are important limitations. Pigeonpea is basically a new crop in Indonesia, except for small areas of traditional cultivation for use as a green vegetable. Studies of other uses of pigeonpea seed that were initiated in Phase I will be continued and expanded in Phase II.

In particular, pigeonpea has major potential as a substitute for soybean in the production of tempeh, which absorbs about 1.2 million t of soybean annually. Indonesia is not self-sufficient in soybean; locally produced pigeonpea could substitute for imported material, or could supplement soybean production. Phase II will also examine the new crop's potential as a component of poultry rations. This research may best be undertaken in Thailand and Australia, where appropriate expertise is available, and transferred to Indonesia later.

In Thailand, Phase I research clearly indicated a potential for pigeonpea, especially in the northeast, and as an intercrop with rubber in the south. Phase II

research will concentrate on northeastern Thailand to address the limitations identified there—adaptation and productivity of the crop on low-fertility, acid soils and appropriate control methods for pests (and possibly diseases). The research will evaluate pigeonpea as food, feed, and export crop, and will incorporate an economic analysis by ICRlSAT of its production in borne farming systems.

The addition of India to the project offers an opportunity for detailed research into factors influencing short-season pigeonpea yield, in collaboration with ICAR. 1CAR's institutes and a number of universities maintain large pigeonpea programs, offering significant discipline-based knowledge and experience with the species. The research will exploit this capability in investigating yield accumulation, productivity limits, and use of short-season pigeonpea in a wide range of Indian farming systems.

In Australia, detailed studies will continue in two major areas: agronomy/ physiology and plant breeding/genetics. With Phase I data, research in agronomy and physiology will assist in developing a growth model for early-season pigeonpea. Research will address such specific factors as nitrogen fixation and its contribution to crop rotations, water stress, low radiation, and low temperature. Breeding and genetic studies will concentrate on improving the understanding of inheritance of important characters and on methods of incorporating them into improved genotypes. Continuing analyses of multienvironment adaptation will also contribute to development of the model.

Close collaboration with ICRlSAT will continue, particularly in pest and disease control and in the ICRISAT Asian Grain Legume Program.

Effective interaction of collaborators, both in Australia and overseas, during Phase I proved effective and creative. It will be continued and strengthened during Phase II.

Food Legume Constraints and Strategies for Improvement

More than 300 participants from 18 countries and 9 international organizations attended the ACIAR-sponsored Workshop on Food Legume Improvement for Asian Farming Systems in Khon Kaen, Thailand, 1-5 Sep 1986. The theme was limitations to productivity and adaptation of food legumes for farming systems of Asia. Because the intention was to avoid being crop-specific, country-specific, or discipline-specific, the workshop took an integrated look at the factors limiting food legume production in Asian farming systems and discussed their resolution. Increased food legume production has been, and will continue to be, of vital importance to the countries and scientists of the region.

The workshop addressed the basic theme in a number of ways. The 16 invited papers covered the major limits to productivity and adaptation, as well as the role of the legume crops in the farming system. The 140 contributed papers addressed the major limitations and aspects of legumes in production systems. A poster session encompassed the research, training, and publication activities of various institutions in the region. A field tour of the region around Khon Kaen was designed to observe some regional limitations to legume crop improvement and to inspect aspects of research aimed at their resolution. At concurrent plenary forum sessions, the major issues and potential resolutions were raised.

Food legumes are, and will remain, important components of Asian farming systems. Legume crops in Asia commonly are secondary to the major cereal crops and therefore are relegated to marginal land, with little if any inputs. Food legumes received little government support and, in part because of this, are perceived by farmers as low-yielding. high-risk crops. The situation is likely to continue in the foreseeable future unless government policies are changed to encourage production through incentive schemes such as those currently operating for many other crops.

These problems are compounded by the large number of legume crops grown in Asia and by the limited scientific knowledge available about them compared with the major cereal crops. A multidisciplinary team approach is necessary, with teams involving appropriate scientists from local, national, regional, and international research institutions. Institutional interaction may have to be modified to ensure an appropriate system of rewards and incentives to encourage collaboration among all levels of research and extension.

Resources for research into the tropical food legume crops are limited; coordination and collaboration should avoid unnecessary duplication. Integrated research into common mechanisms and problems across crops may be possible. It may be possible to centralize appropriate research into universal problems, dovetailed with local evaluation. While problems of local significance, which reveal large environmental interactions, will require devolution of research, close collaboration across the research sectors is necessary.

In principle, no fundamental differences in constraints to food legume productivity and adaptation were recognized between irrigated and rainfed farming systems. However, certain special aspects of the irrigated rice system were noted, including a lower incidence of soil-borne disease organisms, modified soil chemistry, and water stress related to soil compaction.

The question of the appropriate nature of the environments for selection and testing was debated at length, and divergent views were expressed regarding use of testing in controlled environments vs testing in farmers' fields. It was noted that the primary objective must be effective discrimination among genotypes for the character and system of interest, and management should be used as necessary to accomplish that. Crop improvement within the low input/low output systems may emphasize genetic resolution. Coordinated cross-disciplinary research into production system-neutral vs technology-dependent objectives was discussed.

A fundamental difficulty was identifying and defining major farming systems, the roles of legume crops within them, and the primary constraints to crop productivity and adaptation. Dynamic crop production models were considered useful in identifying the primary limitations and in guiding research strategies.

The traditional strong disciplinary focus in research organization and conduct was seen to be a fundamental constraint to crop improvement. An integrated, multidisciplinary approach to research into legume crop improvement was considered desirable and appropriate.

The forage legume program

Multipurpose Shrub Legumes for Infertile Soils in the Tropics (Dec 1985-Nov 1988)

Objectives. To evaluate the performance of a range of shrub legumes in diverse soil and climatic environments, to characterize their nutritional requirements, and to define the soil factors limiting their growth.

Collaborating institutions. In Australia, CSIRO DTCP, Brisbane; in Indonesia, Balai Penelitian Ternak (BPT), Gawi.

Leaders. In Australia, Dr. R. Bray, DTCP; in Indonesia, the Director of BPT.

Description. Many tropical countries use shrub legumes as multipurpose plants—for fodder, living fences, hedges, shade, fuel wood, and erosion control and as a source of nitrogen for other crops. In southern Philippines and eastern Indonesia, widely adopted alley cropping systems based on shrub legumes are among the few sustainable food production systems. However, shrubs such as *Leucaena* spp. that are adapted to neutral to alkaline soils do not thrive in the acid soils covering most of the tropics; new lines are needed. Australia has one of the largest collections of *Leucaena* germplasm in the world, and a substantial collection of other shrub legumes. An ongoing program studying such species is designed to identify elite lines and hybrids for further testing.

This project will seek to identify and provide high-yielding shrub legumes for a broad range of environments in developing countries. It will cover a broad range of species, including selected lines of *Leucaena, Acacia, Gliricidia, Calliandra,* and *Sesbania,* initially provided from Townsville. Any promising local selections (of any genus) could be included.

Research will concentrate on three goals: to evaluate the performance of these plants in diverse soil and climatic environments (multisite testing), to characterize their nutritionalrequirements and define the soil factors limiting their growth, and to provide and maintain improved genetic resources of shrub legumes.

Multisite shrub legume trials in progress as part of the Indonesian Forage Research Project (which involves UNE with Australian Development Assistance Bureau [ADAB]) have already provided substantial evidence of species × site interaction. In cooperation with that group, the ACIAR team will utilize some or all of their present test sites. Additional sites are planned in cooperation with other Indonesian research organizations and in the Philippines, Thailand, Malaysia, and northern Queensland. Ten sites covering a range of soil and climatic conditions are envisaged.

The experiments will relate the performance of various species to chemical and physical characteristics of the sites to determine the best species for each site and to provide more precise selection criteria for future work. Morphological and analytical chemical descriptions of the experimental sites will be prepared in conjunction with soil scientists in the countries concerned.

In characterizing nutritional requirements of shrub legumes, the team will give priority to identifying the role of factors likely to be involved in soil acidity limitations to plant growth-namely, low phosphorus, calcium, magnesium, and molybdenum; low soil pH; and aluminum and manganese toxicities. A major aim will be to identify soil or plant diagnostic criteria that can be used to predict the performance of a species.

A study of these aspects in the glasshouse in Brisbane will involve a small range of shrub legumes with known, contrasting tolerances for acid soils. Feedback between this work and the multisite trials will facilitate choices of appropriate species and detailed examinations of reasons for the success or failure of any species at a particular site.

DTCP already has considerable genetic resources, with one of the largest collections (700 accessions) of *Leucaena* in the world and a much smaller one of other shrub legume genera of potential value. These collections, held at the Lansdown Research Station near Townsville, will be used to provide improved genotypes to extend the climatic and edaphic range of the shrub legumes. New accessions will be sought, especially in the *Gliricidia* and *Calliandra* genera; these will be described and their seed multiplied.

Seed of promising genotypes identified in the multisite trials will be multiplied. Testing of accessions will include monitoring their quality as animal feed to ensure that selected lines are neither toxic nor unpalatable.

The project will especially benefit farmers in marginal areas with low soil fertility—often the poorest farmers—but will also have wider application throughout the region.

The Southeast Asia/Pacitic Forage Research and Development Project (Dec 1985 - Nov 1988)

Objective. In collaboration with ADAB, to develop the research capability of forage scientists via germplasm exchange, information dissemination, and visits.

Collaborating institutions. In Australia, DTCP, CSIRO, St. Lucia; in other countries, forage research institutions in Australia, Fiji, Philippines, Thailand, Malaysia, and Indonesia.

Leader. T. R. Evans, DTCP.

Description. Southeast Asian and western Pacific countries share a growing interest in pasture and forage production and its utilization by ruminants. The increasing numbers of scientists and research centers active in these fields have been handicapped by a lack of regular access to information on new developments and of opportunities to discuss problems of mutual interest.

In 1984, ADAB and ACIAR jointly commissioned a feasibility study to assess pasture and forage research in the Philippines, Thailand, Malaysia, Indonesia, and Fiji, and to establish a regional forage research network. (Other Pacific islands with no identifiable forage research programs are included in seed distribution and communication activities and are encouraged to participate in developing regional interaction.)

Although the selected countries have a wide climatic diversity (mean annual rainfall ranges from 570 to 7,000 mm), similarities exist: central and eastern Indonesia, northeast Thailand, and the western parts of Luzon and Visayas in the Philippines share distinct wet and dry seasons; west Indonesia, southwest Thailand, Malaysia, Fiji, and eastern parts of the Philippines have either a short dry season (2-3 mo) or no dry period. Many common soils occur throughout the region, and similar soil chemical and physical attributes are widespread.

Thus, results from location-specific research can have relevance to a much larger area. Major constraints to utilizing knowledge is lack of access to research results and lack of communication between scientists and extension workers.

Three major areas of research for improving forage production are common to all the countries: backyard or small-holder farming systems, extensive native pastures, and use of forage crops in intercropping systems, including plantations.

This project, sponsored jointly by ADAB and ACIAR, seeks to catalyze research in pasture and forage production and utilization, support research planning and execution, assist in publication of results, and aid in dissemination of this information to other scientists and extension services within the region. It will absorb the present Pasture Seeds Distribution Project funded by ADAB and operated through the CSIRO DTCP. A computer-based system will record and supply information for both projects.

All the participating countries have difficulties in problem definition and in developing systematic research programs for problem solution. Research appears to be too discipline-oriented. The project will encourage in-country discussions between those involved in setting research priorities and scientists from different disciplines who could contribute to research programs. It will also encourage collaboration within and between institutes.

Improvements in technological capacity will come through four approaches: assistance with choice of experimental design and techniques, with data analysis and interpretation, and with publication of results; training programs and instruction booklets for technicians; removal of constraints imposed by lack of small items or equipment; and visits by specialist consultants.

To aid communication among scientists, the project will establish a database and a newsletter, and will conduct annual workshops. The database will contain a list of scientists, their locations, and their research activities; a record of literature published from within the region; and the proceedings of workshops and conferences. The newsletter will contain abstracts of published literature, technical information, results of work in progress, and reports of research not readily accepted by scientific journals.

Communication between researchers, extension workers, and farmers will also be fostered. Inclusion of extension workers in the annual workshops can help, as will research discussions at the local level. The project will provide senior extension officers with reports on research and its results in layman's terms.

Rationalization of research on a regional basis is a longer-term goal. In some areas such as seed production, the project will encourage research in the country with greatest expertise and the most experience as a regional program. It will also provide

an umbrella for publicizing research results from ACIAR forage projects in the region.

Forages Under Plantation Crops (proposed)

Objectives. Evaluation of forage species from shaded environments and identification of plants whose nitrogen economy and nutritive value is not adversely affected by shade; management of forages to optimize animal and tree crop productivity and conserve soil resources; and study of socioeconomic constraints to the integration of animals into small-holder plantation systems.

This project is in its final draft stage and will be submitted for approval by ACIAR's Board of Management.

Related ACIAR Projects

Ecological studies of root nodule bacteria and the use of legume inoculants. This project has six parts and involves activities in Malaysia, Thailand, Philippines, and Jordan. It is coordinated by Dr. R. Roughley of the New South Wales Department of Agriculture. Crop and forage species covered include peanut, soybean, mungbean, *Leucaena, Pueraria, Centrosema, Stylosanthes,* and *Medicago.* Besides conducting specific research on particular problems associated with both crop and forage nodulation, the project assists the ACIAR Food Legume Program with advice and interpretation of problems identified by collaborating institutions.

Development and evaluation of methods and measurement of biological nitrogen fixation. This project, based at the CSIRO Division of Plant Industry, Canberra, is aimed at developing techniques that will reliably estimate biological nitrogen fixation in food legumes and cover crops in small rubber holdings in Malaysia and in legume intercropping systems in Thailand. The research is designed to estimate nitrogen inputs of both legume crops and cover crops to provide a rational basis for the efficient management of intercrops, their residues, and nitrogen fertilizers.

Phosphorus and sulfur efficiency in tropical cropping systems. These studies based in Thailand and Indonesia are coordinated by Dr. G. Blair at the University of New England. The primary aim is to study the dynamics of phosphorus and sulfur in upland and flooded cropping areas with a view to increasing the efficiency with which crops utilize these nutrients. Crops included are maize, soybean, sweet potato, and rice. Other studies relate to accession rates of sulfur and the establishment of criteria for determining the phosphorus and sulfur status of plants and soils.

Boron and other micronutrients for food legume production. This project replaces an earlier ACIAR project on Micronutrients for Growth and Biological Nitrogen Fixation in Legumes coordinated by Murdoch University. Both projects have conducted research in Thailand and Malaysia. Initially, research was on a range of micronutrients. However, the new project will focus on the role of boron. This change in emphasis is based on the finding that boron deficiency has a significant effect on seed quality and yield of peanut, mungbean, and sunflower, and is relatively widespread in some parts of Thailand. The major objective is to determine the extent, severity, and yield effects of boron deficiency in mungbean,

peanut, and soybean in Thailand. In addition, procedures for the diagnosis, prediction, and correction of boron deficiency in farmers' fields will be developed. Other micronutrients (such as iron, copper, and molybdenum), which have been shown to be deficient for some legume crops in some soils in Thailand, will also be studied.

Management of soil acidity for sustained crop production. This project, based at the University of Queensland and in Malaysia, is aimed at providing a basis for the improved use of acid tropical soils previously regarded as marginal for food crop production. The major species of interest are the food crops maize, soybean, and peanut and the cover crops *Pueraria* and *Calopogonium.* Research will evaluate the responses of these species to the acid soils of Malaysia with and without soil amendment. Studies to examine the relative effectiveness of various indigenous ameliorating agents will also be conducted. An important component will be detailed economic analyses of the required soil amendments to help determine the viability of the cropping systems of interest.

Management of soil erosion for sustained crop production (proposed). This project is awaiting final approval by ACIAR's Board of Management. Coordinated by QDPI, the project will operate in Malaysia, the Philippines, and Thailand. The primary objectives are to develop experience in measuring soil and water loss and rate of runoff from defined cropped areas in a range of cropping systems. The aim is to develop an improved understanding of the principles involved in achieving sustained agricultural production from each cropping system, and in determining alternative systems with greater stability.

Conclusion

Coverage of ACIAR's activities in crop and forage legumes and some related areas here has necessarily been brief; further details are available on request.

Both forage and crop legumes are important parts of the farming systems of Asia. Their roles are highly diverse, and their importance relative to the major cereal crops often discounted. The reputation of the food legumes as secondary crops has created a series of related problems that often tend to further discriminate against these species.

ACIAR is investing significant resources in this area, and welcomes active collaboration with other institutions to ensure the efficient use of resources. Sustained research across a wide range of disciplines on the production, improvement, and use of the crop and forage legumes in Asian farming systems is needed. Major objectives must include identifying the primary limitations to productivity and adaptation, and searching for resolutions of those limitations. ACIAR has a firm commitment to collaboration with national and international research programs in pursuit of these objectives.

Notes

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Effect of green manure on rice soil fertility in the United States

M. P. Westcott and D. S. Mikkelsen

Use of green manure crops in United States rice production is limited; it has declined from about 21 %of the planted area in 1955 to less than 5% in 1987. The high costs of producing green manure N, the need to supplement it with fertilizer N, uncertain green manure performance from year to year, and loss of management flexibility in rice cropping are current constraints. Various leguminous green manure crops, including annual clovers, vetches, lespedeza, winter peas, and fava beans, have been used in areas where they are adapted. Green manure crops and crop rotations have been used to improve the N status of the soil and to facilitate desirable soil management practices. Green manure crops can supply rice with significant amounts of available N, but the contribution depends on the quality and quantity of green manure applied, the time and method of application, soil fertility status of the treated area, the kind of crops grown, and cropping methods. In general, leguminous green manure crops can supply 30-50% of the N required for high-yielding rice varieties.

Rice production in the USA is a highly mechanized enterprise; average farm sizes are 100-250 ha. Although a relatively minor crop on a national scale, rice is of great regional importance in the southern states of Arkansas, Louisiana, Texas, and Mississippi (900,000 ha combined) and in the Central Valley of California (200,000 ha). Production practices and cropping systems vary between the regions, but a common factor is a fall-to-spring period when temperatures are too cold for rice growth and development. This period may be as short as 3 mo in the southernmost area of the southern region, where ratoon cropping is feasible, to 6 mo in the more northern areas. The period between crops provides an opportunity for green manure production as a source of N and as a contribution to soil organic matter status. Although the benefits of green manure have been demonstrated, the practice is currently extremely limited.

Field practices and crop management for rice

Crop rotations

Rotation cropping is a good agronomic practice on rice soils and usually returns reasonable benefits. Benefits include maintenance of soil fertility (organic matter [OM] and N), reduction or control of weeds, and diversified marketing options. It can also provide opportunities for the extensive land preparation necessary for proper water control. Crop rotations must, of course, be adapted to local soil types, climatic conditions, and markets. On clay-textured, poorly drained soils, the expense of land preparation and the low yields of many crops favor long rotations, or even continuous rice. On lighter-textured soils. a greater variety of rotations is possible.

In the Gulf Coast prairie area, riceland may be utilized as pasture 1-3 yr before going back to rice. In other areas of southern U.S. with heavy soils, rice is rotated primarily with soybean and, to a lesser extent, with grain sorghum. Wheat or oats may be grown as double crops during the winter and spring months, although this practice necessitates planting rice late, beyond the optimal dates. On lighter soils, cotton is a high-value rotation alternative.

No definite scheme of rice-based rotation has emerged in California. Cropping patterns range from continuous rice to rotations with oilseed crops, wheat, maize, sorghum, beans, tomato, etc. One widely practiced rotation is to follow two or three rice crops with a summer fallow and fall sown wheat or barley. Another option is to alternate rice with summer fallow, using a spring plow-down of the rice stubble in fallow years. Purple vetch seed may be broadcast on ricefields just before draining for harvest, although this practice has declined in recent years. One drawback to rice rotation is the development of P deficiencies in upland crops on some soils that undergo flooding and drainage cycles (Brandon and Mikkelsen 1979, Sah and Mikkelsen 1986a,b).

Seedbed preparation and planting

In the southern region, seedbed preparation begins in the fall. Rice stubble is lightly disked or rolled flat, then left until spring when fields are more deeply disked (10-20 cm) or, less commonly, plowed. When rice is to be drill-seeded (90-100 kg seed/ ha), a smooth seedbed is prepared. If water-seeded (direct seeding of presoaked seed into floodwater at 120-160 kg seed/ha), the seedbed is left cloddy (1- to 5-cm-diameter clods) or grooved to provide sites for seedling anchorage. In California, rice straw is partially eliminated by burning in the fall or early spring. Soil is cultivated with a chisel or stubble disk or a moldboard plow to 10-20 cm depth, then reworked as required to provide the seedbed described above for water seeding.

Drill seeding requires intermittent irrigation for roughly 30 d before permanent flooding. During that period, the crop emerges and develops to the 4- to 5-leaf stage. If not already in place, levees may be constructed or reinforced during this interim. Water seeding requires prior levee construction to ensure proper water control throughout seedling development. With either seeding system, levees must be sufficiently high (40-50 cm) to maintain floodwater depths of 5-15 cm and to resist

rain and wind erosion throughout the growing season. Levees are constructed by tractor with disk plows, V-dikers, or other special equipment designed to heap soil into suitable forms.

Fertilization

Fertilizer requirements vary with soils, cropping and fertilizer history, rice cultivars, and environmental conditions. In California, rice yields averaging 8.5 t/ha require 90-140 kg N/ha. In the southern region, rice yields averaging 5-7 t/ha generally require 65-90 kg N/ha, although this will likely change with the introduction of higher-yielding cultivars. Needs for P are met with 4.4-13.2 kg P/ha. Where Zn deficiencies exist (Mikkelsen and Kuo 1976), ZnO or $ZnSO_4$ is applied to the soil.

In Mater-seeded fields (including virtually all California rice and an increasing percentage of southern rice), most of the fertilizer N or N-P combination is incorporated or banded 5-10 cm deep in the prepared seedbed before establishment of the permanent flood. Drill-seeded fields in the southern region may have 10-30 kg N/ha applied at seeding as a starter fertilizer; the bulk of the total rate is applied to the soil surface, usually as urea, just before permanent flooding. In either system, a midseason topdressing of N may be applied at the mid-tillering to panicle initiation stage.

Irrigation

Early season irrigation practices are dictated by seeding method. With water-seeding, the fields are flooded at the time of seeding and drained, if at all, for only a few days to allow seedling anchorage and to avoid drift. Otherwise, water levels are maintained 5-15 cm deep throughout growth. Drill-seeding requires a delay in permanent flooding, usually to about 30 d after planting, when plants are 10-15 cm tall and can withstand flooded conditions. Fields may be flushed as necessary for germination before permanent flooding. Once permanently flooded, the crop is treated the same as water-seeded rice. Draining of fields is usually avoided unless problems arise to justify removal of water. Floodwaters are drained 2-4 wk before crop maturity to facilitate crop maturation and mechanical harvest.

Green manure practices and management

Relatively few references appear in the U.S. literature on the use of green manure in rice culture. After World War II, leguminous green manuring utilized primarily vetch (purple vetch or common vetch) and occasionally bur clover (Williams et al 1957). It was estimated that about 21% (150,000 ha) of U.S. rice in 1955 was grown on land treated with green manure crops. Since that time, use has dropped to less than 5% of the rice hectarage.

Crop selection and management

The criteria for selecting a green manure crop include a large yield of biomass in a short time during the cool, early-spring months; a leafy rather than woody plant to ensure rapid decomposition; N_2-fixing capabilities (leguminous); and tolerance for

wet or flooded soil and cold conditions during the winter months. Seed and production costs should be moderate and be offset by yield benefits.

Additional factors to consider include individual grower preference as to ease of incorporation or familiarity with green manure used with other crops. A final consideration, one which perhaps may play the largest role in future uses of green manure, is the reseeding capability of the green manure crop selected. The short-term economics of green manuring do not favor its use unless more than one green manure crop can be produced from a single seeding.

Annual clovers, vetches, lespedeza, winter peas, and fava bean have been the primary green manure crops used in U.S. rice-based cropping systems. Rates of seeding vary considerably with seed size, ranging from 6-17 kg ha for clovers to 40-45 kg/ ha for fenugreek, 34-90 kg/ ha for vetches, and 110-220 kg/ha for fava bean (Williams et al 1957). Inoculation with the appropriate *Rhizobium* species, preferably a commercially prepared inoculum, is beneficial, particularly where the same species of green manure has not been previously grown.

Fava bean *Vicia faba* has been used as a green manure crop in California. *Vicia* varieties flower about 76-80 d after emergence, mature in 142-162 d (Schnurrenberger 1986), and have good N_2-fixing capability. The varieties grown, however, are susceptible to several viruses (beet western yellow, clover redleaf, and legume yellow viruses) and fungal diseases (ascochyta blight, alternaria, root rot, and wilt). Fava bean tested in northern Louisiana gave promising first-year results, but it failed to withstand cold conditions in succeeding years (Westcott et al 1984). The major constraints are that fava bean does not reseed itself, it requires a high seed rate, and seed is relatively expensive.

Vetch as a green manure in California ricefields is normally seeded by airplane before harvest. Williams and Dawson (1980) found that submergence tolerance is important with such a system, and that Lana and purple vetch were superior to common and hairy vetch in this respect. They, identified the period between 2 d before and 2 d after water drainage for harvest as the ideal time for seeding. This technique allows for seedling establishment and growth prior to the onset of cold winter conditions. Vetch has good N_2-fixing capabilities in well-drained soils, but like most other high-yielding legumes, it grows poorly or dies in waterlogged soils (Williams 1963).

Berseem clover *(Trifolium alexandrinum)* was recently evaluated for winter forage green manure and cover crops in California and Louisiana (Graves and Williams 1987, Westcott et a1 1984). It appears well adapted to both regions. Recent tests in Louisiana (Eastman 1986) showed promise for reseeding by subclover if allowed to mature sufficiently (i.e., incorporated 7 May). Flooding of the rice crop appears to induce dormancy in the subclover seeds, but they sprout adequately after drainage for harvest.

These findings give some hope for a long-term benefit from a single seeding of a green manure crop. One drawback is the relatively late date required for green manure incorporation, delaying rice planting. There is some indication that bur clovers may offer much earlier dates for incorporation, setting seed as much as 1 mo earlier than subclovers (S. M. Dabney, pers. comm.).

Azolla filiculoides has received attention as a green manure crop for flooded fields during winter months in California (Rains and Talley 1979; Talley and Rains 1980a,b, 1982; Talley et al 1977). Azolla has produced N yields comparable to those of winter legumes and can be grown in fields too wet for terrestrial green manure species. No mechanized system has been developed for its use, however, and production costs are likely to be greater than for other green manure crops.

Contributions to soil fertility

Long-term cultivation of rice causes marked changes in soil properties related to crop growth. A study of rice soils in Louisiana found that 40 yr of rice cropping on a Crowley silt loam decreased soil N levels from an original 0.20% to 0.08%, and organic matter declined to 1.6%, a value 40% that of the virgin soil (Sturgis 1957).

Crop rotations and crop residue management are major factors affecting the N status of rice and economic production. Legume-pasture rotations (pasture 5-6 yr) have provided soil N levels for optimum fertility. With long periods of cropping to rice, benefits from rotations decline and the dependency on fertilizer N increases. This has been further accentuated by the introduction of short-statured high-yielding varieties that benefit from high levels of available N.

Rotation and green manuring before rice cropping have usually produced highly satisfactory benefits. Direct green manure application to the soil can have several effects, depending on conditions (Oh 1979, Singh 1984): increases in soil organic matter, available N, and other nutrients may occur; N availability may be temporarily reduced; leaching may be reduced and nitrification-denitrification increased; nutrients may concentrate in the plow layer. Green manuring usually does not affect all these soil reactions simultaneously, and sometimes may not have any effect.

The availability of N from green manure crops, which is a primary benefit, depends on four factors: 1) green manure quality and quantity, 2) time and method of application, 3) soil fertility status, and 4) kinds of crops and cropping methods.

Simultaneous increases in both N availability and soil organic matter content rarely occur. Humus content appears to increase when fairly resistant plant materials, typically low in N, are added. Available soil N is increased only when succulent, readily decomposable materials high in N are mineralized. These factors are largely determined by the maturity of the green manure when incorporated and the method of application. Improvements in soil physical conditions may be realized, but the major benefit of crop rotation, crop residue, and green manure is the improvement of soil fertility, particularly N availability (Hesse 1984).

Nitrogen fixed

The amount of N fixed by leguminous green manure varies with plant species, the effectiveness of the specific *Rhizobium*, the growing conditions, and the time of incorporation. From the information provided by Pieters (1927), it is reasonable to conclude that about 2/3 of the total N in the plant is derived from symbiotic N fixation. If the plant tops are removed, no net gain in N is realized, since this

essentially represents the entire amount of N fixed because the roots contain no more than 1/3 of the total plant N.

Clovers (sweet and crimson) have 24-26% of the entire crop biomass in the roots, which contain 2.0-2.3% N; the tops contain 2.4-2.9q N. Vetch typically has 17-19% of the biomass in the roots, with average N levels 2.2% in the roots and 3.3% in the tops. A typical vetch green manure crop (about 1 t/ha) contains 66.8 kg N/ ha in the tops and about 9 kg N/ ha in the roots, representing a total of 54 kg fixed N/ ha. Vetch may supply 90-100 kg biologically fixed N/ ha to a maize crop (Ebelhar et al 1984). Cowpea typically contains 54 kg N/ha in the tops and 4.9 kg N/ha in the roots, totaling an estimated 39.3 kg fixed N/ ha. N-fixation rates for azolla can be as high as 2.7 kg/ha per day (Talley and Rains 1980a); total levels for a single season (fall-spring) are 40-93 kg N/ ha.

Experience with vetch in California has shown that it can provide 3045% of the 140 kg N/ ha required for rice. Unfortunately, green manure crop growth varies with season and its N contribution is unpredictable. Growers typically gauge the N content of a vetch green manure crop by measuring the fresh weight in 1.5 m^2 and multiplying by 2.4 to get N produced in kg/ha. With appropriate sampling, adjustments to supplemental fertilizer N rates can be estimated.

In Louisiana, a subclover green manure crop was found to contain 104 kg N/ ha in mid-March and 165 kg N/ha in mid-April (Eastman 1986). Delaying incorporation until seed set (mid-May, necessary for reseeding) resulted in the transfer of 26% of the N into the seed.

Indirect effects

Upon submergence, rice soils undergo drastic transformations in their chemical properties. The normally oxidized constituents, such as Fe^{+3}, Mn^{+4}, and some SO_4^{-2}, in the soil virtually disappear with flooding and are replaced by their reduced counterparts, Fe^{+2}, Mn^{+2}, NH_4^+, and sometimes S^{-2}. Organic matter decomposition occurs at a slower rate in submerged soils and anaerobic fermentation diverts CO_2 production to the generation of organic acids and methane, at least for short intervals (Rao and Mikkelsen 1977a), with possible deleterious effects to rice seedlings (Rao and Mikkelsen 1977b,c). These processes and the biochemical consequences of O_2 deficiency are described by Ponnamperuma (1955, 1972) and Patrick and Reddy (1977). The addition of organic residues has been shown to accelerate the depletion of soil O_2 upon submergence and to lower the oxidation-reduction potential eventually reached. An indirect effect of green manure, therefore, is to hasten and accentuate the physiochemical changes brought on by flooding.

The most significant differences between aerobic and anaerobic decomposition of green manure are in the rate of decomposition and in the end products. Under aerobic (upland) conditions, a large group of organisms associated with a large energy release, rapid cellular synthesis, high N demand, and high CO_2 evolution exists. Mineralized N occurs principally as NO_3-N. Under anaerobic (flooded) conditions, anaerobic and facultative anaerobes occur, which have a much lower energy requirement and slower substrate assimilation requirements. Under this

condition, NH_4^+-N increases to a maximum value characteristic of the soil. The accumulated NH_4^+-N remains in the soil as a continual nutritional source to rice unless O_2 is introduced. That may stimulate nitrification and subsequent denitrification losses.

Green manure confers other benefits. By growing off-season, it reduces leaching losses of N and other nutrients; upon soil incorporation, it can use forms of P and Zn less available to rice and increase their availability to rice; by decomposing rapidly, they produce large quantitites of CO_2 that can improve soil nutrient availability. By withdrawing soil moisture during winter months, a green manure crop may enable earlier land preparation in the spring, although such benefits may be negated by the additional time required for incorporation. The well-known effects of organic amendment on soil physical properties may be of importance in upland crop rotations, but may have little effect on rice.

Handling methods

Proper seedbed preparation and incorporation of green manure for maximum benefit are primary considerations at planting. Crop residue decomposition and N mineralization require that the residue be in contact with moist soil; they are greatly stimulated by residue incorporation (Douglas et al 1980; Pal 1974, 1975). Comparisons of green manure benefits to upland crops under conventional and no-till systems have shown that while residue incorporation is not necessary for the utilization of green manure N (Hargrove 1986, Touchton et a1 1982), more rapid mineralization occurs with tillage and incorporation (Wilson and Hargrove 1986) and greater crop utilization of green manure N is likely (Goya and Scheaffer 1985, McKay et al 1952).

There are further considerations when incorporating green manure in flooded rice culture, however. Rice crop utilization of applied N is maximized if fertilizer materials are deep-placed (10-20 cm) in the soil before flooding (Broadbent and Mikkelsen 1968, Mikkelsen and Finfrock 1957), provided mineral N is maintained in the NH_4^+ form from time of incorporation to flooding. The aim is to minimize denitrification by minimizing nitrification before flooding and retaining NH_4^--N in the reduced zone thereafter.

These concepts apply equally well to green manure N. In California soils, water-seeded rice responds significantly better to deep (10-15 cm) incorporation of vetch than to shallow incorporation (Williams and Finfrock 1962) and, if soil conditions are favorable to nitrification, incorporation should be followed as soon as possible by permanent flooding. Drying a green manure crop (which is usually unavoidable before incorporation) lowers the N efficiency to the immediate rice crop because of changes in the physical material. In upland crops, field drying has reduced the mineralization rate of the green manure as much as 20% (Lohnis 1926).

Dry seeding presents additional constraints to N management for rice (Westcott et a1 1986). Green manure incorporation must occur before planting. However, the time required between planting and permanent flooding in this system (30 d) allows for considerable nitrification and does not favor the application of more than relatively small amounts of N (20-30 kg/ha) by incorporation. Early-

season N fertilization must therefore be carefully timed as a topdressing on dry soil just before permanent flooding (Brandon and McKenzie 1984).

In dry seeded rice production systems, incorporation allows for a period of mineralization and nitrification of green manure N prior to permanent flooding. Presumably, a delay in mineralization would reduce the nitrification rate and losses after flooding would not be as great as for fertilizer N, but this has not been tested. There is evidence that rice can better utilize green manure N in a dry seeded system if green manure is left on the surface rather than incorporated (Dabney et al 1987), but this requires planting rice without tillage—a system that is not yet fully developed. With conventional dry seeding methods, the best practice for N conservation appears to be incorporation of green manure at the earliest practical date for seedbed preparation and permanent flooding.

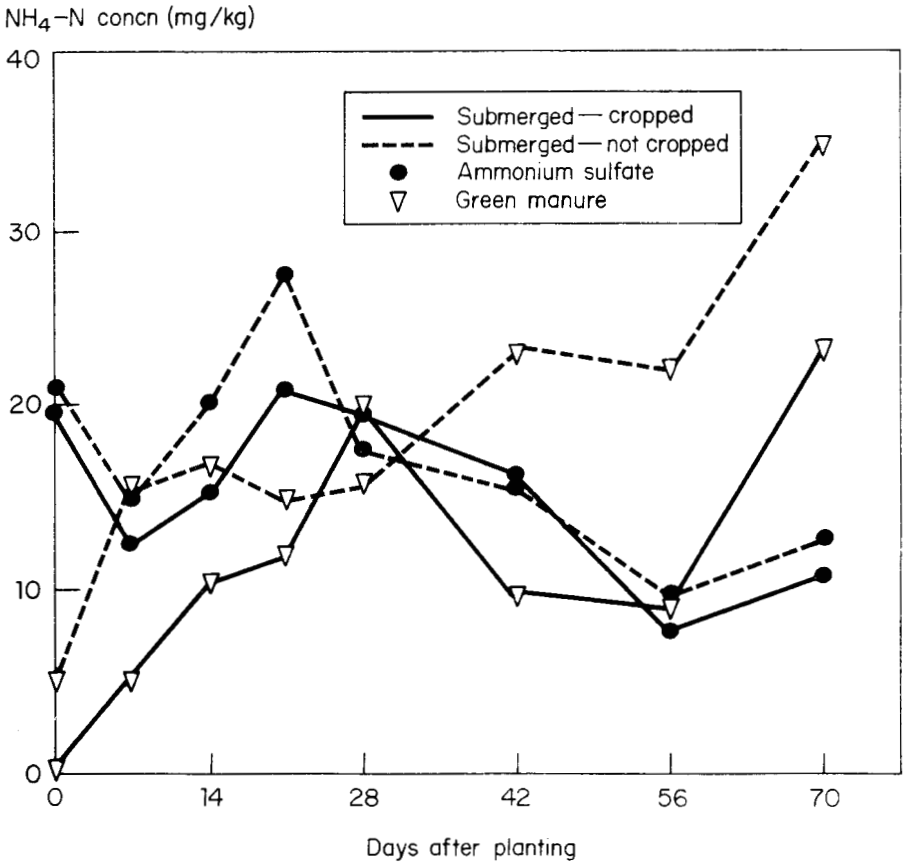
Benefits of green manure vs chemical fertilizers

The primary nutrient contribution from green manure is N, and any appraisal of green manuring must include a comparison with other sources of N. In U.S. rice-based cropping systems, the primary source of added N is ammonium-form fertilizers. which provide 12-57% of total N uptake by the crop (Broadbent and Mikkelsen 1968, Reddy and Patrick 1980, Westcott et al 1986), with averages in the 30-50% range. Green manure is not likely to be able to provide the levels of N currently required by high-yielding varieties (Talley and Rains 1982). But central questions concerning the behavior of the two sources in flooded soils and their overall effect on crop performance remain.

Soil nutrient availability

When organic and inorganic sources of N are compared. it is conventional to grant special properties to the pattern of N availability of the organic source. Janssen and Metzger (1928) demonstrated that the transformations of N in submerged rice soils differ markedly for inorganic fertilizers and green manure, suggesting different availability patterns. Extractable NH_4^+-N increased progressively after soil submergence in areas treated with green manure; with inorganic amendment, it declined with time (Fig. 1).

Presumably, when an inorganic fertilizer source is added to a flooded soil, all the microbial and chemical processes work to its disadvantage, as if the system were thrown out of balance and is working to reinstate an equilibrium. Evidence shows that upon flooding, as much as 10-66% of an added chemical source may be initially immobilized, depending on soil properties, application methods, presence and properties of organic substrates, and previous soil moisture status (Broadbent and Stojanovic 1952, Broadbent and Tusneem 1971, Rao and Mikkelsen 1976, Reddy and Patrick 1980, Yoshida and Padre 1975). As the season progresses, rice is in serious competition with such N loss processes as nitrification-denitrification (Broadbent and Tusneem 1971, Watanabe et al 1981), ammonia volatilization (Freney et al 1986, Mikkelsen et al 1978), and (perhaps) leaching (Patrick and Reddy 1976).



1. Changes in ammonium-N in soil treated with green manure (soybean) and ammonium sulfate fertilizer (Janssen and Metzger 1928).

Early season application of an inorganic N source contributes primarily to early season plant uptake; measurements of midseason N availability are invariably quite low (Moore et al 1981, Patrick and Reddy 1976, Westcott and Mikkelsen 1987). For midseason and late season N requirements, plants are heavily dependent on concurrent mineralization of soil organic N. This may necessitate aerial broadcasting of midseason N topdressing.

Behavior of green manure N is not as well documented. Information on soil microbial processes suggests that, since the availability of N from this source depends upon a gradual mineralization process, the pattern of availability will more closely match the pattern of native soil N availability (a continuous N release in some instances) and may better meet the N needs of rice plants (Morris et al 1986a,b).

This is, of course, an oversimplification. Total N mineralization will depend on both plant material, soil properties, and crop management practices. Rice N

requirements depend on an interplay of soil, environment, and crop growth factors. The net effect of any organic amendment is highly dependent on its N content and the factors affecting mineralization. Williams et al (1968), for instance, found that rice straw of less than 0.54% N had a negative effect on N availability and rice yield response. Green manure normally has considerably higher N content, and thus a positive effect on N mineralization. But no reports from the U.S. imply a greater effect of a given rate of green manure N addition on N availability, uptake, or yield than the effect of an equivalent rate of fertilizer N addition.

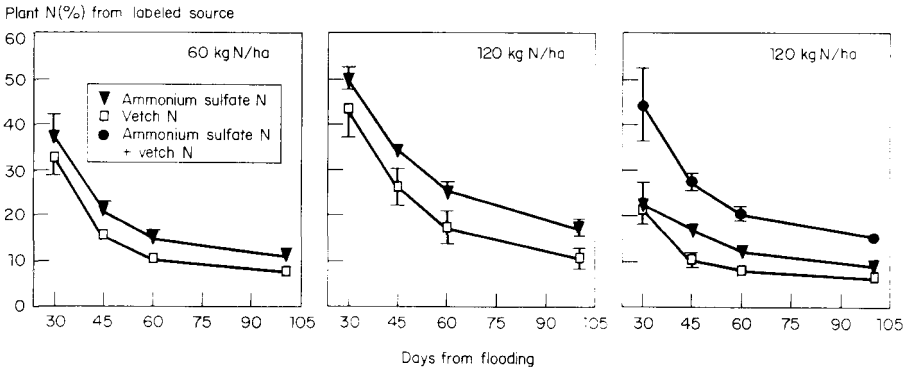
In a study of one California rice soil, Westcott and Mikkelsen (1985) found that while $(NH_4)_2SO_4$-N was rapidly immobilized upon flooding, concurrent mineralization of soil N also was affected. Vetch N mineralization was similar to soil N mineralization but, at equal rates of N, total N availability throughout the 30 d of assay was consistently lower with vetch treatments than with $(NH_4)_2SO_4$. These results were confirmed in a field study that documented no evidence of a larger period of N availability due to organic N source than to the fertilizer source (Westcott and Mikkelsen 1987). Temperature also plays a large role in the rate of green manure N mineralization (Westcott and Mikkelsen 1985). The relatively cool early season conditions in some rice soils may restrict N availability from organic sources.

Recovery of added nitrogen

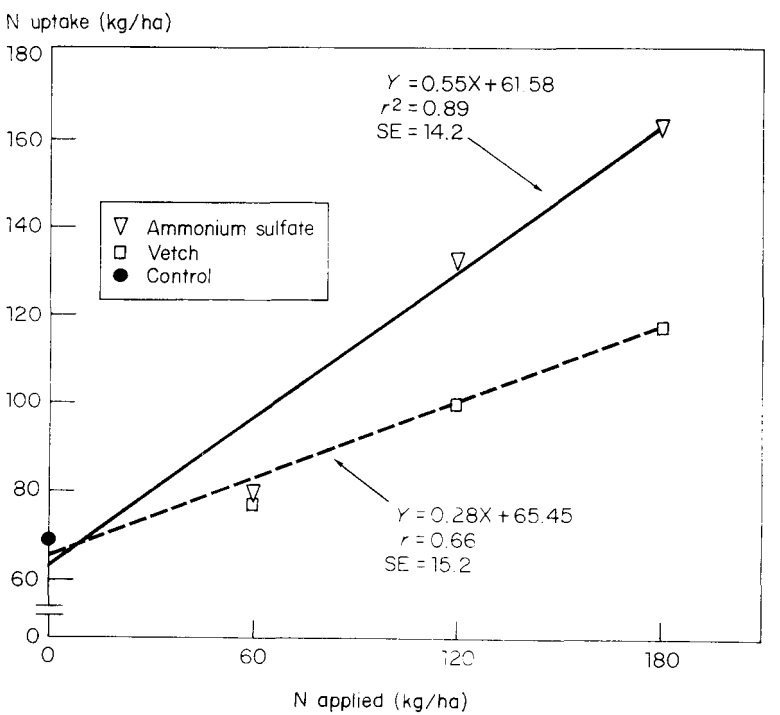
Green manure N recovery in a U.S. rice cropping system measured directly using ^{15}N labeling techniques found 10% of added vetch N (60-120 kg N/ha) in plants at harvest (Westcott and Mikkelsen 1987). With $(NH_4)_2SO_4$, N recovery was 16-25% of equivalent N rates. Calculations based on the difference method, reflecting net effects on increased N uptake over control, gave apparent recovery rates of 9-26% of vetch N and 19-53% of $(NH_4)_2SO_4$-N; values were higher with higher rates of each source (Fig. 2). These uptake data mirrored early season N availability data. This indicates that when conditions inhibit the rapid early-season mineralization of green manure N, recovery rates will not compare favorably with that of fertilizer N (Fig. 3).

These results differ from those of Williams and Finfrock (1962), who found apparent vetch N recovery rates as high as 103%, with decreasing values for increasing rates (34-168 kg N/ha). This study was conducted on a soil and a rice cultivar different from those used in the California work, and the 20 yr separating them renders explanations of the differences in results highly conjectural, particularly in light of similarities in some aspects of experimental design. However, one is tempted to wonder if several decades of continuous rice cropping without green manure may have decreased the potential mineralization rate of green manure N in some rice soils. Nevertheless, as with fertilizer N, the rate of green manure N recovery will vary considerably from one site to the next.

Soil recovery of green manure N, from 15 to 35% of the added amount, has been found to be higher than recovery of fertilizer N (Westcott and Mikkelsen 1987). When combined with the plant uptake data cited above, total recovery of N in the soil-plant system was similar for both sources and rates. This implies that at least a portion of the difference in uptake between sources is explained by incomplete green



2. Relative contribution of N source to N status of rice plants as a function of time from flooding. Vertical bars represent SE of means (Westcott and Mikkelsen 1987).



3. Relationship between total aboveground N uptake by rice plants and rate of application for organic and inorganic N sources (Watcott and Mikkelsen 1987).

manure mineralization. This necessitates consideration of residual soil effects for a complete comparison.

Crop growth response and yield

A common evaluation is to compare the net agronomic effect of a green manure on the following rice crop. The simplest technique is to measure N content of the green manure when turned under and compare its effect on growth and yield to a known or equivalent rate of fertilizer N or, better, to a fertilizer N response curve. The first and most extensive work of this nature in the California rice-growing region was performed in the 1950s, when winter crops of vetch were the primary source of added N for rice production (Williams et a1 1957, Williams and Finfrock 1962). These studies dealt with a green manure N contribution of 30-45 kg/ha. Grain yield increases over control varied from 1.0 t/ha to a high of 2.5 t ha, depending upon such factors as depth of incorporation. These yield responses compared with those from equal rates of fertilizer N.

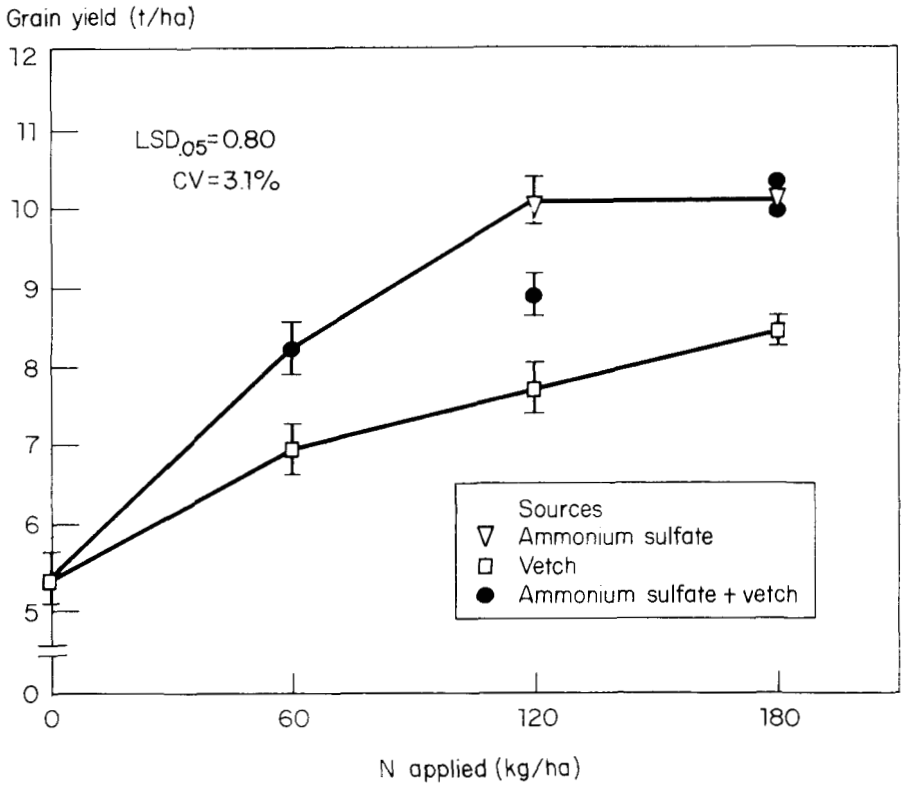
This work was expanded in the 1960s to include varying rates of vetch N in combination with rice straw (Williams et a1 1968). Yield increases with vetch N without rice straw at 101 kg N/ha were 3.9 t/ha; vetch with straw at 34 kg N/ha increased yields 2.9 t/ha. Harvest index values tended to decrease with increased vetch N additions up to optimal rates, similar to responses to fertilizer N.

The lack of work in the U.S. on green manure for rice from 1950 until the late 1970s reflects the increase in fertilizer N usage, and that trend's considerable effect on related research—which, of course, continues. The revival of research on green manure for rice systems was prompted by several considerations, a primary one being the precipitous rise in oil prices during the last decade. This factor has stimulated research into alternatives to fertilizer N sources for many U.S. cropping systems, particularly in combination with reduced-tillage systems (Hargrove 1986, Touchton et al 1982). In a broader sense, concern also developed over the long-term stability of agricultural systems that had grown dependent on inputs of uncertain price and supply. Other stimuli included unanswered questions about the behavior of N from green manure and the recognition that azolla offered possibilities as a green manure in U.S. rice cropping systems.

The effects of azolla and $(NH_4)_2SO_4$ on rice yields were equivalent at the relatively low rate of 40 kg N/ ha, with yield increases of 1.2t/ ha over control (Talley and Rains 1980b). This compares to a rice yield increase of 1.6 t/ha with incorporation of 60 kg N as azolla/ha (Talley et a1 1977). At a higher rate (93 kg azolla N/ha), however, the yield response (2.6 t ha) was only 70% of the response to an equal rate of $(NH_4)_2SO_4$ (Talley and Rains 1980a). They concluded that azolla N production of 228 kg/ha per yr would be necessary to meet current needs for rice cropping in California.

Westcott and Mikkelsen (1987) compared rice yield response with varying rates of vetch and $(NH_4)_2SO_4$ (60-180 kg N/ha) (Fig. 4). Yields reflected the previously cited effects on N availability and uptake. From a control value of 5.3 t/ha, yields increased to 10.1 t/ ha with 120 kg $(NH_4)_2SO_4$-N ha and 7.7 t/ ha with an equivalent rate of vetch N. Yields did not respond to increased rates of $(NH_4)_2SO_4$, but reached 8.4 t/ha with the highest rate of vetch (180 kg N_2/ha).

While there is some disagreement between these studies as to the efficacy of low rates of green manure N (<60 kg N/ ha), the most recent studies dealing with higher



4. Rice grain yields [12%(wt/wt) moisture] as affected by N source and rate of addition. At 180kg N/ha; source as ammonium sulfate (AS) alone; 2/3 AS + 1/3 vetch; and 1/3 AS + 2/3 vetch did not differ significantly. Vertical bars represent SE of means (Westcott and Mikkelsen 1987).

rates show a consistent advantage for fertilizer N. The most likely explanation is the incomplete mineralization of green manure N, since there is no evidence of greater N losses from this source.

Residual effects

The residual value of a fertilizer N application to a succeeding rice crop has been measured as roughly 3% of an original application of 100 kg N as $(NH_4)_2SO_4$ ha (Reddy and Patrick 1978). This represented less than 10% of the amount remaining in the soil and straw at the end of the first season. Residual values for green manure N have not been measured in the field in U.S. rice-growing areas. The nearest approximation was obtained in a greenhouse study using soils collected from a field trial that measured the residual effect by ^{15}N uptake and by a regression technique comparing effects on uptake to a fertilizer response curve (Westcott 1982). Vetch N recovery by the succeeding rice crop, measured by ^{15}N technique, was 4.6-6.5% of the original application, representing 19-26% of the labeled vetch N remaining in the soil at harvest (straw N was not included). Values for $(NH_4)_2SO_4$-N were 4.2-5.1% of the

original application, or 23% of that remaining in the soil. Calculations based on the regression technique were slightly higher, 7.5-8.7% for vetch N and 5.0-6.0% for $(NH_4)_2SO_4$-N, denoting a slight effect on soil N mineralization.

These findings confirm a higher residual value for green manure sources of N, but evidently this effect does not compensate for the first year differential in efficacy. This area deserves more attention, particularly in regard to long-term residual effects. Also lacking is documentation on the effect of successive green manure applications on N mineralization.

Constraints to use of green manure

Green manure crops in rice production must be evaluated on the basis of the cost of increased rice production achieved or on the basis of the competitive costs of commercial fertilizer N (Kumazawa 1984). Often, residual effects of green manure are neglected, although the value continues beyond a single crop. The long-term benefits are difficult to predict, but may contribute from 2 to as much as 9% of N applied to subsequent crops.

In California, vetch is usually seeded by airplane when ricefields are being drained. Winter rains provide moisture for growth and green manure is incorporated in the spring as part of seedbed preparation. Usually, vetch must be disked or rolled flat before plowing to incorporate the aboveground biomass. Vetch seed cost about $1.50/kg in 1987, or $67.35 at a seeding rate of 44.9 kg/ha. Aerial seeding cost about $11.12/ha and disking/rolling cost an additional $16.80, for a total production cost of $95.10/ha. Vetch typically supplies 33-67 kg N/ha. If 18.2 kg N is produced, this represents a cost of $2.10/kg of fixed N; with 27.25 kg N, the cost of N from the vetch is $1.40/kg N (60 kg N/ha = $1,59/ha). Urea and competitive fertilizer N is typically about $0.47/kg, with aerial application costs of about $2.70/45.45 kg. Nitrogen from field-applied commercial fertilizer averaged about $0.62/kg at 1987 prices.

The analysis is no more favorable with azolla green manure. Talley and Rains (1982) estimated that N from azolla produced in California using the labor-intensive methods of China would cost 115-158 times as much as inorganic fertilizer N. Even a best-case scenario using the most efficient system for azolla production showed production input costs to be prohibitive for the economic benefits received.

A segment of the agricultural community would choose to exclude chemical fertilizers and make the evaluation on the basis of green manure alone, because of a philosophical bias or with the idea of selling rice with an “organic” label through specialty markets. With a good green manure crop containing 60 kg N/ha, at a production cost of $95.10/ha, with a yield response of 1.6 t/ha, the cost would be $59.44/t of rough rice yield increase (Talley et al 1977, Westcott and Mikkelsen 1987). This additional cost must be considered alongside another fact pertinent to rice production schemes: green manure crops will not supply enough N to achieve current U.S. yield levels. Any production scheme dependent solely on green manure N must weigh production costs against a well-below-average rice yield.

Another constraint to green manure use is the time, effort, and additional management involved in incorporation, regardless of cost. Seeding time is a busy

time of year for any grower. The ease of application and evenness of distribution for chemical fertilizers and the predictable amount of N available for crop growth have won them a place in production systems that will be difficult for green manure to fill.

Future considerations

Green manure will regain acceptance in the U.S. when its use makes economic sense. The preceding, simple cost analysis points to three possibilities: a) the cost of fertilizer N could rise, b) the green manure crop could be engineered or cultivated to make more N available to the rice crop, or c) the cost of production for green manure could decline. These possibilities are, of course, not mutually exclusive. A rise in fertilizer N prices might lower the relative cost of green manure N. But if the causal factor were a rise in oil prices, then green manure N production costs also might rise.

The most promising approach is to lower the annual production costs for green manure by identifying species and production systems that allow reseeding. Work on this concept has been underway for no-tillage systems with upland crops (Touchton et al 1982). The advantage of a no-till system is that it allows for green manure growth until shortly before or even after seeding, permitting a longer period for seed set and hardening by the green manure species. As was mentioned, some initial steps have been taken by Dabney et al (1987) toward applying this concept to a rice-based system. Preliminary results on green manure species identification are encouraging, but the development of a reliable no-till system for rice production will take considerable effort.

Such a system would have trade-offs. General observations are that green manure species that set seed early in the growing season are restricted in dry matter accumulation. The advanced stage of plant development at incorporation also may restrict the rate of decomposition and N mineralization, with considerable translocation of N to the seed and reduction of the amount of N available to the crop.

In the last 40 yr, rice production in the U.S. has gone from near-complete reliance on green manure for N input to complete reliance on fertilizer input. If green manure use is to increase in the future, it will almost certainly be in conjunction with fertilizer N. Rice growers are not likely to give up the considerable yield advances made through the introduction of high-yielding varieties and the integral advances in fertilizer N management—factors representing a highly successful approach to rice production development that continues to be the main thrust of rice research units throughout the country.

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Notes

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Effect of green manure on physicochemical properties of irrigated rice soils

Wen Qixiao and Yu Tianren

The effect of green manure on some physicochemical properties of irrigated rice soils is discussed. Becausethey contain abundant, easily decomposable components, green manure crops can promote development of soil reduction processes, leading to changes in redox potential, acidity, ion exchange, complexes, and surface properties. Many of these changes in soil properties are of practical significance in plant growth.

Use of green manure has a long history in China. Records of green manure for upland crops date from as early a5 2,300 yr ago; rotating irrigated rice with green manure crops dates from the third century (Shi 1957, Wang 1980). In addition to supplying such nutrients as N, P, and K, green manure is an important source of organic matter and can improve such soil physical properties as porosity and strength.

Green manure is composed of a variety of organic compounds. Once applied to the soil, these compounds are decomposed by microorganisms. The decomposition process affects a number of physicochemical properties of the soil through oxygen consumption and through production of various organic and inorganic substances.

Because irrigated rice soil usually suffers from the submergence and drying cycle, its decomposition processes are different from those in upland soils. Changes in some characteristic features of soil physicochemical properties may have an important bearing on soil fertility and on plant growth.

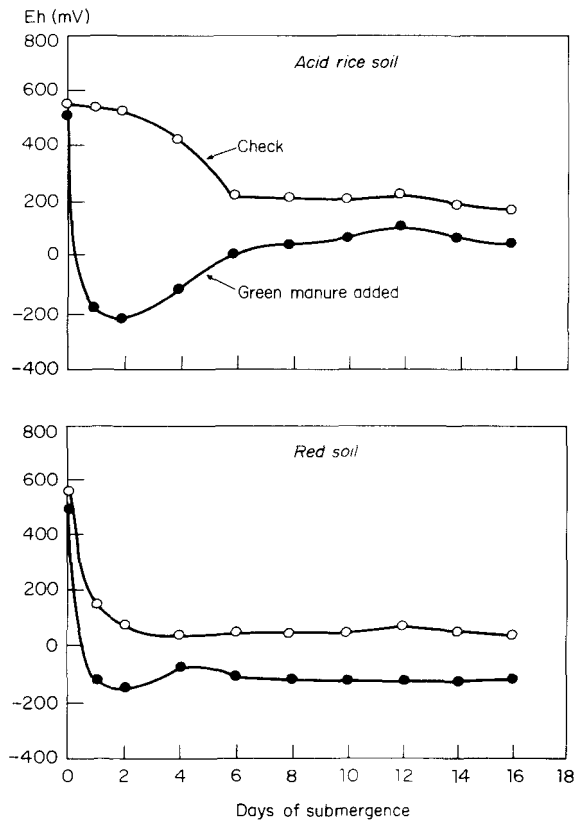
The effect of green manure on some of those physicochemical properties—redox potential, acidity, ion exchange, complexing, and surface properties—andthe practical implications of the changes are discussed here.

Redox potential

A periodic change in redox potential is the most remarkable physicochemical property of irrigated rice soil. Green manure can have a pronounced effect because the organic compounds it contains can act as electron donors. Because of their high susceptibility to microbiological decomposition (compared with native soil organic matter). they are usually more active in inducing changes in redox properties, especially under submerged conditions.

The rate of oxygen diffusion in water is very low. Under submerged conditions, the rate at which oxygen is supplied in the soil is less than the consumption rate. This leads to a lower redox potential. The rate of reduction depends on the relative rate of production of organic reducing substances and the supply of oxygen. The magnitude of the lower rate is determined by the amounts of easily reducible iron, manganese oxides, and nitrate and sulfate on the one hand and by the amount of easily decomposable organic substances on the other.

The effect of green manuring in hastening the lowering of redox potential after submergence is shown for two soils in Figure 1. For an acid soil with a very low organic matter content, redox potential remained higher than 200 mV for several days after submergence. With green manure application, it dropped suddenly, to as low as minus 200 mV within 1-2 d of submergence. In another experiment, treatment with milk vetch or milk vetch plus other organic manure resulted in a more distinct lowering of redox potential, not only in the surface layer but also in the subsoil, before elongation of rice plants (Table 1).



1. Effect of green manure on change in Eh of a red soil and of an acid rice soil after submergence.

Table 1. Effect of green manuring on Eh of a rice soil profile, neutral paddy soil, Nanjing, China.[a]

Depth (cm)	Eh (mV)		
	3 Jun	30 Jun	27 Jul
		Check	
0-1	380	230	325
5-7	405	165	285
13-15	590	205	220
20-25	635	395	485
40-50	585	455	520
		Milk vetch	
0-1	215	110	325
5-7	215	115	180
13-15	330	215	255
20-25	520	365	480
40-50	645	455	480
		Milk vetch + pig manure + sludge	
0-1	190	105	285
5-7	225	75	385
13-15	235	135	-
20-25	-	410	410
40-45	-	365	500

[a] Institute of Soil Science, Academia Sinica, 1961.

Table 2. Sequence of redox reactions in rice soil.[a]

System	E_7° (V)	Actually measured Eh (V)
$O_2 + 4H_2 + 4e$ D $2H_2O$	0.82	0.65-0.3
$NO_3^- + 2H^+ + 2e$ D $NO_2^- + H_2O$	0.54	0.5 -0.2
$MnO_2 + 4H^+ + 2e$ D $MN^{2+} + 2H_2O$	0.43	0.4 -0.2
$FeOOH + 3H^+ + e$ D $Fe^{2+} + 2H_2O$	0.17	0.3 -0.1
Organic systems	−0.03-(−0.2)	0 -(−0.2)
$SO_4^{2-} + 9H^+ + 6e$ D $HS^- + 4H_2O$	−0.16	0 -(−0.15)
$2H^+ + 2e$ D H_2	−0.414	−0.15-(−0.3)
Methane fermentation	---	−0.2-(0.3)

[a] Yu 1976.

In addition to the organic reducing substances produced as a result of the decomposition of green manure or other organic materials, a variety of inorganic redox systems in soils can participate in redox reactions and can act as redox buffers (poising). Some of the most important redox systems in soils and their relevant parameters are shown in Table 2.

The redox reaction that will occur at a given redox potential can be predicted from the sequence in the table. Theoretically. only under conditions where almost all the oxidized forms of a system with a higher E° value have changed to the reduced form can the next system with a lower E° value begin to be reduced. Actually, because of the involvement of microorganisms and the sluggishness of some redox

reactions, some reactions can occur simultaneously, especially if the difference in E^o value between two adjacent systems is not very large. In the table, the actually measured Eh ranges at which a redox reaction can occur are given for each system.

Nitrate amounts are usually low in irrigated rice soil. The content of easily reducible manganese also is not high. The most important material that can retard the lowering of redox potential is easily reducible iron. If the amount of organic reducing substances is smaller than the amount of easily reducible iron, the redox potential of the soil can be maintained at 100-200 mV. If it is larger, the potential can be negative, and under extreme reducing conditions can even be lower than −100 mV.

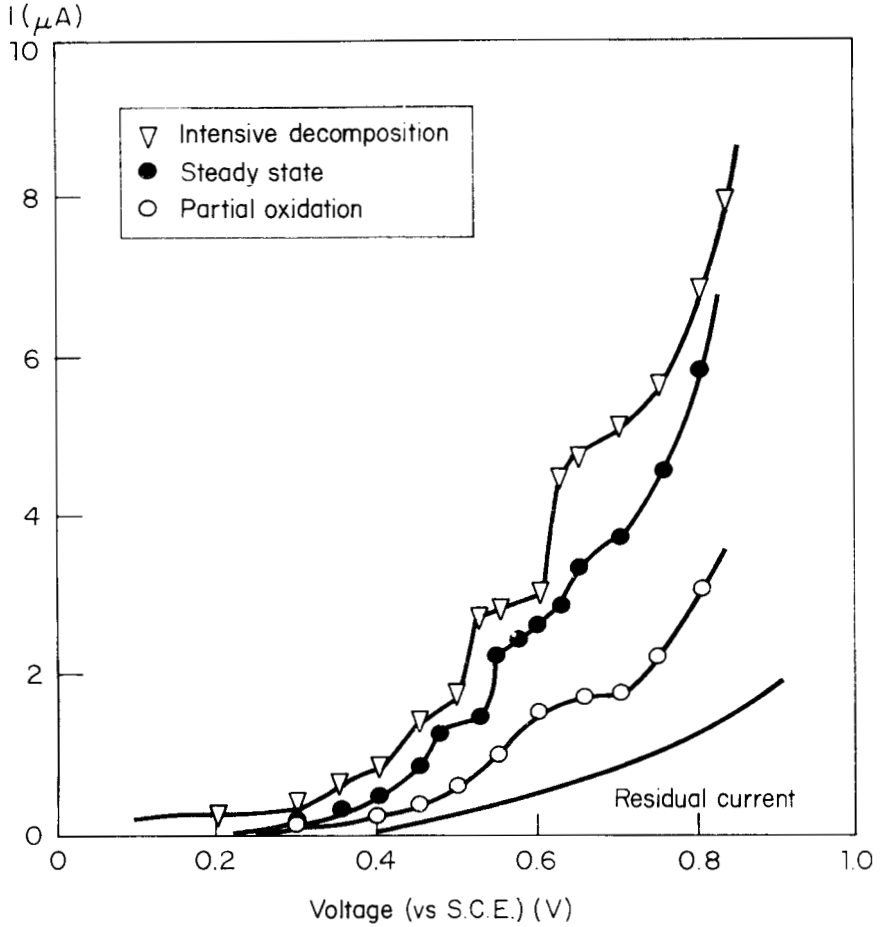
The rate of production and amount of organic reducing substances produced are determined by the amount and the composition of the organic material involved and the environmental conditions under which decomposition proceeds. Generally speaking, milk vetch has a relatively high amount of easily decomposable components. For this kind of green manure, the rate of reduction and the amount of organic reducing substances produced are high. On the other hand, the persistence of these substances is short. Using a voltammetric method, we found that organic reducing substances are highest in kind and amount at the stage of vigorous decomposition. 4-7 d after submergence. Then the kinds of substances diminish gradually. Eventually, only one or two groups with weakly reducing properties remain (Fig. 2).

The molecular weight of these reducing substances is rather low. It has been estimated that for milk vetch, most of these compounds have a molecular weight of 120-160; for rice straw, molecular weights are within the range of 140-160 (Ding et al 1987). Okazaki et al (1981) identified formaldehyde, acetaldehyde, propanol, n-butanol, n-pentanol, etc., from water-soluble decomposition products of native soil organic matter and found evidence of the existence of aldehydes in molecular-weight fractions within the range of 500-100,000.

The practical significance of changes in redox potential is essentially indirect. Redox potential is a comprehensive reflection of the oxidation-reduction regime of the soil. In the majority of cases, rice can adapt to or tolerate a moderately to strongly reducing condition. However, if a large amount of fresh green manure is plowed under at a high temperature and rice seedlings are transplanted immediately, the seedlings may suffer from too large a concentration of organic reducing substances in the soil.

pH

One of the important consequences of the lowering of redox potential after flooding is the change in pH. In most of the reduction processes occurring in soils, such as the reduction of iron, manganese oxides, and sulfate, there is a corresponding consumption of protons (Table 2). But organic acids and carbon dioxide produced during organic material decomposition can furnish protons to the soil, inducing a decrease in pH. Therefore, the direction and the magnitude of change in soil pH during submergence are determined by the relative amounts of protons consumed and released.

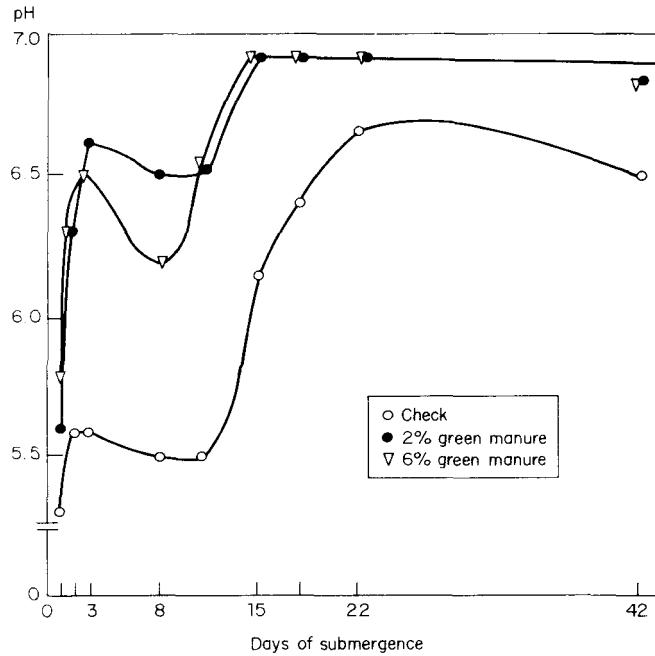


2. Changes in reducing substance, of different reduction intensity in rice soil (plus 3% green manure) after submergence (Inst. Soil Sci., Academia Sinica, 1978)

In acid rice soils, at the beginning of the decomposition of native soil organic matter, with intensification of the reduction of iron and manganese oxides, the pH value increases sharply as a result of the overwhelming excess of protons consumed over those released. But at the stage of vigorous organic matter decomposition, pH can decrease to some extent because of the rapid production of protons. At a still later stage, following the further decrease in Eh, pH increases gradually and stabilizes.

What is interesting is that the application of green manure can hasten the attainment of the steady state and can lead to higher pH values (Fig. 3).

If different kinds of acid rice soils are considered, the effect of the application of green manure on soil pH can be expected to differ because of differences in original pH, amount of easily reducible iron and manganese oxides, and amount of easily decomposable organic matter already present. For soils containing high amounts of easily decomposable organic matter and low easily reducible iron and manganese



3. Influence of green manure on change in pH of acid rice soil alter submergence (Yu 1985).

oxides, such as those derived from the weathering products of granite, the effect is usually small. On the other hand, for rice soils derived from Quaternary red clay or the weathering products of basalt that have high amounts of easily reducible iron and manganese oxides and low, easily decomposable organic matter, the effect is usually large. In extreme cases, pH after submergence of soils treated with green manure can be higher by 1.5 units than that of soils without green manure. The time required for attaining a steady pH value is also considerably shorter.

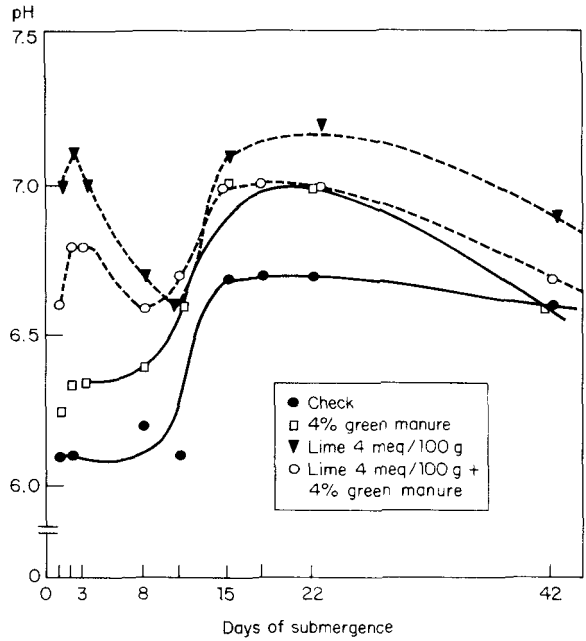
Because liming has a favorable effect on decomposition of organic materials, including those already present and those added, applying green manure with liming can lead to a soil pH lower than that from a single liming treatment (Fig. 4).

The pH of calcareous paddy soils is controlled by the chemical equilibrium of the $CaCO_3$-CO_2 system. Usually, it decreases, due to the accumulation of CO_2 during submergence. Applying green manure to such soils can lower soil pH by as much as 0.5 unit compared to a no-green manure plot because of the larger amount of organic acids produced.

The decrease in pH in alkaline soils and the increase in pH in acid soils caused by green manuring would undoubtedly benefit crop growth.

Ion exchange

Another consequence of flooding of rice soils is the formation of large amounts of ferrous and manganous ions as a result of the reduction of their high-valent oxides.

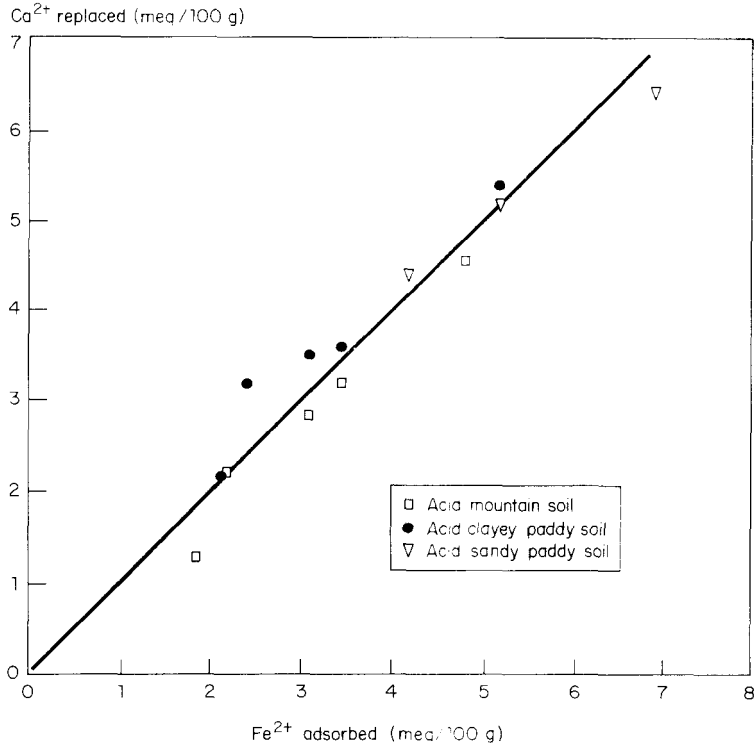


4. Influence of lime and green manure on change in pH of acid rice soil after submergence (Yu 1985).

These ions will be adsorbed by negative charges on clay surfaces, replacing basic cations such as Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, and NH_4^{+} from the exchange sites. It has been found experimentally that the exchange between ferrous ions in solution and adsorbed calcium ions follows a stoichiometric relationship (Fig. 5), suggesting that. because of the intensification of reduction conditions, the amount of exchangeable ferrous iron in soil will increase following green manuring.

It is not clear whether cation exchange involving manganous ions also obeys the stoichiometrical rule in rice soils. Ding (Inst. Soil Sci., Academia Sinica, 1964. unpubl.), in studying the exchange between Mn^{2+} ions and adsorbed Ca^{2+} for a laterite and a red earth, found that the amount of adsorbed Mn^{2+} and the amount of replaced Ca^{2+} were nonequivalent. The higher the content of iron oxides of the soil. the more conspicuous this nonequivalency. It should be expected that, as for ferrous iron, applying green manure will lead to an increase in exchangeable manganese.

The leaching loss of nutrient cations under reduced soil conditions, especially when large amounts of green manure are applied, should be mentioned. It has been estimated that, under strongly reducing conditions, the amount of ferrous iron can be larger than the cation exchange capacity of many types of rice soil in South China. If all the ions are adsorbed by the soil, then all the exchangeable nutrient cations will be replaced, with a subsequent leaching loss from the cultivated layer. Fortunately. because of the involvement of other chemical reactions, especially the precipitation of ferrous iron as sulfide and hydroxide, the amount of exchangeable ferrous iron in rice soils is not high (less than 10% of the cation exchange capacity). Since the



5. Exchange of Fe^{2+} and Ca^{2+} in rice soils (Bao et al 1964).

proportion of precipitated ferrous iron is highly pH-dependent, the increase in pH as a result of reduction can help diminish leaching loss of nutrient cations from submerged soils.

As is well-known, repeated cycles of soil submergence and drying can result in acidification and a subsequent destruction of clay minerals. Brinkman (1969) called this phenomenon ferrolysis. The enhancing effect of green manure was demonstrated by He and Chen (1986) in a simulation experiment with two Ca-saturated soils (Table 3). In nearly all treatments, the amount of exchangeable hydrogen and aluminum increased to some extent, with decreases in exchangeable ferrous iron and manganous ion after air-drying. This can only be interpreted as a destruction of clay minerals caused by soil acidification as a result of the oxidation of exchangeable Fe^{2+} and Mn^{2+}. The increase in exchangeable magnesium before air-drying in the glucose and milk vetch treatments suggests that magnesium octahedron has also been disrupted under the action of the decomposition products of these organic substances during submergence.

In a decomposition experiment in the field, Lin and Zhong (Inst. Soil Sci., Academia Sinica, 1984, unpubl.) observed that the application of green manure led to an increase in hydrolytical acidity and a slight increase in cation exchange capacity (Table 4).

Table 3. Change in composition of exchangeable cations of soils after submergence.[a]

Condition before analysis	Treatment	Exchangeable cation (meq/100g)				
		Ca^{2+}	Mg^{2+}	Fe^{2+}	Mn^{2+}	$H^{+}+Al^{3+}$
		Neutral paddy soil				
Wet	Check	24.5	0.52	0.11	0.80	0
	Glucose	10.8	0.99	5.44	0.62	1.71
	Milk vetch	18.6	1.04	1.75	1.18	0
Dried	Check	25.7	0.54	0.03	0.20	0.39
	Glucose	10.8	0.98	0.30	0.71	6.85
	Milk vetch	20.0	1.05	0.03	1.09	0.14
		Acid paddy soil				
Wet	Check	6.09	0.08	0.06	0.04	2.08
	Glucose	2.17	0.39	2.17	0.11	2.71
	Milk vetch	5.19	0.54	3.00	0.12	1.06
Dried	Check	6.45	0.10	0.04	0.03	1.82
	Glucose	2.17	0.54	0.14	0.08	4.57
	Milk vetch	5.19	0.57	0.05	0.10	1.33

[a]He and Chen 1986. Soil incubated under waterlogged conditions for 6 mo during which water was drained off temporarily 5 times. The soil was then washed with deionized water until free of Fe^{2+} under N atm. for analysis, or air-dried before analysis.

Table 4. Effect of green manure on hydrolytical acidity and cation exchange capacity (CEC) of an acid soil (4% organic material added).[a]

Duration of experiment (yr)	Treatment	Hydrolytical acidity (meq/100g)	CEC (meq/100g)
1	Check	3.93	12.6
	Milk vetch	6.00	12.5
	Azolla	4.90	12.7
	Rice straw	7.53	13.8
2	Check	3.22	12.4
	Milk vetch	5.30	12.3
	Azolla	5.15	13.6
	Rice straw	6.55	13.6

[a]Lin and Zhong 1984, Inst. Soil Sci., Academia Sinica, unpubl.

Complexes

A variety of products are formed during decomposition of organic materials. For green manure, the amount of water-soluble products is comparatively high because of the abundance of easily decomposable components, but their molecular weights are relatively low (500-1,000) (Ceccanti and Ding 1985). On the other hand, the amount ofwater-soluble products from native soil organic matter is low, but most of them have a molecular weight greater than 1,000 (Okazaki et al 1981). Some of these products are charged negatively; some, positively (Table 5). The amounts of these

Table 5. Concentration of active groups of decomposition products of various green manures.[a]

Green manure	C_m (M × 10^5)[b]		
	Negatively charged		Positively charged
	Reducing group	Chelating capacity	Chelating capacity
Alfalfa	30	1.8	0.8
Hairy vetch	43	1.6	1.6
Vetch	-	3.8	2.2
Milk vetch	47	2.2	2.6
Crotalaria	79	2.9	2.7
Rice straw	91	1.8	2.2

[a] Yu 1981. [b] C_m denotes the complexing capacity, expressed as moles of Fe^{2+} complexed by each liter of complexed solution (Bao et al 1983). Titration with $KMnO_4$.

Table 6. Concentration of complexing agent in decomposition products of plant materials at different decomposition stages.

Treatment	Plant material	Cm (M × 10^4)[b]		
		3 d	6 d	14 d
Check	Milk vetch	8.9	10.4	10.4
	Vetch	8.9	11.5	10.6
	Rice straw	8.8	9.5	9.6
Yellowish brown earth	Milk vetch	6.4	7.2	-
	Vetch	6.4	6.5	-
	Rice straw	3.9	5.0	-
Laterite	Milk vetch	4.8	5.5	-
	Vetch	5.3	5.7	-
	Rice straw	5.3	6.2	-

[a] Bao and Yu 1986. [b] C_m denotes the complexing capacity, expressed as moles of Fe^{2+} complexed by each liter of complexed solution (Bao et al 1983).

products which have the ability to complex with some metal ions vary with the kind of green manure and are time-dependent (Table 6).

Bao et a1 (1978,1983) and Bao and Yu (1986) studied the dynamics and stability of water-soluble Fe(II)- and Mn(II)-complexes in soils. They found that the amount of water-soluble Fe(II)-complexes generally reached maximum 4-7 d after green manure began to decompose and decreased after 10 d. The peak period for Mn(II)-complexes was earlier than that for Fe(II)-complexes. Most of these complexes were positively charged.

The stability constants of water-soluble Fe(II)- and Mn(II)-complexes vary considerably with the stage of green manure decomposition. They are generally within the range of 3.4-6.5, and are highest at the stage of vigorous decomposition of organic material (Table 7). Contact of the decomposition products with soil leads to

Table 7. Log K values of Fe (II)-complexes for decomposition products of plant materials at different decomposition periods.[a]

Treatment	Plant material	Log K values		
		3 d	6 d	14 d
Check	Milk vetch	4.0	4.5	4.4
	Vetch	4.6	5.0	4.0
	Rice straw	4.0	4.5	3.8
Yellowish brown earth	Milk vetch	3.8	3.2	-
	Vetch	3.9	2.7	-
	Rice straw	3.2	3.5	-
Laterite	Milk vetch	3.1	3.0	-
	Vetch	3.5	2.3	-
	Rice straw	3.0	2.8	-

[a]Bao and Yu 1986.

a decrease of log K value, presumably because of the retention by soil particles of those substances that have a stronger complexing ability. In accordance with the Irving-Williams series, the log K values of Fe(II)-complexes are larger than those of Mn(II)-complexes by an average 0.8 unit (Bao et al 1983, Bao and Yu 1986).

Under field conditions, part of the water-soluble complexes are leached out of the soil solum with the percolation water. Another part can be retained along root holes or on the surface of cracks in the lower part of the cultivated layer. After the field is drained, these materials can be precipitated, forming orange- or red-colored coatings. If green manure has been applied, the coatings can be frequent and brilliantly colored. Gu and Li (1981) reported that the coatings are net-structured organic substances attached to different forms of iron oxides.

Complexing of Fe^{2+} and Mn^{2+} ions may have a beneficial effect on rice growth. It has been suggested that this is the reason why rice plants can grow normally on some strongly reducing soils where the concentration of water-soluble ferrous iron is quite high but with a considerable part of the iron in the complexed form (Yu 1985).

Surface properties

If the ratio of amorphous iron oxides to free iron oxides (Fe_o/ Fe_d) is used as an index of the activity of iron oxides, the addition of milk vetch to the soil before incubation results in an increase in this activity (Table 8). This can be assumed to have been caused by the reduction of ferric oxides under submerged conditions and the subsequent oxidation of reduced iron after soil drying. This change in the activity of iron oxides can have some bearing on surface properties of the soil. In a simulation experiment, Wu and Chen (1981) observed that the extent of specific adsorption of copper ions correlated significantly with the activity of free iron oxides.

In the long run, it can be expected that reductive eluviation in soil can be expected to result in a gradual decrease in iron oxide and manganese oxide content. This is one of the important criteria for distinguishing rice soils, especially acid rice

Table 8. Effect of green manure on the activity of free iron oxides of soils.[a]

Soil	Milk vetch added (%)	Fe_d (%)	Fe_o/Fe_d			
			Submerged	pF2	Air-dried	Ovendried
Yellowish brown earth	0	2.41	0.35	0.14	0.20	0.18
	2	2.22	0.59	0.41	0.39	0.22
	5	2.23	0.56	0.40	0.38	0.23
Red earth	0	4.77	0.13	0.06	0.06	0.02
	5	4.77	0.38	0.11	0.13	0.09
Laterite	0	13.0	0.05	0.02	0.04	0.04
	5	13.1	0.12	0.04	0.06	0.06

[a]He and Xu 1981. Soils incubated under submerged conditions for 8 mo.

Table 9. Amount of Cd absorbed by colloids (*y*) as affected by concentration of Cd added (X_1), pH (X_2), and free iron oxides (X_3).[a]

Soil colloid[b]	Parameter				R^2	Test for significance[c]
	B_0	B_1	B_2	B_3		
I B	−10.58	0.12	2.35	0.00	0.98	*
Y B	−14.41	0.11	2.82	0.41	0.97	*
R	−16.46	0.07	3.60	0.19	0.97	*
L	−20.09	0.10	3.84	0.13	0.95	*

[a]H. M. Chen 1986, Inst. Soil Sci., Academia Sinica, unpubl. [b]IB = indigotic black soil, YB = yellowish brown earth, R = Red earth, L = laterite. [c]*P < 0.05.

soils, from their parent soils. This decrease in free iron oxide and manganese oxide content can have practical implications. Chen (Inst. Soil Sci., Academia Sinica, 1985, unpubl.) reported that the amount of specifically adsorbed cadmium was correlated positively with free iron oxide content of the soil clay (Table 9). The behavior of zinc was similar to that of cadmium (Song K, Inst. Soil Sci., Academia Sinica, 1985, unpubl.). As is known, specifically adsorbed metal ions are less mobile than exchangeable ions.

The decrease in free iron oxide content also leads to an increase in the negative charges and a decrease in the positive charges carried by soil particles. This is significant for soil nutrient-retaining capacity. Because ferric oxides have a high affinity for phosphate ions, a decrease in their content would mean a reduced fixation of phosphate by soils. For many acid soils in south China, the development of rice soil along with reductive eluviation usually implies an improvement in fertility status. Because green manure crops contain large amounts of active substances that cause reduction processes. it can be assumed that they not only supply nutrients and organic matter; they also must have a long-term beneficial effect on rice soils by inducing changes in soil surface properties.

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Notes

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Annual legumes for food and as green manure in a rice-based cropping system

K. R. Kulkarni and R. K. Pandey

The development of high-yielding, fertilizer-responsive, and photoperiod-insensitive crop varieties has made possible multiple cropping, with very high levels of total production. But that technology needs high levels of chemical fertilizers and pesticides and an assured water supply. As fertilizer costs escalate, poor farmers with limited cash resources need alternative technologies to achieve and sustain high productivity. Integrated nutrient management, with dual-purpose food legumes grown for grain and for green biomass, could be one strategy. Short-duration legumes—mungbean, cowpea, and blackgram—have been used as green manure to supply part of the N needs of rice. They can provide 25-60 kg N/ha to a rice crop. Permanent plot experiments in India have shown it is possible to maintain high yields in rice-based cropping systems where 25-50% of the N is supplied by green manure.

With current land resources, multiple cropping is necessary to produce adequate food for a growing population. Nitrogen is the key nutrient limiting higher yields (Allen 1980).

The development of high-yielding, fertilizer-responsive cereal crop varieties leveraged the development of technology that uses high levels of chemical fertilizers and pesticides in high-intensity cropping systems. The primary limitations to the adoption of these technologies by resource-poor farmers are water availability and high fertilizer and pesticide costs. In traditional agriculture, farmers—particularly those farming near cities—practiced moderately intensive cropping systems involving vegetables, fodder crops, and cereals. The principal cultural practices in such sustainable production systems were liberal use of bulky organic manures, local manure resources, and green manure and crop rotations involving crops with different rooting patterns and nutrition requirements and legumes to restore soil fertility.

Asian farmers traditionally have practiced green manuring. Apart from growing such leguminous crops as sunn hemp *Crotalaria juncea* L., sesbania *Sesbania speciosa*, dhaincha *Sesbania bispinosa* Jacq. and W. F. Wight, and cowpea *Vigna unguiculata* L. Walp., farmers in high rainfall areas with dense vegetation also collected leaves and twigs of trees to incorporate in their ricefields.

Joffe (1955) traced the practice of green manuring in China to 1134 B.C. Although the advantages of green manuring are well known, the practice is declining because of its high cost and the time a green manure crop occupies land in intensively cropped areas.

Legumes as green manure

Leguminous crops are known to improve soil productivity and benefit a succeeding cereal crop. Xiao (1981) found that rice yields in China increased 21% when rice was grown after *Vicia sativa* L. and 14% after *Pisum sativum* L. Yields decreased 20% when rice followed wheat.

In India, De (1982) reported that growing cowpea or mungbean *Vigna radiata* L. Wilcezk before rice provided 50-70 kg N/ ha to the rice crop. Meelu and Rekhi (1981) found that including a legume in a rice-based cropping system in north India saved 30 kg N/ ha. In Sind Province, Pakistan, Jakhro and Faroque (1982) observed an increase in rice grain yield after lentil *Lens esculenta* L. and lucerne *Medicago sativa* L. Rice responded to applied N only up to 90 kg N/ ha.

These studies suggest that N fixation by a preceding legume improved growth and yield of a succeeding rice crop grown with moderate levels of N fertilizer.

In experiments on soil with low available N and P in Punjab, India, green manure alone increased rice yield more than 60 kg N/ ha (Meelu and Rekhi 1981). Tiwari et al (1980) reported increased rice yields and a residual effect on wheat *Triticum aestivum* L. from green manure grown as a catch crop between wheat and rice in normal as well as in partially reclaimed sodic soils in north India (Table 1).

Maskina et al (l985) found that green manure plus poultry manure increased rice yields 0.9 t/ha without additional N. Relwani and Ganguly (1959) found that green manuring rice with dhaincha *Sesbania bispinosa* Jacq. increased effective tillers, plant height, and grain and straw yields. Meelu and Morris (1984) reported that green manure contributed 45-80 kg N/ ha to a rice-based cropping system.

Dual-purpose legumes with rice

All India Coordinated Agronomic Research Project investigations of the production potential of crops and cropping sequences with adequate inputs in different agroclimatic regions of the country started in 1968. The project monitored crop productivity and soil changes in the cropping systems at fixed sites. High productivity of rice-based cropping systems, leading to 12-13 t rice/ha or 9-10 t rice and other grain crops/ ha per year, was achieved in different agroclimatic regions (Kulkarni 1979).

In Indonesia and China, where rice double cropping is practiced, soybean *Glycine max* Murr. is grown in the dry season for protein and oil. A substantial amount of crop residue (leaves, roots, and nodules) is returned to the soil, contributing to the maintenance of soil fertility.

Most rainfed lowland areas have traditionally been monocropped. Development of early-maturing rice varieties made double cropping possible. The rice

Table 1. N economy in rice - wheat sequence with green *manuring.*[a]

N Ikg/ha)	Rice grain yield[b] It/ha)		Wheat grain yield[c] (tiha)	
	Fallow	Green manure	Fallow	Green manure
0	2.4	3.8	1.7	2.3
40	4.0	4.9	1.7	2.8
60	4.6	5.3	1.9	3.2
120	5.0	5.3	2.3	3.4
Mean	4.0	4.8	1.9	2.9
CD at 5% N		0.5		0.1
GM		0.4		0.1
GM × N		0.7		0.2

[a]Tiwari et al 1980. [b]Direct effect. [c]Residual effect.

Tabla 2. Wet season rice grain yield and nutrient uptake in different multiple cropping sequences.[a]

Crop sequence	Grain yield[b] (t/ha)	Nutrient uptake[c] (kgiha)		
		N	P_2O_5	K_2O
Rice - rice - sweet potato	3.7	71.5	15.3	76.2
Rice - rice - cowpea	3.9	711	15.3	73.2
Rice - rice - sesamum	3.8	75.4	16.1	81.4
Rice - rice - peanut	3.9	72.4	13.1	75.0
Rice - rice - rice	3.6	69.5	14.9	72.9

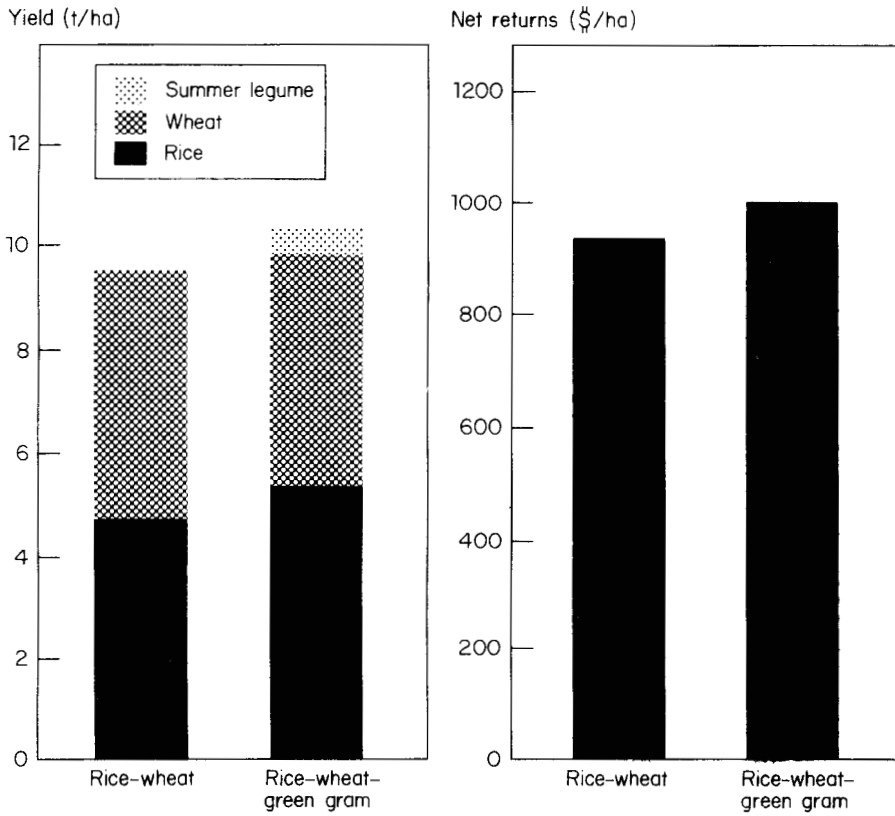
[a]Shashidhar and Sadanandan 1980. [b]Mean of 3 yr. [c]Mean of 2 yr.

fallows are ideal for relay or sequential cropping of mungbean, black gram *Vigna mungo* L., cowpea, soybean, and pigeonpea *Cajanus cajan* L. Millsp. Legumes can be grown as catch crops on residual moisture and nutrients, with or without fertilizer. With residue incorporation, a dual-purpose grain legume could increase the soil nutrient supply and rainfed rice system productivity.

Including leguminous crops such as cowpea and peanut *Arachis hypogaea* L. in acrop rotation had consistent beneficial effects on wet season rice yields (Shashidhar and Sadanandan 1980). Yields were higher than with three rice crops (Table 2). The effect of the leguminous crop on rice yield reached statistical significance during the third year. At Ludhiana, inclusion of mungbean in a rice - wheat sequence maintained productivity and gave higher monetary returns. A similar benefit of mungbean with rice - wheat was observed at Masodha and Navsari (Fig. 1). At Thanjavur and Karamana, a rice - rice - peanut pattern was more productive than rice - rice - mungbean (Fig. 2).

These experiments show a potential for grain legumes during the summer in rice-based crop sequences. However, yields of grain legumes in most situations are low, for the following reasons:

- If sowing of the summer legume is delayed, the crop is exposed to high temperature at flowering, reducing the number of pods per plant.



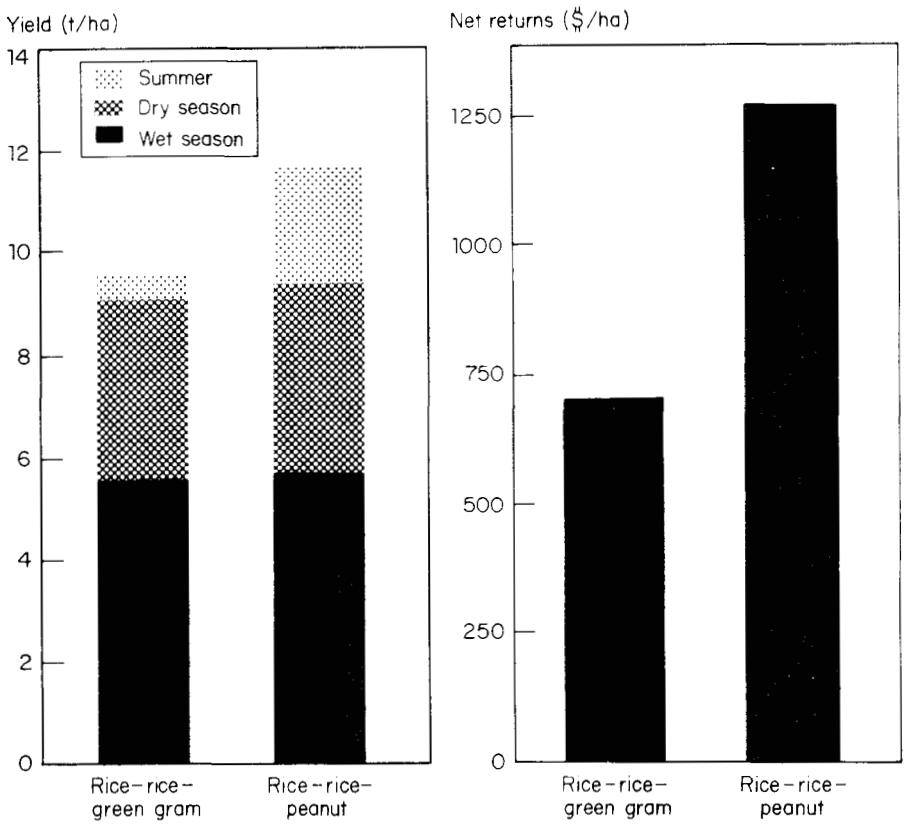
1. Effect of including grain legumes on productivity of rice-based cropping systems, All India Coordinated Agronomic Research Project, 1982-85. Av of 3 locations: Masodha, Varnashi, and Ludhiana.

- Where the soil type is heavy, with an impervious subsoil layer and cloddy tilth, crop establishment and root penetration are poor.
- In a three-crop sequence with the grain legume sown in summer, inadequate availability of irrigation water may result in low yields.

Efforts to introduce short-duration grain legumes in the wet season have not been successful, primarily because of the high incidence of pests and diseases. If suitable pest- and disease-resistant genotypes become available, grain legumes could be introduced before wet season rice. In situations where water is limited, particularly in the winter months, oilseeds and grain legume crops could replace wheat.

Identifying grain legumes with high grain and stover production potential suitable for different agroclimatic conditions and cropping systems is very important. A few reports suggest that a dual-purpose grain legume can substitute for a green manure in a welldrained soil, and can provide good grain yield.

Rekhi and Meelu (1983) reported from India that mungbean *V. radiata* stover incorporated with 60 kg N/ ha after pod harvest produced a rice yield similar to that



2. Productivity of mungbean and peanut in rice-baed cropping systems, All India Coordinated Agronomic Research Project, 1982-85. Av of 2 locations: Thanjavur and Karamana.

Table 3. Effect of burying summer mung straw on the rice yield in the wheat summer mung - rice cropping sequence.[a]

N (kg/ha)	Rice grain yield (t/ha)			
	1980	1981	1982	Mean of 3 yr
		Straw removed		
0		3.2	3.2	3.2
60	5.0	4.6	6.0	5.2
120	7.1	7.0	7.2	7.1
		Straw buried		
0		6.4	6.5	6.5
60	7.2	7.4	7.5	7.4
120	8.9	7.8	8.9	8.5
CD at 5%	0.5	0.5	0.6	0.5

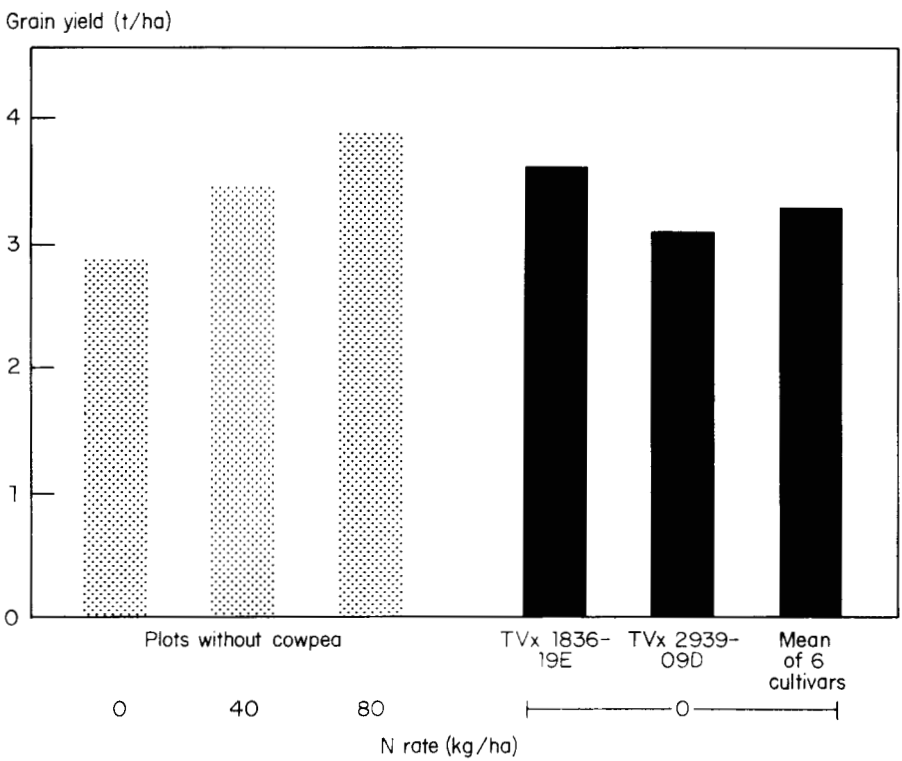
[a] Rekhi and Meelu 1983.

Table 4. Seed yield, dry matter yield, and N yield of 6 cowpea cultivars.[a]

Cultivar	Seed yield (t/ha)	Biomass yield (t/ha)	N (kg/ha)
TVx 1948-01E	1.658	4.67	74.6
TVx 1836-19E	1.301	4.73	102.8
TVx 2939-09D	1.761	5.06	83.7
TVx 289-4G	1.514	5.48	80.0
EG #2	1.490	4.16	83.7
All Season	1.551	4.43	56.4
Mean	1.547	4.75	80.2

[a]Timsina 1981.

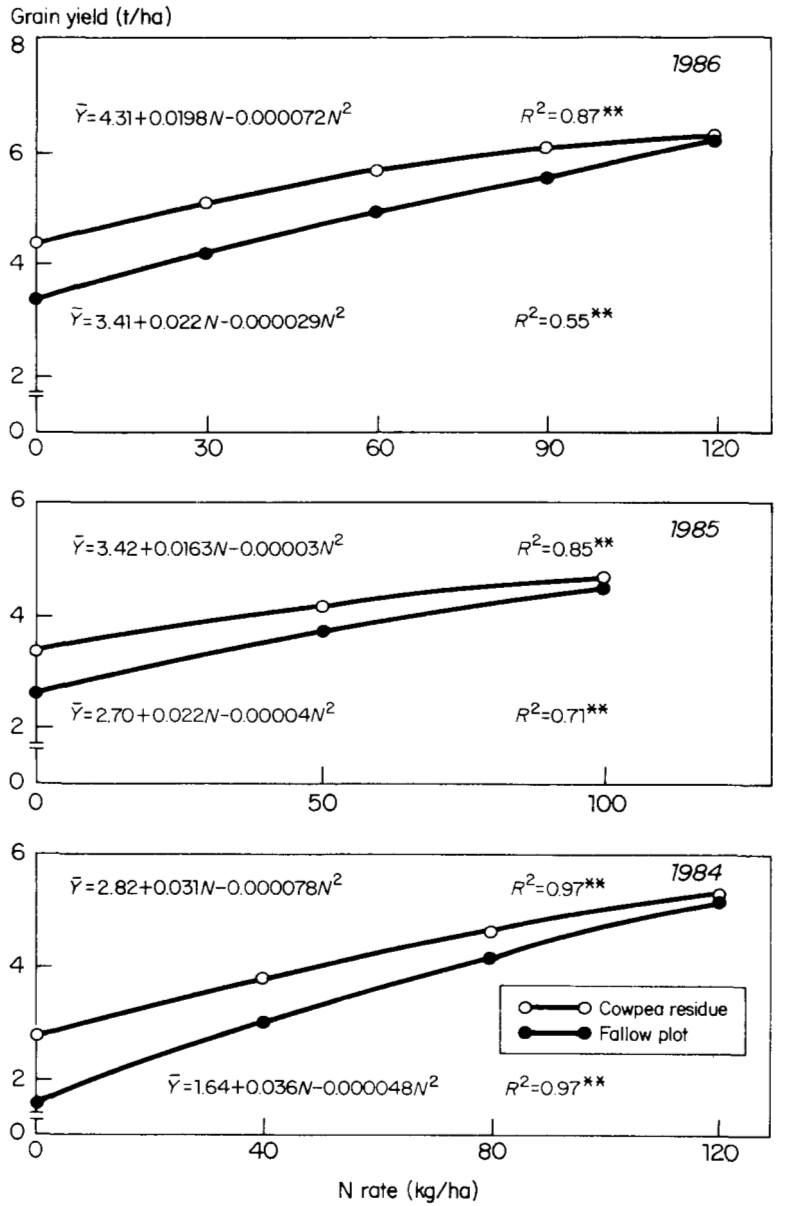
obtained with 120 kg N/ha without stover incorporation (Table 3). From China, Xiao (1980) reported that incorporating a winter crop of beans *Phaseolus vulgaris* L. after pod harvest gave a 19% increase in the subsequent rice crop yield. Timsina (1981) compared six cowpea cultivars for total dry matter, seed yield, and N yield (Table 4). Incorporating the cowpea residue increased dry seeded upland rice yield more than fallowing did (Fig. 3), but the magnitude of the response was lower than expected, probably because of the effects of dry seeding. At IRRI (1984-86 unpubl.



3. Effect of cowpea residue incorporation on rice yield in 1981 (Timsina 1981).

data), yield increases in transplanted rice were significant in plots with cowpea residue incorporated, compared to yields in fallow plots (Fig. 4). Seed crop residue and N yield with cowpea are given in Table 5.

Introducing early-maturing pigeonpea cultivars after lowland or upland rice can open an opportunity for a dual-purpose food and green manure crop. The 20



4. Effect on rice yield of N with and without cowpea residue incorporation. IRRI, 1984-86.

Table 5. Seed yield, biomass, and N yield from cowpea residue, 1984-86.[a]

Year	Seed yield (kg/ha)	Biomass incorporated (t/ha)	N yield in biomass incorporated (kg/ha)
1984	741	2.7	56.6
1985	912	2.9	47.2
1986	995	2.4	54.0

[a] IRRI, unpubl. data,

pigeonpea lines evaluated after rice at IRRI yielded 1-3 t seed/ha in 110 d (IRRI 1983). The crop was harvested by pruning at the lowest pod-bearing node. The ratoon yield was 300-1,200 kg/ ha. After the onset of rains, the ratoon crop grew vigorously and produced 12-15 t green biomass/ha, supplying 80-90 kg N/ha. That biomass can be incorporated as green manure (IRRI 1985). This practice could be more acceptable to rice farmers because it saves the cost of seed and land preparation.

Biomass production and N yield

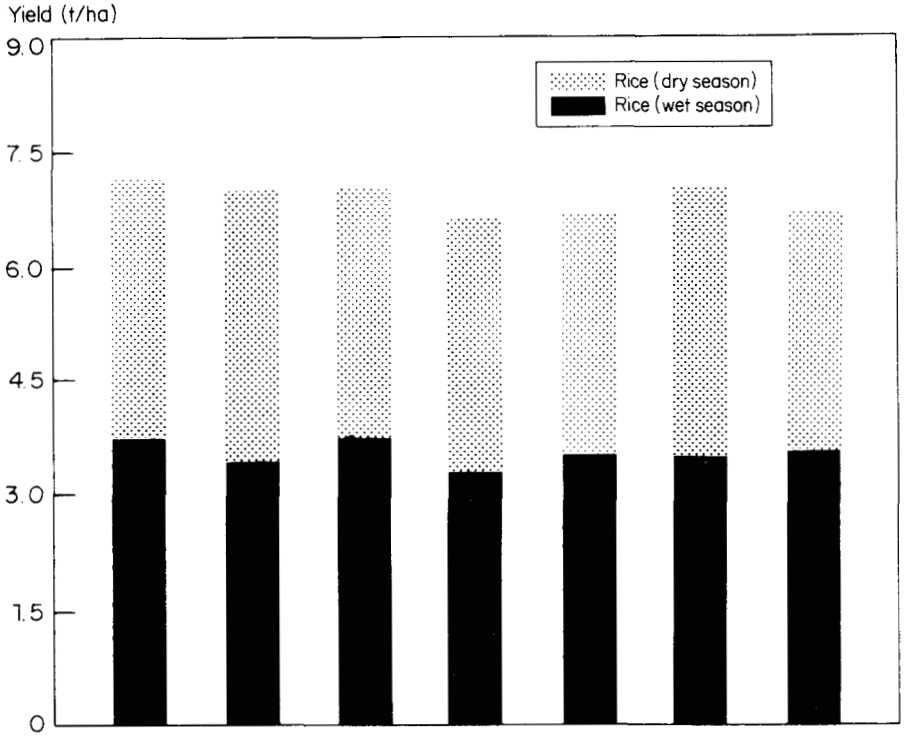
Alonso (1934) examined nine green manure crops for the relationship of days to flowering, fresh and dry matter yield, and N and P content to yield. Biomass N and P production increased, but N and P concentrations in the legume plants decreased toward maturity. When growing time was limited. mungbean and cowpea as green manure crops performed best.

Gonzales (1962) obtained fresh green manure yields of 9 t/ha in the wet season and 13 t/ha in the dry season from mungbean grown for 40-50 d. Bronson (1983) obtained dry matter yield of 1.55 t/ ha and N accumulation of 3 1 kg ha from cowpea 40 d after emergence.

Meelu et al (1985) evaluated *Sesbania bispinosa, Crotalaria juncea,* soybean, lablab *Dolichos lablab* L., pigeonpea, and cowpea for grain production (one priming) and green manure. At 60 d, dry matter yields ranged from 2.5 t/ ha for mungbean to 9.9 t/ha for sesbania. Mungbean produced 9.9 t grain/ha. N yield ranged from 50 kg/ha for mungbean to 224 kg/ha for sesbania.

In tropical areas with two rice crops, a shortduration grain legume (mungbean, black gram, or cowpea) can be grown for seed and green biomass incorporation. In field experiments on a rice - rice sequence at 5 locations in India, green manure was substituted for 50% N in wet season rice; yields equaled those with 100% N fertilizer (Fig. 5).

Green manure substituted for part of the N requirement of wet season rice at Pantnagar, Ludhiana, Pura Farm, and Jabalpur in India (Fig. 6). In most cases, substituting farmyard manure or crop residue for part of the N in the wet season crop affected total productivity of the rice - wheat sequence. When N as green manure or compost was increased from 25% to 50%. a productivity loss of 0.4-0.5 t/ ha resulted.



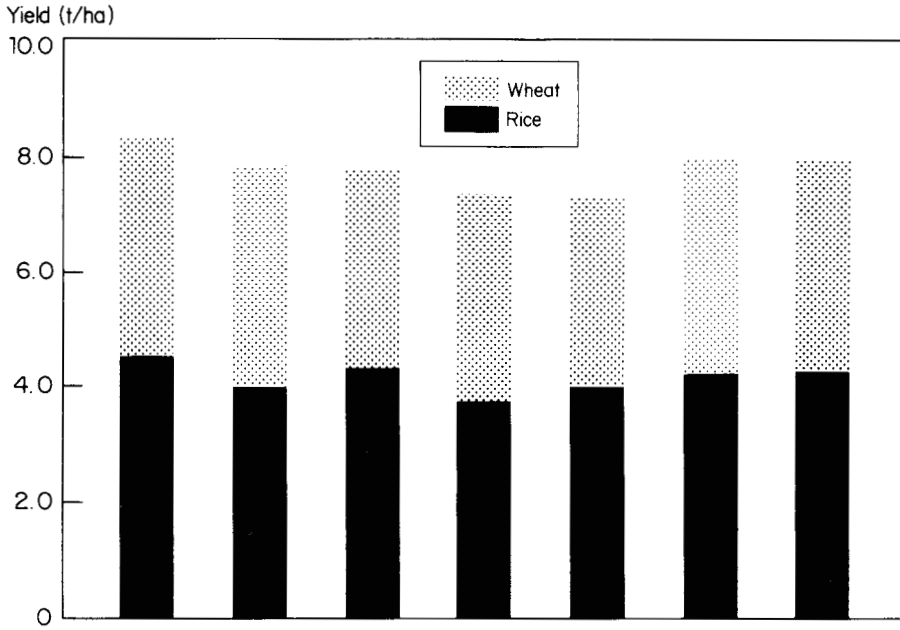
Treatments							
% NPK	100+100	50+100	75+75	50+100	75+75	50+100	75+75
% NC	-	50	50	-	-	-	-
% NCR	-	-	-	50	50	-	-
% NGM	-	-	-	-	-	50	50

5. Productivity of rice - rice sequence at different levels of N from various sources: NC = N from compost, NCR = N from crop residue, and NGM = N from green manure. All India Coordinated Agronomic Research Project, 1983-85. Av of 5 locations: Rudrur, Bhubaneswar, Eriplima, Sujuppy, and Karamana.

Future research

Available research shows the advantages of including dual-purpose grain legumes (food and green manure) in cropping systems. The residue can be incorporated to supply 30-60 kg N/ha. The long-term effects of green manuring on sustaining high yields cannot be overemphasized. Dual-purpose legumes offer considerable potential for harnessing atmospheric N to replace some chemical fertilizers in agricultural production. However, a fuller understanding of factors influencing their suitability for different production systems, soils, crop seasons, and farm resources is needed. A constraint to using dual-purpose crops is labor shortages during harvest.

Development of shortduration food legume cultivars coupled with high seed and biomass yield under drought stress and excess moisture deserves greater



Treatments							
% NPK	100+100	50+100	75+75	50+100	75+75	50+100	75+75
% NC	-	50	50	-	-	-	-
% NCR	-	-	-	50	50	-	-
% NGM	-	-	-	-	-	50	50

6. Productivity of rice - wheat sequence at different levels of N from various sources. All India Coordinated Agronomic Research Project, 1983-85. Av of 8 locations: R. S. Pura, Pantnagar, Sabour, Ludhiana, Pura Farm, Jaransi, Masodha, and Jabalpur.

attention. Management of these crops for biotic and soil factors also needs attention. Information on the effect of crop residue incorporation on chemical kinetics, N release and patterns, and physical properties of the soil will be needed to design benefit-maximizing systems.

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Notes

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Use of perennial legumes in Asian farming systems

P. K. R. Nair

Integration of leguminous(woody) perennials in crop and animal production fields is an age-old practice in Asian farming systems. The farming systems practices include a) using fast-growing, soil-improving woody species as fallow-improvers in shifting cultivation, b) planting multipurpose trees on or near farmlands for food, fodder, and fuel wood, c) multispecies, multilayer home gardens, and d) intercropped plantation combinations. In addition to their productivity, woody species also have protective functions, such as improvement of soil productivity, soil conservation, microclimate amelioration, watershed stabilization, and environmental protection. Research on multipurpose trees and integrated farming systems involving them has been rudimentary. Some recent attempts to exploit their potential, especially for soil fertility improvement, include alley cropping and other forms of mulch and green leaf management. Some significant results have been obtained, and substantial international efforts have gone into developing the exploitation of leguminous trees for production of fuel wood and tree fodder. Because of the lack of scientific data, the potential of these species remains vastly underexploited; the land-use systems involving woody species are mostly location-specific and tradition-bound. It is important to research technical aspects of the species and their management and the sociocultural aspects of farming systems involving them.

Asian farmers have a long tradition of raising food crops and trees, and sometimes animals, in an integrated and sustainable manner. However, such integrated land-use systems (which are usually low-input) have until recently been ignored by modern agricultural and forestry research. Agriculturalists and foresters operated, especially in the 1960s and 1970s, within rather rigid disciplinary boundaries. Although efforts resulted in substantially enhanced production of individual crop species, trees, and animals. it has become evident that high rates of production cannot always be sustained ecologically or economically.

As a consequence, the conservation benefits and the potential for sustained yields provided by integrated farming systems involving woody perennials have attracted quite a lot of attention. Perennial legumes that provide multiple outputs—food, fodder, and green manure—and farming systems involving them have aroused considerable enthusiasm and interest among land use researchers. This paper evaluates current use of perennial legumes in Asian farming systems and discusses the problems and prospects of the practice.

Farming systems involving perennial legumes

The International Council for Research in Agroforestry (ICRAF) has almost completed a global inventory of existing agroforestry systems. Information concerning agroforestry systems and practices in which trees and other woody perennials are grown in close association with crops and animals has been synthesized (Nair 1988). A search of the extensive database built from the inventory shows that leguminous woody species form a significant component in several farming (land use) systems in Asia. Using the component-based classification of agroforestry systems developed by Nair (1985), these agroforestry systems can be subdivided into three categories:

agrisilvicultural (crops, including tree crops, + trees),
silvopastoral (trees + pasture and animals), and
agrosilvopastoral (crops + trees + pasture and animals).

Although several agroforestry systems have been recorded under each category in Asia, only a few distinct combinations (practices) make up these systems in various ecoregions. The most common are considered here.

Improved fallow in shifting cultivation areas

Shifting cultivation (also known as the bush fallow, slash-and-burn, swidden, and a large number of local terms) is still a major land-use system in many parts of Asia. Forested land is cleared and cropped for a number of years, then left for regeneration of the bush (fallow period). The fallow period is much longer than the cropping period.

Two functions are commonly ascribed to the fallow phase:

1. To accumulate and conserve nutrients in the vegetation, protecting them from leaching, and
2. To increase the organic matter of the topsoil, thereby increasing the cation exchange capacity and the total nutrient availability in the soil.

Considering sociocultural and ecological circumstances, several alternatives have been suggested to replace or improve resource-depleting and environmentally degrading practices. One of the most promising is to plant appropriate tree species as soil improves during the fallow and to exploit the ability of rain forest to accumulate large quantities of biomass, even on infertile soils.

An ideal fallow species would be one that grows fast, takes up available nutrients, and recycles nutrients efficiently within the system—shortening the time required to restore fertility. Plant species differ in their nutrient uptake capacities, because of different uptake kinetics and root distribution. Among the several multipurpose leguminous trees rated fallow-improvers (Nair et al 1984, Nair and Fernandes 1984, Nair 1987b), those for the lowland humid tropics include *Albizia falcataria, Calliandra calothyrsus, Erythrina* spp., *Gliricidia sepium, Inga* spp., and *Sesbania grandiflora.* Several relatively short-duration leguminous species, such as *Cajanus cajan, Stylosanthes guianensis, Centrosema* spp., *Sesbania* spp., *Desmodium ovalifolium, Pueraria phaseoloides,* also can be used in short rotation fallows of 1 or 2 yr with agricultural crops.

Multipurpose trees on farmlands

Traditional Asian farming systems integrate various multipurpose trees on farmlands. An example is various *Acacia* and *Prosopis* species used in the dry regions for soil fertility improvement, fodder (leaves and pods), and fuel wood. Khejri *(Prosopis cineraria)* is mentioned in 2,000-yr-old writings as a tree on farmlands in the dry parts of western India. Other multipurpose trees are found on farmlands in other parts of India (Jambulingam and Fernandes 1986, Sankar-narayan et a1 1987) as well as in other countries of Asia (Amin 1987, Fonzen and Oberholzer 1984, Weerakoon, unpubl.).

One of the best-known uses of leguminous trees in Asian agriculture is incorporating tree loppings as green leaf manure in arable cropping, especially rice. Species of *Sesbania* are used for *in situ* green manure as well as for green leaf manure. *G. sepium, Leucaena leucocephala, C. calothyrsus, Erythrina* spp., *A. falcataria, Flemingia macrophylla, Delonix elata,* etc. grown on plot and field boundaries or in woodlots also are used as green leaf manure.

Leguminous fodder trees

A vast array of leguminous trees and shrubs serve as animal fodder in the tropics and subtropics (Brewbaker 1985, Pandey 1982, Singh 1982). Although grass species will continue to be the primary tropical fodder, shrub and tree species are viewed as protein sources and soil improvers. Most leguminous trees and shrubs are N fixers (92% of mimosoids and papilionoids and 34% of caesalpiniodes). The leguminous N-fixing genera with high fodder nutritive value and wide use in Asia include *Acacia* spp. *(aneura, nilotica, xanthophloea), Albizia* spp. *(lebbeck, odoratissima, stipulata), C. calothyrsus, Desmodium discolor, G. sepium, Hardwickia binata, L. leuco-cephala, Pongamia pinnata, Prosopis* spp. *(cineraria, spicigera), S. grandlflora,* etc. Some leguminous genera of good fodder value *(Bauhinia* and *Cassia)* are not known to nodulate, and therefore do not fix nitrogen (Allen and Allen 1981, Brewbaker 1985, Halliday 1984).

Leguminous shrubs and trees are incorporated into Asian farming systems as scattered trees on farmlands, woodlots, and boundary planting for plot or field demarcation or avenues. They are also grown on communal lands, roadsides, railway rights-of-way, waterways, and wastelands.

Home gardens

Home gardens are land-use systems involving deliberate management of multi-purpose trees and shrubs in intimate association with annual and perennial agricultural crops and livestock within the compounds of individual houses. The whole crop-tree-animal unit is intensively managed using family labor (Fernandes and Nair 1986). These agroforestry systems are common all over Asia, and analytical descriptions of a number of them have been published recently—the Javanese home gardens (Soemarwoto and Soemarwoto 1984, Wiersum 1982), the Philippines home gardens (Sommers 1975), the Kandyangardens of Sri Lanka(Jacob and Alles 1987). homestead farming in Kerala, India (Nair and Sreedharan 1986), and the home gardens of Bangladesh (Leuschner and Khalique 1987). Food production is the

primary function of most home gardens. Alhough the average size is less than 0.5 ha, they usually have a large number of woody and herbaceous species, carefully structured to form 3-5 vertical canopy strata, with each component having a specific place as well as function.

Leguminous trees and shrubs are found in most home garden systems, although they seldom form a major component. Those found in Asian home gardens include *C. cajan, Cassia* spp., *G. sepium, L. leucocephala, Tamarindus indicus,* and *Pithecellobium dulce* (Fernandes and Nair 1986).

Multistory plantation crop combinations

Another common land-use system in the thickly populated areas of the humid tropics is multistory crop combinations involving plantation crops such as coconut, areca nut, spice trees, rubber, etc. Such systems also have been described in India (Nair 1979) and Sri Lanka (Liyanage et al 1984). Leguminous trees and shrubs can be found in some of these systems, for example:

1. Use of leguminous trees such as *G. sepium, Erythrina* sp., *A. falcataria,* etc. as live standards for black pepper (Jacob and Alles 1987, Nair 1979):
2. Shade trees or overstory species for shade-tolerant plantation crops, such as *L. leucocephala* over cacao in the Solomon Islands (Vergara and Nair 1985), *Inga* and *Erythrina* spp. over coffee and cacao in Java and Brazil (Alvim and Nair 1986), and *Albizia molucana* as shade over tea in Sri Lanka (Liyanage et al 1984); and
3. Leguminous tree species along with plantation crops (e.g. *Leucaena* under coconuts) for firewood, green manure, and soil improvement (Nair, unpubl.).

Leguminous trees in dry regions

Some leguminous trees (*Acacia* spp., *Prosopis* spp.) are common components of farming systems in the dry (arid and semiarid) zones of Asia, where their beneficial effects include soil fertility improvement (Mann and Saxena 1980) and fodder and fuel wood (Sankarnarayan et al 1987). Other notable uses of such species in the dry parts of Asia are

1. For sand dune stabilization—*Acacia tortilis* and other species of *Acacia, Prosopis juliflora, P. cineraria,* etc.;
2. As shelterbelts and windbreaks—*Acacia nilotica, Dalbergia sissoo, Cassia siamea, Inga dulce, Parkinsonia aculeata,* and other species of *Acacia;* and
3. In fuel wood plantations.

These few field examples indicate the importance of leguminous trees and shrubs in Asian farming systems as well as in the livelihood of the people. The perennial legumes that are commonly used in these farming systems are listed in Table 1, with their main uses, roles, and ecological adaptability.

Role of perennial legumes

The role and function of trees in agroforestry systems can be grouped under two major categories: production of basic needs (food, fodder, fuel wood, etc.) and protection of the environment (soils, microclimate, watershed, etc.).

Table 1. Perennial legumes commonly used in Asian farming systems (Nitrogen-Fixing Tree Association and ICRAF database on N_2-fixing, nodulating trees).

Species	Ecological adaptation	Growth form and characteristics	Major uses or function[a]	N_2 fixation (nodulation) capability[b]	Other remarks
Acacia albida	Dry zone, drought-tolerant	Tree to 20 m, thorny	F, GM, A, SF, WLR	+	Leafless in rainy season, common in African farming systems
Acacia auriculiformis	Lowland humid tropics	Tree to 20 m	PW, Or, SC, FW, ST	+	Pulpwood species
Acacia mangium	Lowland humid to subhumid	Tree to 20 m	FW, SC, T, PW, SB	+	Plantation species, fast-growing
Acacia nilotica	Dry zones, drought-tolerant	Tree to 10 m, very thorny, deciduous	SC, FW, T, A, DS WLR	+	Widespread in dry regions
Acacia polycantha (A. catechu)	Lowlands, low drought tolerance	Tree to 25 m, coppices well	A, FW, G	+	Good fodder
Acacia saligna (A. cyanophylla)	Dry zones, low- and midlands; tolerant of salt, drought	Tree to 10 m, fast-growing, shrubby	FW, T, DS, WLR	+	
Acacia senegal	Dry zones, low- and midlands	Tree to 10 m, thorny, deciduous, shrubby	FW, WLR, DS, G	+	Gum-arabic tree
Acacia seyal	Dry zones	Slender tree to 12 m, long thorns	A, G, T, WLR	+	Important animal feed
Acacia tortilis	Dry (arid) zones, tolerant of alkalinity, drought	Flat-topped tree to 15 m, thorny	FW, A, WLR	+	More popular in Africa
Acacia xanthophloea	Dry to subhumid tropics	Tree to 20 m, spiny	O, Or, FW	+	Lopped fodder

Continued on next page

Table 1 continued.

Species	Ecological adaptation	Growth form and characteristics	Major uses or functions[a]	N_2 fixation (nodulation) capability[b]	Other remarks
Albizia chinensis	Up to 1500 m, dry to subhumid subtropics	Tree to 15 m, deciduous, fast-growing	T, A, ST	+	Rapid growth
Albizia falcataria	Humid to subhumid lowlands	Tree to 30 m	SF, PW, Or	+	Common in Southeast Asia as plantation species
Albizia lebbeck	Wide adaptability, dry-humid tropics	Tree to 25 m	FW, A, CT, Or	+	Rapid growth
Albizia odoratissima	Tropical highlands	Tree to 25 m	A, Or	+	Highly lopped for fodder
Cajanus cajan	Wide adaptability	Annual to perennial	F, GM, FW, SC, A	+	Widely used for a variety of purposes
Calliandra calothyrsus	Humid tropical midlands	Shrub to 8 m, fast-growing, acid tolerant	FW, SC, BF, GM, A, Or, T	+	Low fodder value
Cassia siamea	Semiarid to subhumid	Shrub to 8 m, coppices vigorously, drought tolerant	FW, SC, FW, A	-	Good for alley cropping
Dalbergia sissoo	Tropical and sub-tropical midlands, subhumid to humid	Tree to 30 m	T, FM, ST, A	+	Indian teakwood
Erythrina spp.	Humid lowlands to highlands	Tree to 20 m, often thorny, coppices well, propagated by stem cuttings	GM, ST, Or, WB, A	+	Used as live standard for black pepper
Flemingia macrophylla	Humid lowlands	Shrub to 3 m	GM, A	+	Common in Southeast Asia as a green manure crop in plantations
Gliricidia sepium	Humid to subhumid lowland tropics	Tree to 20 m, vigorous coppicing, fast growth	GM, A, FW, ST, SC	+	Very commonly used multipurpose species

Hardwickia binata	Dry tropics, drought-tolerant	Tree to 30 m, slow-growing	W, SC, A, FW, DS, Fi	0	Valued heavy wood
Leucaena leucocephala	Humid to subhumid lowlands	Tree to 20 m, vigorous coppicing, fast-growing, not acid-tolerant	GM, A, FW, ST, SC, PW, F	+	Widely studied and extensively used
Pithecellobium dulce	Wide adaptability from dry to humid zones	Tree to 20 m, thorny	A, FW, Or	+	Pods and leaves browsed
Pongamia pinnata (Derris indica)	Low and midland humid tropics	Small tree to 8 m, salt-tolerant	FW, A, CT, ST, Fi	-	
Prosopis cineraria	Dry zones, heat resistant	Tree to 8 m, thorny	SF, GM, A, T, DS, FW	0	Highly valued in Indian desert
Prosopis juliflora	Dry zones, heat and alkali resistant	Tree to 10 m, coppices	FW, GM, A, DS, SC, WLR	+	Widely lopped for fodder in India
Pterocarpus marsupium	Dry to subhumid lowland tropics	Tree to 30 m, coppices well	A, FW, T	+	Widely lopped for fodder in India
Samanea saman	Highland to lowland tropics	Spreading tree to 40 m, fast growth	T, Or, CT, A, F	-	Pods good for human as well as animal consumption
Sesbania spp. *bispinosa, grandiflora, rostrata, sesban*	Lowland humid to midland semihumid	Low trees, very fast growth, some are annuals (*S. sesban*)	GM, A, SC, SF, FW, PW, Or	+	Widely used
Tamarindus indica	Wide adaptability	Large trees to 30 m	F, A, CT, FW, ST	-	Pods rich in vitamin C

[a] A = animal feed (pods, leaves, bark, etc.), BF = bee forage, CT = construction/craft timber, DS = dune stabilization, F = food (human consumption), Fi = fiber, FW = firewood, GM = green (leaf) manure, Or = ornamental, PW = pulpwood, T = timber, SC = soil conservation, SF = soil fertility improvement, ST = shade tree (over cacao, coffee, tea), WLR = wasteland reclamation. [b] + = reported to nodulate, - = reported not to nodulate, 0 = no report available.

Productive role

ICRAF's multipurpose trees and shrub (MPT) database has records of over 50 leguminous woody species with edible parts, such as fruits, pods, leaves, flowers, etc. (Carlowitz and Wolf, pers. comm.). The extent to which these plants contribute to human dietary requirements in different countries depends on a number of site-specific factors.

Protective role

The protective role of perennial legumes depends on their soil-improving and soil-conserving functions. Leguminous woody perennials can improve and enrich soil conditions through fixation of atmospheric N, addition of organic matter through litter and dead and decaying roots, and modification of soil porosity and infiltration rates, leading to reduced erodability and improved nutrient cycling efficiency within the soil-plant system (Nair 1984).

The role of woody perennials in the physical conservation of soil is also very important in farming systems. The long tradition of planting *L. leucocephala* in contour hedges for erosion control and soil improvement in Southeast Asia, especially in Indonesia and the Philippines, is an example. Indirect terraces are also formed when washed-off soil collects behind 1ive hedges. Loppings and prunings from such hedgerow species could provide mulch to help prevent sheet erosion between trees (Neumann 1983). More plant cover, alive or as mulch on the soil, also reduces the impact of rain, minimizing splash and sheet erosion. Perennial legumes are not only potential physical barriers against erosive forces, but also useful as mulch or fodder and fuel wood (Lundgren and Nair 1985, Young 1986).

Other protective functions of woody perennial legumes in farming systems are as live fences, shelterbelts, and windbreaks. Using woody perennials to protect agricultural fields from trespassing or against the adverse effects of wind is widespread in many agricultural systems. Encouraging results with shelterbelts and windbreaks have been obtained at the Pakistan Forestry Research Institute, Peshawar (Sheikh and Chima 1967, Sheikh and Khalique 1982) and the Central Arid Zone Research Institute, Jodhpur, India (Sankarnarayan et a1 1987). The beneficial effects of trees on soil productivity and protection are given in Table 2.

Using perennial legumes in Asian farming systems

Despite the seemingly significant role of perennial legumes in Asian farming systems, research has been rudimentary. The reasons include the commodity and discipline orientation of researchers, lack of an institutional niche for integrated land-use systems in research institutions set up along disciplinary lines, and improper understanding of the value of such farming systems. With increasing awareness of the potential of such systems, and the failure of some monocultural, high-input production strategies, the situation is slowly changing. The efforts that are under way are predominantly examining the potential for soil fertility improvement of legumes, especially through alley cropping and green leaf manuring.

Table 2. Potential benefits from trees on different soils (Nair 1987c).

Nature of processes	Processes	Main effect on soil	Scientific evidence
Input (augment additions to the soil)	Biomass production	Addition of C and its transformations	Available
	Nitrogen fixation	N enrichment	Available
	Rainfall	Effect on rainfall (quantity and distribution) and therefore nutrient addition through rain	Not adequately demonstrated
Output (reduce losses from the soil)	Protect against water and wind erosion	Reduce loss of soil as well as nutrients	Available
Turnover	Nutrient retrieval, cycling, or release	Uptake from deeper layers and "deposition" on surface via litter	Not adequately demonstrated
		Withholding nutrients that can be lost by leaching	Not demonstrated
		Timing of nutrient release: this can be regulated by management interventions.	Available
Catalytic (indirect influences)	Physical processes	Improvement of physical properties (water-holding capacity, permeability, drainage, etc.) at the microsite as well as at the watershed (macrosite)	Available
	Root growth and proliferation (enhanced)	Addition of (more) root biomass; growth-promoting substances; microbial associations	Partially demonstrated
	Litter quality and dynamics	Improvement of litter quality through diversity of plant species; better timing of quantity, and method of application of litter possible	Now being increasingly studied in alley cropping and other intercropping experiments
	Microclimatic processes	Creation of more favorable microclimate; shelterbelt and windbreak effects	Available
	(Bio) chemical or biological processes (net effects of various processes)	Moderating effect on extreme conditions of soil acidity, alkalinity, etc.	Partially demonstrated

Alley cropping

In alley cropping, arable crops are grown in the interspaces (alleys) between rows of planted trees or woody shrubs. The trees and shrubs are pruned periodically during the cropping season to prevent shading and to provide green manure or mulch to the

arable crop (Kang et al 1981, 1985; Wilson and Kang 1981; Wilson et al 1986). The practice has been widely used for along time in upland farming systems of Southeast Asia. Alley cropping experiments are being undertaken in many agricultural research institutions of Asia, mostly in the tropical lowlands and, to some extent, in the semiarid tropics. Data from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, over the past few years (Kang et al 1985) show the benefits of alley cropping on crop production (Table 3,4).

The woody leguminous species that are commonly used as hedgerows in alley cropping are *L. leucocephala, G. sepium, C. siamea, C. calothyrsus, C. cajan, Tephrosia candida, Flemingia congesta,* etc. The one most widely tested is *L. leucocephala.* Some examples of biomass production from *L. leucocephala* hedgerows are presented in Table 5. With proper management, this species can be successfully grown for alley cropping, even in semiarid areas (ICRAF 1987).

Recent investigations indicate that there may be even more promising woody leguminous species for alley cropping in humid regions. In trials at Mahaillup-pallama, Sri Lanka, using *L. leucocephala* and *G. sepium,* both species produced about 6 t leaf dry matter/ha per yr. Maize yield was consistently higher in *G. sepium* plots than in *L. leucocephala* plots (Weerakoon 1987). Data from Nigeria showed the superiority of *C. siamea* over *G. sepium* and *L. leucocephala* in initial biomass production and litter fall, although estimates of N made available by *C. siamea* to alley-cropped maize showed a shortfall (Yamoah et al 1986a,b).

Table 3. Effect of *Leucaena* prunings and N on grain yield of maize[a] variety TZPB alley cropped with *L. leucocephala.* International Institute of Tropical Agriculture, Ibadan, Nigeria.

N fertilization rate (kg/ha)	*Leucaena* prunings	Maize grain yield (t/ha)				
		1979	1980	1981	1982	1983
0	Removed	-	1.04	0.48	0.61	0.26
0	Retained	2.09	1.91	1.21	2.10	1.92
80	Retained	3.54	3.26	1.89	2.91	3.16
LSD 0.05		0.36	0.31	0.29	0.44	0.79

[a] The maize crop was seriously affected by drought during early growth.

Table 4. Chemical properties of surface soils (sandy Entisol) after 6 yr of alley cropping *Leucaena leucocephala* with maize and cowpea (Kang et al 1985). IITA, Ibadan, Nigeria.

Treatment (kg N/ha)	*Leucaena* prunings	pH-H_2O	Organic C (%)	K	Exchangeable Ca (meq/100 g)	Mg	P (ppm) (Bray no. 1)
0	Removed	6.0	0.65	0.19	2.90	0.35	27.0
0	Retained	6.0	1.07	1.28	3.45	0.50	26.2
80	Retained	5.8	1.19	0.26	2.80	0.45	25.6
LSD 0.05		0.2	0.14	0.05	0.55	0.11	5.3

Table 5. Some examples of biomass production from *Leucaena leucocephala* hedgerows (Huxley 1986).

Spacing	Country	Reference	Biomass production (t dry matter/ha per yr)	Comments
2 x 2 m	Indonesia	Soekotyo (1982)	3.6 (cultivar Cunningham)	Sun-dried
1 x 1 m	Ambarnath, India	Sudhir et al (1982)	20.6 (extrapolated)	Cultivar K8 (?)
Various	Various areas in tropics	Torres (1984)	6.1-17.6	Summarized yield data from 7 authors
0.25 X 4.0 m	Nigeria	Kang et al (1985)	5.77-7.04 (prunings removed)	40 + 80 kg N/ha raised biomass production 1 yr out of 3 - not including woody stems
			5.46-6.32 (prunings retained with woody stems) Means= 11.15 (removed) = 10.40 (retained)	

More research is needed before alley cropping can be adopted as a sustainable practice. We need to understand more fully the ways in which the components in such a mixed system interact and to identify more clearly the processes by which environmental resource-sharing can be optimized, both by selecting species with appropriate characteristics and by suitable management practices (Huxley 1986).

Mulch and green leaf manure

Another successful age-old practice in plant residue management in Asian farming systems is using green (leaf) manure derived from appropriate short-duration species grown *in situ,* then incorporated, or from relatively long-duration species grown away from the crop field. Agronomic literature of the 1950s and 1960s are full of references to various aspects of green manure use.

Among the plants used for green manure in rice, various species of the genus *Sesbania* are the most prominent. Singh (1984) concluded that *S. aculeata* (syn. *S. cannabina*) and *S. speciosa* are the most commonly used species in India. They could increase rice yields more than the application of 90 kg N/ha. Bhardwaj and Dev (1985) found that incorporating *S. aculeata* grown as a catch-crop in a wheat - rice crop rotation system in northern India just before transplanting rice resulted in rice yield equivalent to that with 100-120 kg fertilizer N/ha. Some data on the addition of organic matter and N to soil through the aboveground biomass of the plant are given in Table 6.

In field studies in Sri Lanka, *S. rostrata, S. aculeata,* and *S. sesban* were the most promising in terms of leaf biomass production (Palm et al 1987).

Transporting nutrient-rich, easily decomposable green leaf manure from trees and woodlots situated near crop production fields and applying them as a supplement to chemical fertilizers is another popular aspect of mulch and organic

Table 6. Addition of organic matter and N to soil through the aboveground biomass of *Sesbania cannabina*[a] (Bhardwaj and Dev 1985).

Age(d) when turned in	Green matter (t/ha)	Dry matter (t/ha)	Moisture (%)	N (%)	Total N added (kg/ha)	Carbon (%)	C:N
45	18.2	3.1	83	3.12	97.6	56	18
55	28.0	5.3	81	2.78	147.3	55	20
65	37.1	7.3	80	2.25	165.1	52	23

[a] Average of 3 locations in each case.

matter management in Asian farming systems. Both legumes and nonlegumes commonly are used as woody species. In a trial with *L. leucocephala* grown on the bunds of rice paddies, Weerakoon and Gunasekera (1985) reported that about 2.5 t leaf dry matter/ha could be obtained every cropping season. When this leaf manure was applied to the rice crop, grain yield was 2.2 t/ha, 750 kg more than the yield from the plot fertilized with 43 kg mineral N/ha. *S. grandiflora, G. sepium,* and *F. congesta* are some other perennial legumes popularly used for this practice.

Difficulty in transporting and handling bulky green materials is a major problem in the adoption of a cut-and-carry practice (Weerakoon and Seneviratne 1984). Growing the trees on field bunds also could be unattractive to farmers because the bunds usually are used as footpaths. A drawback of the *in situ* system in a sequential multiple cropping system is that land is occupied by the legume during a cropping period which could be used for a short-duration cash crop.

One aspect often overlooked in green leaf manure cropping technologies is the amount of plant material required to change long-term characteristics of the soil vis-a-vis the quantities of such materials that can be expected to be available under ordinary farming conditions, particularly in semiarid regions where climate imposes a serious restriction on the biomass production of plant species. This should be an important consideration in assessing the merits of alley cropping, as well as other mulch management technologies.

Fuel wood and tree fodder

In response to the gravity of the fuel wood problem in developing countries, substantial international efforts have gone into planting trees for fuel wood in recent years. But, apart from identifying and describing tree species suitable for various agroecological conditions, research has not addressed the problems and constraints that restrict improvement in the production of fuel wood and the productivity of different species.

Essentially any woody plant can be used as a firewood. However, the term firewood species as it is used in the current literature denotes plant species deliberately cultivated to provide firewood for cooking, space heating, and lighting. The U.S. National Academy of Science identified over 1,200 firewood species. About 700 were given top ranking, signifying that they are potentially valuable and deserve increased research attention; 87 have been described in some detail (NAS 1980, 1983). The primary emphasis in that compilation was the suitability of a species for growing as firewood for individual family needs. Most of the plants

described are little known in traditional forestry production, but are common in agricultural systems. Many are legumes; the most promising are listed in Table 1.

Nair (1987) examined the ways in which these species could be incorporated into agroforestry farming systems. He considered it unlikely that substantial areas of forests or agricultural lands will be available for fuel wood production. Therefore, the most feasible approach would be to integrate appropriate species of fuel wood trees into farmlands in a complementary rather than competitive way and to employ agroforestry techniques to reclaim and utilize degraded lands and wastelands. Efforts are being made on using *S. sesban, S. aculeata,* and *C. cajan* for firewood production in alkaline soils in India (Rao and Gill 1987) and on using *Acacia tortilis, A. nilotica,* and *P. cineraria* for firewood production and sand-dune stabilization in the arid parts of India (Sankarnarayan et al 1987) and Pakistan (Amin 1987).

Reports on the use of leguminous trees for fodder are many (Fonzen and Oberholzer 1984, Pandey 1982, Singh 1982), but efforts to improve the output and quality of fodder or to refine the management of fodder trees as well as the land-use systems involving them are minimal. Fodder quality and the plant's multipurpose nature are two important characteristics that govern their value in integrated farming systems. In this context, the nutritive values of the common leguminous fodder plants reported by Brewbaker (1985) are very important (Table 7).

Some of the highly palatable leguminous fodder trees in the tropics are non-N fixers — *Bauhinia, Cassia, Ceratonia, Gleditschia, Parkinsonia,* etc. (Le Houerou 1980). N-fixing woody species become progressively more rare the further from the equator (Brewbaker 1985).

Research considerations

This review shows the renewed interest in the age-old use of leguminous and other woody perennials in Asian farming systems. The value of the practice in providing multiple outputs and its role in imparting sustainability and environmental protection to farming systems are being increasingly realized. However, controlled research data are scarce. Information on the management options for exploiting the suggested potentials of the species also is scanty. These circumstances clearly warrant detailed research.

The immediate objectives of research into the use of leguminous perennials in farming systems should be

- To establish the scientific validity of the often-mentioned, but experimentally not proven, virtues of practices and technologies involving leguminous woody perennials;
- To understand the processes by which incorporation of these species accomplish the expected benefits;
- To suggest the optimal management of different species so as to derive maximum potential under different conditions;
- To devise appropriate experimental methodologies (research designs, sustainability parameters, assessment of indirect benefits, etc.) to study these perennials; and

Table 7. Forage quality [a] of some leguminous tree fodder (Brewbaker 1985).

Species	CP	Fat	CF	NFE	Ash	P	Ca	Mg	K	Si
Acacia albida	14.7	1.7	18.5	58.9	5.7	0.18	0.90	0.19	1.25	0.5
A. nilotica	13.6	8.1	10.7	59.8	7.1	0.14	1.80	0.19	0.80	0.8
	15.0	5.1	20.1	51.6	8.2	0.19	1.5			
	19.2	3.2	8.1	61.5	8.0	0.38	1.9			
Fruits	10.4	1.6	17.0	66.7	4.2	0.14	0.66	0.14	1.1	0.1
A. polycantha	15.5	3.8	22.1	48.7	9.7	0.15	2.60			
A. senegal	22.4	3.8	20.2	44.7	8.7	0.20	1.22	0.30	1.0	0.78
Mature	14.1	3.4	43.1	33.7	5.7					
Immature	33.6	3.0	29.0	28.1	5.6					
A. seyal	18.5	2.5	18.3	54.1	6.1	0.27	1.1	0.34	1.14	0.57
	15.2	2.7	19.2	55.9	7.0	0.17	1.39		0.72	0.37
A. tortilis, mature	10.3	3.0	46.1	34.4	6.2					
Immature	6.5	2.8	34.1	47.8	8.8	0.13	3.14			0.32
Fruits	17.8	1.7	17.5	54.6	8.4	0.36	1.34			
A. xanthophloea, mature	10.0	2.5	45.2	37.6	4.7					
Immature	16.0	2.0	18.0	55.8	8.2	0.15	0.98		1.89	0.55
Albizia falcataria	21.2	4.6	37.0							
A. lebbeck	21.6	3.7	31.8	33.6	9.3	0.20	1.9			
	29.2	3.5	25.3	34.5	7.5	0.20	1.8	0.50		
Cajanus cajan	17.3	6.0	28.1	39.7	6.7					
Leaf	15.8		29.2		5.5	0.22				
Small stem	10.5		48.7		4.4	0.25				
Whole plant meal	14.8	1.7	28.9	39.9						
Calliandra calothyrsus	24		24		4.1					
Dalbergia sissoo	17.7	4.0	23.9	43.5	11.7	0.27	2.0			
Av many	12.6	3.0	22.3	53.0	9.1	0.19	2.87			
Gliricidia sepium, leaf	15.6		21.2		5.5	0.13				
	25.0		35.0		3.8					
Hardwickia binata	9.0	4.0	30.4	49.7	6.9	0.13	2.28			
Leucaena leucocephala	20.3	5.5	18.3	47.5	9.3	0.16	2.3	0.6	1.3	
	21.5	6.5	14.3	49.5	4.3	0.17	2.7			
	15.2	3.0	15.0	55.7	11.1	0.19	2.99			
	20.0	6.5	14.1	48.3	11.2					
Leaf tips	18.8	2.3	37.7	34.5	6.6					
Leaf	15.9		18.3		9.3	0.17				
Stem	4.4		57.7		3.4	0.22				
Pithecellobium dulce	23.5	3.0	23.1	45.6	5.0					
Leaf	29.0	4.4	17.5	43.6	5.6	0.35	1.14			
Pongamia pinnata	17.6							0.22	2.23	
Prosopis chilensis	21.2	3.2	28.5	41.8	5.4	0.16	1.91	0.21	1.48	
Fruits	12.6	2.0	25.1	53.3	4.6	0.20	0.65			
Fruits	13.7	1.9	27.9	52.6	3.9	0.20	0.65	0.11	1.42	
P. cineraria	14	3	19	57	7	0.3	2.5			
Fruits	14.6	3.5	19.5	55.8	6.6	0.32	2.72			
P. juliflora (=pallida)	19.0	2.9	21.6	47.9	8.5	0.22	2.08			
	18.2	3.3	29.7	41.9	6.8	0.16	0.67		1.5	
Fruits	13.2	2.8	23.1	54.4	4.5	0.15	0.27	0.10	1.4	0.10
Fruits	11.8	3.0	26.0	55.0	4.1	0.25	0.35		1.73	
Pterocarpus erinaceus	15.0	2.4	27.3	47.3	7.8	0.16	0.96	0.43	2.8	0.7
	19.0	2.7	35.5	35.6	7.2	0.24	0.56		2.44	
Sesbania grandiflora	34.8	4.2	7.5	48.7	12.5	0.33	2.33			
S. sesban	25.0	2.6	14.4	49.4	7.5	0.271	0.11			

[a] CP = crude protein (N × 6.25%), fat = ether extractable fraction, CF = crude fire (acid detergent), ash = total minerals after calcination, NFE = nitrogen-free extracts, primary carbohydrates. P, Ca, Mg, K, and Si are percent of dry matter.

- To evaluate the socioeconomic and environmental desirability and farmers' reaction to increased use of woody perennials in farming systems.

Both biological and socioeconomic aspects need research attention. Some sociocultural problems are intimately tied up with the general situations of different countries, and hence cannot be easily or quickly overcome. On the other hand, some biological aspects can be effective with rather low levels of inputs. ICRAF's global inventory of agroforestry systems identified some research topics for agroforestry research in general; these are relevant to leguminous perennials as well. They include various aspects of plant species, their arrangements, and their management (Nair 1988).

To achieve these aims and accommodate the various topics, it is essential to have on-station experiments, on-farm trials, and broad-based studies that include data and experience from both.

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Integrated use of green manure in ricefields in South China

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Cultivation of green manure in the ricefield ecosystems of several provinces in South China are summarized and the efficiency of green manure in improving soil fertility and increasing rice yields discussed. Characteristics and cultivation techniques for winter green manure *Astragalus,* and summer green manure sesbania and Chinese honey locust *Aeschynomene indica* L. are described and recent developments in the use of the annual green manure azolla reported. Integrated use of green manure and prospects for increasing its economic value in rice farming systems are described.

Winter green manure

Astragalus sinica L. originated in China, where its cultivation dates back 1,000 yr. During the Ming Dynasty, *Astragalus* was already being cultivated on a large scale along the middle and lower reaches of the Yangtze River (Min 1982).

Since the 1940s, attention by the government and improved cultural techniques have caused the area to grow. During the past 15 yr, the cultivated area has expanded northward along the Long-hai railway and now exceeds 60 million ha, mainly in the plains along rivers and seaboards of Zhejiang, Jiangsu, Shanghai, Anhui, Jiangxi, Hunan, and Hubei Provinces. Beginning in the 1960s, *Astragalus* cultivation also expanded to hilly lands, including red-yellow upland soils.

In Fujian Province, *Astragalus* originally was grown on only about 67 ha in Guangzhe and Shaowu counties. By the mid-l970s, the cultivated area had grown to 223,000 ha distributed all over the province.

Characteristics of *Astragalus*

Because of its suitability for a temperate climate, *Astragalus* could become the primary green manure crop grown in China. Within an optimum temperature range, growth is stimulated as temperature increases. When the average daily temperature is below 3 °C, the top part of *Astragalus* nearly stops growing, although healthy seedlings can tolerate a short period of temperatures as low as –17 to - 19 °C (Li 1979). Even though the leaves freeze and die, the stem tips inside the leaf clusters and the branch buds do not freeze.

At the seedling stage, *Astragalus* shade tolerance is rather strong. When light intensity is less than 6,000-7,000 1x, growth is luxuriant: at less than 3,000 1x, seedling growth is thin and weak.

In experimental plots in northern Jiangsu, middle Henang, and the Guangzhong region of Shanxi Provinces, *Astragalus* biomass reached 40-75 t/ha.

During flowering, when fresh biomass averages 22.5-30 t/ha, the amount of N fixed in the field may reach 81-128 kg/ ha. With 75 t/ ha fresh biomass, N fixing may reach 270 kg/ha. Because of the low lignin and C:N of *Astragalus*, N utilization by rice is high in the first cropping season, with residual N available for the late cropping season (Table 1).

With its high N-fixing capacity and high residual soil N, grain yields are comparable to those with other green manure crops, such as azolla, *Vicia* L., and *Vicia faba*, and those with pig dung, cow dung, and ammonium sulfate (Table 2). Usually, 1 kg fresh biomass of *Astragalus* will increase rice grain yield 12-16 kg. Residual N also can increase late rice yields.

The application of fresh *Astragalus* may speed up the stimulative effect of soil organic matter mineralization, but the carbon accumulated always exceeds the carbon lost to the stimulative effect. Continuous application of *Astragalus* may

Table 1. Residual N efficiency in green manure crops (Shi et al 1980).

Experiment, crop	Residual N efficiency ratio[a]		
	Astragalus	*Azolla*	*Eichhornia*
Second crop (rye)	2.62 ± 0.01	1.39 ± 0.00	1.71 ± 0.01
Third crop (barley)	3.00 ± 0.09	1.04 ± 0.12	1.63 ± 0.15
Hermetic culture[b]	1.61	0.81	1.10

[a] N efficiency ratio = $\frac{\%\text{mineralized or absorbed } ^{15}\text{N in total } ^{15}\text{N remaining in soil}}{\%\text{ soil mineralized or absorbed N in total soil N}}$

[b] Soil after harvest of third crop.

Table 2. Effects of *Astragalus* and other fertilizers on rice yield (Jiao et al 1986).

Experimental site	Fertilizer dose (kg N/ha)	Kind of fertilizer	Early rice		Late rice		Total	
			Yield (t/ha)	%	Yield (t/ha)	%	Yield (t/ha)	%
Hunan Academy of Agricultural Sciences	90	*Astragalus*	4.2	135.06	2.5	107.82	6.7	123.29
		$(NH_4)_2SO_4$	4.3	139.90	2.2	93.22	6.5	119.95
		Pig dung	4.0	128.38	2.5	105.60	6.5	118.54
		Night soil	3.8	124.62	2.5	104.34	6.3	115.87
		Cow dung	3.9	124.24	2.6	109.58	6.4	117.91
		Check	3.1	100	2.4	100	5.5	100
Guangxi Academy of Agricultural Sciences	75	*Astragalus*	5.0	131.94	3.1	103.06	8.0	119.22
		Vicia L.	4.8	126.65	3.1	105.40	7.9	117.32
		Vicia faba	4.4	117.25	3.1	103.21	7.5	111.11
		Check	3.8	100	3.0	100	6.7	100

increase organic matter in the soil. These observations are based on the results of experiments conducted by the Nanjing Soil Institute, Academia Sinica (Shi et al 1980).

In a 3-yr trial conducted by Zhejiang Agricultural University in Hangzhou, soil organic matter in plots where *Astragalus* was applied increased about 16% and the amount of 2-mm soil aggregates increased 2.8 times. Data from Liuzhou Agricultural Experimental Station trials in 1960-63 showed total soil N and organic matter increased in plots receiving *Astragalus.* Soil bulk density decreased (Table 3).

Astragalus decomposition rate is rather high because of its low lignin and cellulose content (which are difficult to decompose), high amounts of easily decomposed components of water- and benzol-soluble matter, high protein, and low C:N. The humus remaining in soil is lower than with azolla, sesbania, *Tamarix chinensis, Vicia,* rice straw, and wheat straw (Jiao et al 1986).

Growing *Astragalus* in irrigated ricefields

Seeds of *Astragalus* are usually broadcast between rice rows during heading of the late rice crop, in order to prolong the growth period of *Astragalus.* The rice canopy also makes a convenient environment for germination and emergence of *Astragalus* seedlings. Weeds can be minimized and fresh biomass of *Astragalus* is increased (Table 4). To minimize pest, disease, and weed infestation and for appropriate soil preparation, this culture method needs to be rotated with rape, wheat, and barley during winter.

Astragalus growth under the rice canopy is 25-35 d. Seed is usually broadcast, but dibble seeding and drilling in soils that are low in fertility and water conservation capacity may increase seedling emergence. Seeding rate is 22.5-37.5 kg/ha.

Astragalus is sensitive to water submergence; ditches 4-5 m apart need to be dug in the ricefields before seeding and the field drained (Lin et al 1965). After harvesting rice, these drainage ditches are deepened and some new ditches may be made.

Early application of P and K fertilizer is an important practice to increase biomass. The recommended calcium superphosphate application is 150-300 kg/ha; that of potassium sulfate-potassium chloride, 75-105 kg/ ha.

Pests and diseases that harm *Astragalus* are *Sclerotinia trifoiorum* Erikson., *Oidium* sp., *Stemphylium astragali* Yoshii, *Aphis fabae, Taeniothrips distalis*

Table 3. Effect of *Astragalus* on soil fertility (Jiao et al 1986).

Treatment	Zhejiang Agricultural College						Liuzhou Agricultural Experimental Station		
	Soil aggregates (%)					Organic matter (%)	Organic matter (%)	Total N (%)	Bulk density (g/cm^3)
	5 mm	5-2 mm	2-1 mm	1-0.5 mm	0.5 mm				
3-yr fallow	77.1	9.0	5.9	4.0	3.4	1.24	3.34	0.146	1.39
3-yr *Astragalus* application	46.6	34.5	13.6	2.3	5.1	1.45	3.41	0.153	1.31

Table 4. Effect of intercropping *Astragalus* and late rice on *Astragalus* biomass. Soil and Fertilizer Section, Guangxi Academy of Agricultural Sciences, China, 1965.

Year	Growth manner of *Astragalus*	Seeding date	Fresh biomass of *Astragalus*	
			t/ha	%
1963	Intercropping before harvest in drained condition	20 Oct	16.7	240.5
	Plowing the soil and seeding after rice harvest	13 Nov	6.9	100
1963	Intercropping before harvest in drained condition	20 Oct	23.0	258
	Plowing the soil and seeding after rice harvest	13 Nov	9.0	100

Karug, *T. sjasdati* (Trybon.), and *Phytomyza paniculafae* Sasakawa. As temperatures in South China are rather high, two to four times the usual pest control is needed. For disease control, one to two times the norm is recommended.

Fresh biomass of *Astragalus* may reach as high as 22-40 t/ ha; in some cases, 50-75 t/ ha. The amount recommended as basal manure is only about 22 t/ ha. So, the fresh biomass from a 1-ha high-yielding field may be used as basal fertilizer for a 2- to 3-ha ricefield. Any excessive biomass can be removed and used as green feed. It is better to incorporate *Astragalus* at the flowering to pod-bearing stages.

Summer green manure

Sesbania

Sesbania is used as green manure in Guangdong, Fujian, Taiwan, Zhejiang, and Jiangsu Provinces. Seven species have been introduced. The most widely distributed is *Sesbania cannabina* Pers. Others are *S. aculeata* Pers., *S. aegyptica* Pers., *S. paludosa* Prain., *S. grandiflora* Pers., *S. speciosa,* and *S. sesban.*

Sesbania contains high amounts of N, P, K, and microelements. Nutrient concentration varies from organ to organ. Larger amounts of N and P are found in leaves, then in roots; lower amounts are found in the stems. K content is highest in the stems (Table 5).

Incorporation of sesbania may significantly increase soil granulation and improve soil structure. It can also decrease soil bulk density, increase porosity, and change a field's water-holding and draining capacities. In a 3-yr experiment on sesbania incorporation in a coastal saline soil in Hubei Province, total water-stable aggregates in the soil increased 147.8%. The amount of water-stable aggregates bigger than 0.25 mm increased by more than 264% (Table 6).

Incorporating sesbania not only increases organic matter and other nutrients; it also improves the quality of soil organic matter, so that the soil's fertilizer-providing or fertilizer-conserving capacities are greatly increased (Jiao et a1 1986). This has a significant effect on crop production. Usually, incorporating 15-22 t/ha sesbania

Table 5. Nutrients in *Sesbania* plant organs[a] Soil and Fertilizer Institute, Guangdong Academy of Agricultural Sciences, China, 1980.

Organ	Dry matter (%)	Nutrients (%)							
		Fresh plants				Dried plants			
		N	P	K	NP		K	C	C:N
Root	22.6	0.33	0.03	0.12	1.86	0.18	0.67	42.22	23
Stem	44.8	0.16	0.01	0.17	1.16	0.07	1.17	44.26	39
Leaf	32.6.	0.71	0.31	0.12	4.03	0.44	0.71	43.95	11
Total		0.38	0.03		2.23	0.21		44.39	20

[a] Seedling age about 50 d.

Table 6. Effect of incorporating sesbania on soil physiological characteristics. Plant Protection and Soil and Fertilizer Institute, Hubei Academy of Agricultural Sciences, China, 1981).

Treatment	Amount (%) of water-stable aggregates in 0-10 cm soil layer				Maximum water-holding capacity (mm)	Draining capacity (mm)	Noncapillary porosity (%)	Aeration (%)	Bulk density (g/cm^3)
	1-0.5 mm	0.5 mm	0.25 mm	Total					
Sesbania incorporated	3.12	1.65	4.15	8.92	46.5	19.6	10.9	45.9	1.33
No sesbania	0.71	0.60	2.29	3.60	43.6	14.0	8.8	36.5	1.48

(fresh weight) increases wheat yield 412.5-1492.5 kg/ha, a 37-260% increase. It can increase rice yield 345-967.5 kg/ha, a 10-46.5%; increase.

Various cropping methods have been devised to increase the effects of sesbania on rice yields.

Dual growth under rice canopy. Sesbania seed is broadcast onto the ricefield. Germination takes place under the rice canopy and the green manure continues to grow after rice harvest. The biomass of sesbania cropped in this manner is not very stable because of the effect of the short growing period, environmental conditions, the rice plant type, and changes in the microclimate of the field.

Multiple growth between early and late rice. Sesbania seedlings are planted after harvest of early rice, when the field is drained or prepared for the second crop. This method is easy because sesbania does not compete with early rice. This practice in South Fujian and Guangdong Provinces uses the interval between early and late cropping.

Intercropping under the rice canopy. This widely used practice combines two methods: mound sowing and seedling transplanting. In the first, mounds are made after the first intertillage to alternate with rice rows. Sesbania seeds are directly dibbled on the mounds. In seedling transplanting, sesbania seeds are sown in a seedbed. When seedling height reaches 30 cm, about 40 d after seeding, they are transplanted into the field.

Intercropping sesbania under the rice canopy may provide a relatively long period for sesbania to share the field with rice. If the intercropping is properly managed, green manure yield is high and has a significant effect on yield of late rice. However, if intercropping is not properly done, the yield of early rice may be decreased. Even though yield of late rice might increase slightly, total annual yield will not differ much. Experiences in different areas have shown that intercropping sesbania with early rice is affected by planting date and planting density of sesbania. The spacing required varies in different areas (Table 7).

In the middle south area (Guangdong and Guangxi Provinces), experiments have shown that the suitable row spacing for sesbania is 400-600 cm. Suitable plant spacing is 24-30 cm, with 34 seedlings/ hill. Fresh biomass may reach 6-8.5 t/ ha with no adverse effect on yield of early rice. Yield of late rice increased 12-14%. The 200-240 × 10-12 cm spacing of transplanted sesbania with 2-3 seedlings/hill practiced in East China (Anhui and Jiangsu provinces) is ideal (Anqing Agricultural Institute 1977). Even if this practice does not influence yield of early rice, a higher harvest of fresh biomass of sesbania is expected (Table 8).

Growing sesbania in the late rice seedling nursery. In Shanghai, Zhejiang, and southern Jiangsu, sesbania has been grown in the late rice seedling nursery to provide basal manure during transplanting time. This method uses the sides of the drainage ditches of the rice seedling nursery to intercrop sesbania. Seedling duration

Table 7. Relationship between sesbania spacing and rice yield (Tian 1981).

Treatment	Fresh biomass of sesbania (t/ha)	Early rice			Late rice			Annual yield increase (kg/ha)
		Grain yield (t/ha)	Yield increase kg/ha	Yield increase %	Grain yield (t/ha)	Yield increase kg/ha	Yield increase %	
With sesbania								
600 × 25 cm	6.03	6.0	+158.3	+2.7	5.6	+597.8	+12.1	756
400 × 25 cm	8.60	5.8	+ 8.3	+0.2	5.7	+719.3	+14.5	727.5
260 × 25 cm	11.45	5.6	−253.0	−4.2	5.9	+969	+19.6	726
Without sesbania		5.8	-	-	5.0	-	-	-

Table 8. Relationship between sesbania planting density and rice yield. Anqing Agricultural Institute, Anhui, China, 1976.

Crop	Plants/hill[a]					Row spacing[b]				
	1	2	3	4	10	12cm	15cm	18cm	20cm	24cm
Sesbania (t fresh weight/ha)	4.0	6.1	8.0	9.3	6.8	6.1	5.0	4.8	3.9	4.1
Ricegrain yield (t/ha)	5.5	5.4	5.0	4.6	5.6	5.4	5.8	5.7	6.0	6.1

[a]Spacing: 200 × 15 cm. [b]Row length: 270 cm.

of intercropped sesbania is about 30 d. Total growth period for sesbania and rice seedlings is 40 d. After removing the rice seedlings, the sesbania is incorporated *in situ* as basal manure. In experiments at the Soil and Fertilizer Institute, Shanghai Academy of Agricultural Sciences, incorporating 8 t sesbania (fresh weight)/ha resulted in 7% higher grain yield than with 0.8 t oil cake/ha.

Growing sesbania in the late rice seedling nursery may enhance the quality of the rice seedlings because of growth of the sesbania root system (Table 9). Removing the rice seedlings is easier, saving 1/4-1/3 of the labor (Jiao et a1 1986).

Two rows of sesbania are usually intercropped. Fresh biomass may reach 7.5-12 t/ha.

Intercropping sesbania in the ricefield. Deficiency of basal manure in the late rice cropping season is a widespread problem: growing sesbania promises to remedy this. However, the submergence tolerance of sesbania seedlings is rather low. Even if a Chinese farmer has had a lot of experience in draining his field, it is difficult to drain irrigation water during the rainy season. But direct seeding faces the problem of sesbania seedling removal. In recent years, the practices of growing rice in double wide-narrow row spacing and in ridge culture are being extended. They may open ways to grow sesbania in irrigated ricefields.

In the double wide-narrow row system, sesbania seed is broadcast under the rice canopy of the wide rows 30 d before rice harvest. The sesbania plants can reach the height of the rice plant by harvest. This method does not influence yield of early rice, but will yield 7.5 t fresh sesbania/ha.

In ridge rice culture, direct broadcasting of sesbania seeds on the ridges may overcome the problem of sesbania seedling submergence during early growth stages.

Table 9. Effect of intercropping sesbania on quality of rice seedlings (Ding and Wang 1980).

Experimental site	Treatment	Plant height (cm)		Stem diameter (cm)		Green leaves (no./plant)		Active roots (no./plant)	
		0-20 cm [a]	40-60 cm [a]	0-20 cm	40-60 cm	0-20 cm	40-60 cm	0-20 cm	40-60 cm
Shanghai County	With sesbania	44.9	41.1	0.63	0.73	5.1	5.2	7.9	7.3
	Without sesbania	37.4	37.2	0.54	0.59	4.5	4.2	6.9	5.6
Qingpu County	With sesbania	51.8	42.5	0.72	0.65	4.8	4.5	7.4	6.8
	Without sesbania	40.1	38.1	0.66	0.56	4.0	3.6	7.5	5.1
Shongjiang County	With sesbania	52.6	44.0	0.84	0.74	7.0	5.8	15.7	13.2
	Without sesbania	44.4	41.4	0.80	0.70	6.2	5.4	14.9	12.9

[a] Distance between rice plants and sesbania plants.

Aeschynomene

Aeschynomene indica L. is a legume belonging to the family Papilionaceae. In 1973, scientists from the Nantong Agricultural Scientific Station found that it can be used as green manure. By 1979, it had been introduced for trials in 102 units of 18 provinces and its value as an aquatic green manure in irrigated ricefields during the summer season further confirmed.

Characteristics. Aeschynomene is an annual, semifrutescent glabrous herb, about 30-150 cm tall. It is widely distributed in Northeast, Middle East, and South China, and is found in the tropics of Africa, Oceania, and Asia. Nodules are found on the roots and stems. The even-pinnately compound leaf is diurnal, with more than 20 pairs of rectangular, ellipsoid leaflets. It is adaptable to warm weather, tolerates shade and humid conditions, and resists high temperatures. It can grow well on low land with shallow water.

When the underground water table is low, root nodules are formed; when the underground water table is high, stem nodules develop on the main stem and branches.

Seed normally germinates at 20 °C. *Aeschynomene* grows rapidly when temperatures are above 25 °C. Growth slows down at the beginning of autumn and stops in October. In Fujian, plants die when frost sets in (Liu 1979).

When used as green manure, *Aeschynomene* has a significant effect on rice yield (Table 10).

Management and utilization. The direct seeding method is used before transplanting a single rice crop, during the interval between the early and late rice crops, or during the interval between the early and late cropping seasons. Fresh biomass may reach 15 t/ha 1 mo after seeding, when it may be incorporated directly as basal manure for late rice.

The field planting method is used to intercrop *Aeschynomene* with early rice as basal manure for late rice. It is also intercropped with late rice for topdressing. Seedlings are transplanted at about 20 d, when plant height is 16-20 cm. At transplanting, seedling roots may be soaked with P, K, and mud. It is better to transplant after the second intertillage, when rice tillering has nearly stopped.

Double wide-narrow row spacing (26.4 + 16.5) × 30 cm may be adopted for early rice cultivation, with *Aeschynomene* planted in the wide rows. About 75,000 seedlings will yield about 1.5 t fresh biomass/ha.

Where seeds are lacking, branches may be cut and used for asexual propagation. Because its regeneration capacity is strong, *Aeschynomene* cut into small branches may be utilized several times.

Aeschynomene may be used as basal fertilizer or topdressing for late rice. The stubble (45 cm height) must remain at harvest, when a suitable rate of fertilizer or a spray of 0.04% ammonium molybdate is applied (Liu 1979).

If *Aeschynomene* emerges from the rice canopy before the milk stage of rice, the top should be cut immediately. Otherwise, the rate of rice grain filling may be affected.

Aeschynomene is sensitive to aphids, pod moths, bollworms, and oidium. Pest control must be given more attention.

Table 10. Effect of *Aeschynomene* on rice grain yield[a] (Jiao et al 1986).

Experimental site	Year	Treatment	Grain (t/ha)	Yield increase	
				t/ha	%
Longnan Agricultural Institute, Jiangxi	1978	1. 16.9 t/ha *Aeschynornene,* basal	6.0	1.0	17.7
		2. 16.9 t/ha uncomposted animal manure, basal	6.1	0.3	-
		3. No organic manure (check)	5.8	-	-
Dayu Agricultural Institute, Jiangxi	1978	1. 5.6 t/ha as topdressing 8 d after transplanting	7.6	1.0	15.1
		2. No application (check)	6.6	-	-
Gangzhou Agricultural institute, Jiangxi	1978	1. 15 t/ha, basal	4.6	1.3	37.5
		2. 225 kg ammonium bicarbonate/ha	4.1	0.7	21.9
		3. 75 kg urea/ha as topdressing	4.4	1.1	31.0
		4. No fertilizer (check)	3.4	-	-
Gangzhou Agricultural Institute, Jiangxi	1978	1. 10.05 t *Aeschynomenelha,* topdressed	5.6	0.7	13.9
		2. 33.75 t *Pistia stratiotes/ha* as topdressing	5.6	0.6	12.4
		3. 75 kg urea/ha as topdressing	5.3	0.4	7.1
		4. No fertilizer (check)	4.9	-	-
Qiangjing Brigade Sanhai Commune	1978	1. 7.5 t Aeschynornenelha. basal	5.7	1.0	22.4
		2. 7.5 t pig dung/ha, basal	5.0	0.4	8.9
		3. No fertilizer (check)	4.6	-	-
Guangxi Autonomous Region	1976	1. 22.5 t Aeschynomenelha	4.5	0.2	4.5
		2. 22.5 t feces/ha, basal	4.3	-	-

[a] Experimental crop: continuous late rice.

Year-round green manure

Azolla represents a fern-algae association. The symbiont *Anabaena azollae* possesses N-fixing capability, enabling azolla to fix N directly from the atmosphere. The fact that N efficiency from azolla is equivalent to the same amount of N as ammonium sulfate or urea has been demonstrated by numerous investigations and field practices. The advantages of using azolla—no additional land needed for cultivation and easy and fast propagation in ricefields where the water supply is continuous—have attracted more and more attention in recent years.

Recent investigations have shown that, in addition to its N-fixing activity, azolla also is able to accumulate trace K from irrigation water (Liu et al 1982). After azolla decomposition, its K content can be utilized by rice plants (Liu et al 1986). Its efficiency is equivalent to that of chemical fertilizer (Table 11).

Thus, azolla can serve as a source of bio-N and bio-K fertilizer in the ricefield ecosystem. Azolla is more beneficial to rice than are other kinds of green manure. With only some P fertilizer, it can satisfy the N and K requirements of rice.

Our studies in recent years have shown that azolla also may serve as livestock fodder or fish food. The livestock or fish feces can be used to manure the ricefield. This use of azolla in China has proven efficient. Azolla is significant as fodder because of its rich nutrient content. With its moderate plant size, it does not need to

Table 11. Effect of fertilizer application method on rice yield (Liu et al 1986).

Treatment	Average yield (t/ha)	
	12 sites in Fujian Province	3 sites in plain area
70% azolla + 30% fertilizer	5.8	5.3
100% N, P, K fertilizer	5.3**	5.1
N and P fertilizer, no K	4.7***	4.0***
No fertilizer	3.5***	3.0***
*5% LSD =	20.0	28.3
**1% LSD =	28.3	38.3
***0.1% LSD =	36.6	50.4

Table 12. Fodder components of azolla (air-dried) (Zhang et al 1987).

Sample	Dry weight (%)	Crude protein (%)	Crude fat (%)	Crude cellulose (%)	Non-N extract (%)	Ash (%)
A. pinnata	7.96	16.18	2.17	9.77	54.07	12.94
A. filiculoides	9.00	21.00	2.57	14.60	50.97	15.00

Table 13. Performance of pigs fed *A. filiculoides* (Zhang et al 1987).

Pigage (mo)	Average weight increase (kg/pig)			Average daily weight increase (g)		
	Fresh azolla	Dried azolla	Vegetable	Fresh azolla	Dried azolla	Vegetable
2.5-3.5	19.92	21.46	20.04	663.9	715.3	666.7
3.5-4.5	13.33	13.08	13.29	444.4	436.4	443.6
4.5-5.5	22.63	21.71	22.08	753.89	723.61	736.11
5.5-6.5	18.92	17.58	17.00	630.6	586.1	566.7

be chopped and can supply fodder year-round. The nutrient components of azolla are listed in Table 12 and the results of a feeding study in Table 13.

In experiments in Changde County, Hunan Province, and Wujiang County, Jiangsu Province. *A. filiculoides* fed to grass carp *Otenopharyn goden* Idellus gave a yield of 1 kg carp for every 25-50 kg fresh azolla.

Recently. we developed a rice - azolla - fish system that combines two traditional farming practices–raising fish in the paddy field and intercropping azolla with rice. The yield and quality of the fish product greatly increased (Table 14). Using azolla as feed for grass-feeding or omnivorous fishes significantly increased individual fish weight, total weight, and edible value.

To measure manuring efficiency after azolla is taken up by fish, then excreted into the ricefield, we fed the fish with ^{15}N-labeled azolla, then traced the utilization of the fish feces by the rice plant (Chen et al 1982). The fish feces contained about 30% of the azolla N (Table 15). The other 30% of the azolla N is incorporated into the

Table 14. Performance of fish species in a mixed azolla-rice culture (Azolla Research Center 1985).

Fishspecies	Fish product (t/ha)		Fish size (g/piece)	
	Fed azolla	No azolla	Fed azolla	No azolla
C. carpio	0.35	0.15	600	350
C. idella	0.17	0.15	150	130
T. nilotica	0.54	0.40	125	100
Total	1.06	0.70	-	-

Table 15. ^{15}N recovery in fish muck[a] (Chen et al 1982).

Time	Na (mg N) (%	Na ^{15}N atom excess)	Ne (mg N)	Ne/Na (%)	^{15}N (% recovery)
8 h	13.07	406.62	3.89 ± 1.03	29.8	14.420 ± 3.878
6 h	453	2094.3	122.11 ± 24.57	27.0	17.580 ± 5.996

[a] Na = nitrogen from azolla, Ne = nitrogen from fish feces.

Table 16. ^{15}N recovery of azolla in different farming patterns (early rice, 1985) (Wen et al 1987).

Treatment	^{15}N recovery (%)		Total
	Fish	Rice	
Rice-azolla-fish	38.24	29.52	67.76
Rice-azolla (azolla as basal)	-	46.06	46.06
Rice-azolla (azolla as topdressing)	-	51.60	51.60

fish's body (Wen et a1 1987). The remaining 1/3 of azolla N may be directly excreted into the water via the physiological metabolism of the fish.

When azolla in a rice - azolla - fish rotation is taken in by the fish, then excreted into the field in the form of fish feces, its total utilization rate is as high as 68% (Table 16). With rice - azolla, ^{15}N-labeled azolla incorporated as basal fertilizer has a N utilization rate of only 46%. When the same amount of ^{15}N-labeled azolla is topdressed during tillering, N utilization increases to 52%.

The slightly higher utilization rate with topdressing may be due to the higher, more developed root system and stronger absorbing capacity of rice plants during middle or late growth. It is very clear that azolla used as fish feed can be utilized by rice plants. The rice - azolla - fish system may also increase soil fertility.

Prospects for green manure

In South China, most areas are planted to two rice crops a year. In recent years, scientists who work on green manure are paying more attention to minimizing the

dependence of farmers on chemical fertilizers by recommending use of more green manure to improve soil fertility and to increase farm income. According to our information, it is not difficult to cultivate 75 t fresh azolla biomass/ ha during the winter season, provided there is no freezing weather longer than 5 d. Azolla can provide the N and K fertilizer needed for early rice growth or be used first as fish feed, with the field manured with fish feces.

In some areas, *Astragalus* is mix-cropped with *Raphanus sativus* L. This is also acceptable, especially for producing animal fodder. Intercropping sesbania in the wide intervals of a double wide-narrow row spacing field in the early rice cropping season may provide sufficient green manure for the late rice crop.

These practices have made possible reasonable integration of organic manure with chemical fertilizers. Taking the green manure grown in the ricefield as feed or fodder for livestock and poultry, then using the animal feces to manure the ricefield gives the highest economic benefit. The rice - azolla - fish system is a promising pattern to utilize green manure in a rice-based farming ecosystem.

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Use of green manure in rice farming systems in West and Northwest Cameroon

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In Africa, few attempts have been made to improve rice soil fertility using organic manure. With less intensive cropping patterns, most African ricefields are kept as grass fallow or bush fallow the season before the rice crop. Soil fertility would be improved if some adaptable legumes were grown as green manure crops during the off-season. In recent studies on the suitability of some legume species as green manure crops in upland and irrigated rice-based cropping systems at Mbo and Ndop Plains, Cameroon, *Crotalaria caricia* from Zaire was the fastest growing. Sesbania and crotalaria can be used for irrigated transplanted rice. A local species of azolla seems to grow well with about 40-60 kg phosphate fertilizer. In upland rice at Mbo Plain, crotalaria with moderate levels of applied N increased rice yields. In irrigated rice, yield increases were even higher. Corresponding yield increases at Ndop Plain were less.

Green manure is an important nutrient source for rice in many countries. Most Asian rice-growing countries practice green manuring; in most cases, yield and soil fertility increase (De Datta 1981, Singh 1978, Vachhani and Murty 1984).

In Africa, where rice is a relatively recent crop, little attention has been paid to the maintenance of rice soil fertility, other than bush fallow or grass fallow after a few crop seasons. Using green manure to maintain soil fertility in intensively cropped areas is an unknown technology to most African farmers.

In Cameroon, most rice is grown by Rice Development Authorities (parastatal organizations). Of the total rice production of 100,000 t in 1986, about 82% was produced by the parastatal organizations and 18% by traditional farmers (IRA/NCRE 5-yr work plan 1986-90).

There are three major rice development projects.

The Society for the Expansion and Modernization of Rice in Yagoua (SEMRY) in the Extreme North Province is the oldest. SEMRY grows irrigated rice in about 10,000 ha. The dry climate is well suited to irrigated rice. The Vertisol soils are fertile, but in some areas are beginning to show P and Zn deficiencies. Organic matter content is moderate to high. Average production in 1985 was about 6.6 t/ha.

The Upper Nun Valley Development Authority (UNVDA), based at Ndop Plain about 1,200 m above sea level in the Northwest Province, has brought 3,000 ha under rice cultivation. Annual rainfall varies from 1,700 to 2,000 mm. Most rice is grown during the rainy season (Jul-Dec), with supplemental irrigation from catchment areas and small dams. The soil is a moderately fertile recent alluvium (Entisols), ideal for transplanted rice when water is not a problem. The area is heterogeneous in soil fertility, especially in soil organic matter status, and needs a good deal of attention and fertilizer application to achieve satisfactory rice yields. At the moment, only one crop of wet season rice is grown. Average yield in 1985 was 3.5 t/ ha, but many farmers harvested 5-6 t/ ha.

The Society for the Development of Rice in Mbo Plain (SODERIM) in the Western Province is based 700 m above sea level. The target area to be brought under irrigated rice cultivation is 2,500 ha. Soils are mostly Ultisols, with poor to moderate organic matter content.

Moormann and Veldkamp (1978) noted that on dryland African soils, the initially moderate level of soil organic matter is favorable immediately after clearing from bush fallow or savanna. After 1-2 yr of cultivation, organic matter content diminishes to 0.5-0.8% organic carbon in the topsoil. This makes dryland rice soil progressively less fertile and affects rice yields drastically within a short time.

The Cameroon Government has studied cutting back on fertilizer subsidies. The need is to encourage use of organic fertilizers and green manure instead of inorganic fertilizers, which are rather expensive.

Field trials were initiated with green manure, organic manure, and fresh rice straw incorporation, to evaluate their effects on rice growth and yields. At the same time, several legume species were planted to evaluate their adaptability as a green manure crop. Results of field trials at Mbo and Ndop Plains indicate that growing a green manure crop *(Sesbania, Crotalaria,* and *Azolla* species) in the off-season (Mar-Jun) improved rice yields. Some physical and chemical properties of the experimental soils are shown in Table 1.

Here we report some results of research with green manure crops at Mbo and Ndop Plains. Use of *Sesbania, Crotalaria,* and *Azolla* species was studied in irrigated and upland rice in the 1983 to 1986 crop years.

Materials and methods

Nine legume species obtained from the International Institute of Tropical Agriculture (IITA), Zaire, and a local collection were screened in 1983-84 at Mbo Plain (Table 2). Single plots were 200 m^2. We studied total dry matter production, nodulation capacities, dates of flowering and maturity, seed production, and reactions to local diseases and insect pests. *Crotalaria* and *Sesbania* were the most adaptable green manure species for both upland and irrigated ricelands. They produced 35-45 t biomass/ha in 75-85 d at Mbo Plain and in 90-100 d at Ndop Plain.

Fertilized green manure crops were seeded with 26-44 kg P/ ha at the onset of rain in March-April and incorporated 2-3 wk before rice was planted in July-August. Plots left as grass fallow received similar amounts of P before rice was seeded.

Table 1. Some physical and chemical properties of the experimental soils for green manure trials in Cameroon[a]

Soil property	Experimental site		
	Bamunka[b] Ndop Plain	Nzock-5[c] Mbo Plain	Mbomi-4[b] Mbo Plain
Texture	Si C	C	SL
pH water (1:1)	4.6	4.7	4.9
Organic C (%)	2.1	0.5	2.3
Total N (%)	0.23	0.1 7	0.24
C: N	9.13	13.76	9.58
Av P (Bray P_1)	0.90	3.0	3.70
CEC (NH_4 OAC) (meq/100g)	-	10.31	-
Effective CEC (meq/100 g)	7.29	-	5.45
Exchangeable bases (meq/100 g)			
K^+	0.43	0.05	0.31
Na^+	0.1 9	0.04	0.05
Ca^{++}	3.00	0.000	2.20
Mg^{++}	1.15	0.21	1.58
Mn^{++}	0.27	-	0.15
Total KCl acidity (meq/100 g)			
Al^{+++}	1.61	-	0.88
H^+	0.64	-	0.28
TEB	5.04	0.31	4.29
Base saturation (%)	69	3.00	79
Soil class	Tropaquept	Paleaquult	Paleudult

[a] Adapted from IRA/NCRE (1984). [b] Analyses done at IITA Analytical Laboratory, Ibadan, Nigeria. [c] Analyses done at FAO Soils Laboratory at Ekona, Cameroon.

Table 2. Legume species under evaluation at Mbo Plain, Cameroon, since 1983 wet season.

Legume species	Origin	Type	Observations
Crotalaria caricia	Zaire	Shrub	Fast growing
Sesbania sp.	Local	Woody shrub	Slow growing
Sesbania rostrata	IITA	Woody shrub	Slow growing
Pueraria sp.	Local	Creeper	Slow growing at start
Psophocarpus palustrib	IITA	Creeper	Slow growing at start
Mucuna utilis	IITA	Creeper	Slow growing at start
Centrosema pubescens	IITA	Creeper	Slow growing at start
Tephrosia sp.	Local	Woody shrub	Slow growing
Leucaena leucocephala	IITA	Woody tree	Very slow growing
Desmanthus virgatus	FAO	Shrub	(Seeds obtained from FAO in late 1986)

Trials were laid out in a randomized factorial complete block design with four replications. Plot sizes varied from 25 to 30 m^2. Four N levels and two green manure levels were used. Depending on the crop and situation, either sesbania or crotalaria was used as green manure.

In the first trial, 100-m^2 plots at Ndop Plain that had been left as grass fallow or had received 5 t sesbania/ ha received 50 kg N, 13 kg P, and 25 kg K/ ha. Plots at Mbo

Plain were planted to crotalaria in March-April or left as grass fallow before being seeded to rice the end of June or early July. Crotalaria was incorporated at flowering. All plots received NPK fertilizer (Table 3,4,5,6,7).

Trials with azolla in irrigated rice at Mbo Plain had nine treatments during the dry season and five treatments during the wet season. Azolla was grown in a fallow plot with 13 kg P/ha applied in 2 splits, then inoculated to experimental plots according to specifications (Table 8,9). The crops were protected against *Diopsis* stem borer with granular carbofuran and were covered with bird nets at ripening. Plant height, tiller and panicle numbers, 1,000-grain weight, spikelet sterility, and yield were recorded. Not all yield component data are reported here.

Results and discussion

Crotalaria caricia from Zaire appears to be the most promising green manure for upland and irrigated rice. It nodulates well, has a fast growth rate under local soil and climatic conditions, and flowers in 70-75 d at Mbo Plain and 85-90 d at Ndop Plain. Total green matter at 50% flowering varies between 4 and 6 t/ha. The crop can be easily incorporated. Small farmers can chop the crop down and partly cover it with soil using local hoes. Under such management, green matter decomposes in about 2 wk. Then rice can be drilled in, with moderate rates of basal fertilizers.

The next most adaptable species seems to be a local *Sesbania* sp. It is more slow-growing and takes longer to be ready for incorporation. Total green matter produced in 90 d was 3545 t/ha. Nodulation was moderate at Mbo Plain but high at Ndop Plain. When succulent, incorporated green matter decomposes quite rapidly; rice can be transplanted within a week.

Sesbania rostrata, tried for two seasons at Mbo Plain, did not show much promise. It had a very slow growth rate and did not produce stem nodules.

The creepers *Pueraria, Psophocarpus, Mucuna,* and *Centrosema* spp. are excellent cover crops, but are very slow growing at early stages. Seeded at least 3-4 mo ahead of rice or other upland crops, they could be used as cover crops. Most nodulate well and produce enough plant cover to suppress weeds. These species, however, are not adaptable to irrigated transplanted rice.

Tephrosia sp. produces 30-45 t green matter/ha in about 3 mo, but early growth is slow. It has high nodulating ability under local conditions, but because of its woody nature must be plowed under 60-75 d after seeding. Leaf fall from mature plants and roots can be used as organic manure, if the woody stocks intended for other uses are cut at ground level at least 2-3 wk before seeding upland rice or other upland crops. Planted between rows of upland crops, it could be an ideal green manure.

Leucaena leucocephala is a tree that grows very slowly under local climatic and soil conditions. Only the twigs and leaves can be used for fertilizer. In alley cropping (about 4 m wide), the green matter is pruned from time to time before a food crop is planted between the alleys. This particular species does not seem to be as well adapted to local conditions.

Desmanthus virgatus, a new species obtained from the Food and Agriculture Organization (FAO) at the end of 1986, was seeded at Mbo Plain in 1987.

Green manuring rice with crotalaria and sesbania

In the first trial at Ndop Plain, incorporating sesbania increased tiller number, panicle number, and grain yield of IR7167-33-2-3 about 34% over grass fallow (Table 3). Plant height was not affected by green manure, but the plot receiving green manure had more uniform flowering and maturity.

A second trial with eight combinations of four N and two green manure levels at Ndop Plain in 1984 showed vigorous rice growth, with higher tillering and more uniform flowering in plots receiving green manure than in those left as grass fallow. Late rice planting resulted in cold injury at the reproductive phase and yield data were not collected.

In 1984, we studied the effect of sesbania incorporation in combination with four levels of N on yield of Cica-8 at Mbo Plain. This land was partially scraped while leveling the poulder in 1982 and produced a very poor crop in 1983.

Yield increases with N and sesbania were very high (Table 4). Sesbania without N improved yields by about 20%; applying 40-80 kg N/ha with sesbania improved yields by more than 100%. Plots treated with sesbania and inorganic N produced more grain than plots left as grass fallow. At 120 kg N/ ha, sesbania did not affect grain yield. N efficiency ranged from 16 to 49 kg grain/kg applied N; the highest was with 40 kg N/ ha, the lowest with 120 kg N/ ha.

Table 3. Effect of green manuring transplanted IR7167-33-2-3 with a local *Sesbania* sp., Ndop Plain, Cameroon, 1983 wet season.[a]

Fertilizer (kg/ha)			Sesbania	Plant ht (cm)	Tillers (no./m²)	Panicles (no./m²)	Grain yield (t/ha)	Yield increase (%)
N	P	K						
50	13	25	5 t/ha	83	281	237	5.5	34.2
50	13	25	None	83	250	216	4.1	-

[a]Adapted from IRA/NCRE (1983). Single plot (100 m²) observational trial. All data were collected on 5 m² subplot area harvests. Tiller and panicle counts were based on 16 hills/subplot.

Table 4. Effect of green manuring transplanted rice Cica-8 with a local *Sesbania* sp., Mbo Plain, Cameroon, 1984 wet season.[a]

N-rate (kg/ha)	Sesbania[b]	Grain yield (t/ha)	Yield increase over check (%)	N efficiency (kg grain/kg N)
0	-	1.72	-	-
0	+	2.06	19.76	-
40	-	3.53	105.23	45.25
40	+	4.01	133.13	48.75
80	-	4.08	137.21	29.50
80	+	4.41	156.39	29.37
120	-	4.70	173.25	24.83
120	+	4.01	133.13	16.25

[a]Adapted from IRA/NCRE (1984). [b]Grown in situ and incorporated into the soil at flowering, about 2 wk before transplanting. With (+) or without (—)sesbania. [c]Av of 4 replications. LSD (5%) = 518 kg/ha, CV = 9.9%.

We conducted similar trials at Ndop Plain in the 1985 and 1986 wet seasons. *Crotalaria* sp. was grown *in situ* and incorporated at 50% flowering (about 45 t green matter/ ha). Rice was planted about 2 wk after incorporation. In the 1985 trial, grain yields of IR7167-33-2-3 ranged from 3 to 4.5 t/ha (Table 5). Plots receiving crotalaria produced higher yields at all N levels than did those left as grass fallow. Yield increases ranged from 13 to 51%, and were higher in plots treated with green manure than in those receiving N alone. Plant height was slightly reduced in plots receiving green manure. Tiller and panicle numbers always were higher in plots with green manure. Grain weight was not affected by fertilizer treatment. Spikelet sterility was slightly reduced in plots with green manure.

The 1986 trial produced a bumper crop, with yields ranging from 4.7 to 6.9 t/ha. Green manure incorporation without N fertilizer increased yields 43%; green manure with N fertilizer increased yields 38-46%. Green manure increased plant height, tiller numbers, and panicle numbers (Table 6).

Table 5. Effect of green manuring transplanted IR7167-33-2-3 with *Crotalaria caricia* from Zaire. Ndop Plain, Cameroon, 1985 wet season.[a]

N rate (kg/ha)	Crotalaria[b]	Plant ht (cm)	Tillers (no./m^2)	Panicles (no./m^2)	1,000-grain wt (g)	Grain sterility (%)	Grain yield[c] (t/ha)	Yield increase (%)
0	-	96.5	218	274	27.9	14.2	3.0	-
0	+	95.5	251	223	28.5	12.0	3.6	21.7
30	-	91.5	228	228	28.0	12.1	3.4	13.3
30	+	90.0	258	247	27.9	15.3	3.6	19.1
60	-	96.0	209	225	27.6	15.6	3.7	24.9
60	+	91.5	237	233	28.0	13.6	4.1	36.3
90	-	98.5	253	247	27.8	16.2	4.1	35.7
90	+	94.0	244	245	27.8	11.8	4.5	51.3

[a]Adapted from IRA/NCRE (1985). [b]Grown in another plot, harvested at flowering stage, and incorporated into the soil at 5 t/ha, 3 wk before rice transplanting. With (+) or without (–) crotalaria. [c]Av of 4 replications. LSD (5%) = 499.8 kg/ha, CV = 9.2%.

Table 6. Effect of green manuring transplanted rice IR7167-33-2-3 with *Crotalaria caricia* from Zaire. Ndop Plain, Cameroon, 1986 wet season.[a]

N rate (kg/ha)	Crotalaria[b]	Plant ht (cm)	Tillers (no./m^2)	Panicles (no./m^2)	Grain yield[c] (t/ha)	Yield increase (%)
0	-	95.5	274	208	4.72	-
0	+	107.5	299	258	6.76	43.2
30	-	90.2	256	193	4.67	–1.0
30	+	109.2	328	283	6.88	45.8
60	-	98.9	293	232	5.18	9.7
60	+	109.5	300	290	6.51	37.9
90	-	100.3	282	248	5.18	9.7
90	+	104.4	290	275	6.75	43.0

[a]Adapted from IRA/NCRE (1986). [b]Seeded in plots in April and incorporated into the soil at flowering about 2 wk before rice planting. With (+) or without (—) crotalaria. [c]Av of 4 replications. LSD (5%) = 654.8 kg/ha, CV = 7.6%.

Results of trials on the effect of crotalaria incorporation on rainfed upland rice (IRAT10) at Mbo Plain in 1985 and 1986 wet seasons are presented in Table 7. Yields at Mbo Plain are normally low; upland yields decline rapidly after land clearing. In 1985, the first crop in an area left as grass fallow for at least 4 or 5 yr produced average yields of 2.1 t/ha. In the second year, yields declined to 1.2 t/ha, in spite of the fact that the crop received the same amount of N and crotalaria as green manure. However, both crops responded to applied N and green manure incorporation. Plots with crotalaria had higher yields than those left to grass fallow. At 90 kg N/ha, the effect of green manure was not positive, possibly because of excessive vegetative growth and higher spikelet sterility at the higher N level.

Results over 2 seasons indicated that green manure for upland rice at Mbo Plain can substantially improve rice yields (50-100%) at moderate N levels (30-60 kg N/ha), provided green manure crop incorporation is timely for planting upland rice the end of June or early July.

Azolla incorporation in transplanted rice

Trials with azolla in irrigated rice were initiated at Mbo Plain on the basis of observations of azolla growing naturally in and around ricefields during the wet season. Azolla in areas where phosphate was applied grew green and healthy; in fallow lands with no phosphate, it was brownish and had a poor growth rate.

In preliminary trials with 0, 8.8, 17.6, 26, and 35 kg P/ha applied in 2 splits during the wet season, local azolla species needed about 17.6-26 kg P/ha to increase biomass from 425 g/m^2 to 2,400 g/m^2 in about 3 wk. Plots receiving no phosphate produced 1,750 g biomass in 3 wk. That azolla was dark brown, compared to dark green azolla in phosphate-treated plots. Details of the azolla treatments and results in the 1983 dry and wet seasons are given in Tables 8 and 9. In the 1984 trials, tadpoles ate almost all the azolla.

Table 7. Effect of green manuring rainfed upland rice IRAT10 with *Crotalaria caricia.* **Mbo Plain, Cameroon, 1985 and 1986 wet seasons.**[a]

N rate (kg/ha)	Crotalaria[b]	Grain yield (t/ha)			Yield increase[c] (%)	Fertilizer N efficiency (kg grain/kg N)
		1985	1986	Mean		
0	-	1.3	0.9	1.1	-	-
0	+	2.0	1.2	1.6	45.2	-
30	-	2.0	1.2	1.6	48.1	17.4
30	+	2.3	1.4	1.8	69.4	25.0
60	-	2.0	1.2	1.6	44.9	8.1
60	+	2.8	1.5	2.1	96.6	17.4
90	-	2.3	1.5	1.9	75.1	9.0
90	+	2.3	1.2	1.7	59.5	7.1
Mean		2.1	1.2	1.7	-	-

[a] Adapted from IRA/NCRE (1985, 1986). [b] With (+) or without (–) crotalaria. [c] Av of 4 replications/season. LSD (5%) for 1985 = 1.2 t/ha, CV = 33.2%. LSD (5%) for 1986 = 0.3 t/ha, CV = 18.3%. Total green matter production at incorporation was 40-45 t/ha.

Table 8. Effect of azolla incorporation on the performance of IR3273-339-2-5 under irrigated conditions. Mbo Plain, Cameroon, 1983 dry season.[a]

Treatment	Plant ht (cm)	Tillers (no./m^2)	Panicles (no./m^2)	Grain yield[b] (t/ha)	Yield increase (%)
Check (no azolla, no N added)	94	488	432	6.45	-
30 kg N/ha in 3 splits	94	485	370	6.84	6.0
60 kg N/ha in 3 splits	94	490	407	6.66	3.2
Azolla incorporated after full cover	95	500	440	7.19	10.1
Azolla inoculated after rice transplanting and incorporated after full cover	97	448	410	6.75	4.6
Azolla inoculated after rice transplanting but not incorporated	95	475	439	7.10	10.0
Azolla incorporated after full cover + 30 kg N/ha	95	480	445	7.40	14.7
Azolla inoculated after rice transplanting but not incorporated + 30 kg N/ha	96	485	450	7.08	9.8

[a] Adapted from IRA/NCRE (1983). [b] Av of 4 replications. Seeding date = 12 Dec 1982, transplanting date: 6 Feb 1983, date of maturity = 22 May 1983. LSD (5%) = 1.20 t/ha, CV = 11.84%.

Table 9. Effect of azolla incorporation on the performance of IR3273-339-2-5 under irrigated conditions. Mbo Plain, 1983 wet season.[a]

Treatment[b]	Plant ht (cm)	Tillers (no./m^2)	Panicles (no./m^2)	Grain yield[c] (t/ha)	Yield increase (%)
Check (no N, no azolla)	85	290	280	4.4	-
30 kg N/ha in 3 splits	87	301	279	4.8	8.9
60 kg N/ha in 3 splits	87	297	290	4.6	3.2
30 kg N/ha + 2 kg fresh azolla/m^2 incorporated at planting	86	325	304	4.8	8.5
2 kg fresh azolla/m^2 incorporated	85	333	319	4.5	1.8

[a] Adapted from IRA/NCRE (1983). [b] Azolla at 2 kg fresh weight/m^2 was inoculated at transplanting and incorporated into the soil at full cover at maximum tillering. [c] Av of 4 replications. LSD (5%) = 0.7 t/ha, CV = 9.7%.

The dry season trial at Mbo Plain was laid out in a newly opened area that was apparently highly fertile (control plots produced 6.45 t/ ha). Response to azolla and N was marginal (3-15%). The highest increase was in plots where azolla was incorporated after full cover and in plots receiving 30 kg N/ ha as urea in 2 splits. Plant height and tiller and panicle numbers were not significantly affected by treatment.

The wet season trial was laid out at a different site, where irrigated rice had been grown for 2-3 yr. Azolla incorporated with 30 kg N/ha applied in 2 splits increased yields from 4.4 to 4.8 t/ ha, equivalent to that obtained by applying 30 kg N/ ha alone. The marginal response to N and azolla in this trial was suspected to be associated with a heavy neck blast attack at the dough stage. Although plant height was unaffected by treatment, tiller and panicle numbers were increased.

Conclusion

Green manure in rice soils of the West and Northwestern Provinces of Cameroon can improve rice yields, depending on initial soil fertility and soil organic matter content. *Crotalaria caricia* from Zaire was the fastest-growing green manure crop at Mbo and Ndop Plains. To be used as a green manure for second season rainfed upland rice, crotalaria must be seeded with the onset of rain in March–April and plowed under at the flowering stage before drilling rice.

Sesbania and crotalaria as green manure for irrigated transplanted rice must be seeded in March-April and incorporated about 2 wk before transplanting rice. Sesbania must be incorporated before it reaches the uoody growth stage. Other legume species are under study, but additional information is needed before conclusions can be drawn about their use as green manure crops for Mbo and Ndop Plains.

A local species of azolla seems to grow well with 17.6-26 kg P fertilizer. Its effect on rice yields needs further study.

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Notes

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Collection and evaluation of tropical legume germplasm

R. Schultze-Kraft

The family Leguminosae comprises of 3 subfamilies some 17,000 species, mainly of tropical origin. Only a very small number of these species are available as germplasm. Collecting the genetic resources of tropical nongrain legumes has only a 40-yr-old tradition. The major collections are held by the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia; the Centro Internacional de Agricultura Tropical (CIAT), Colombia; and the International Livestock Centre for Africa (ILCA), Ethiopia. They were assembled with the objective of providing a broad genetic base for forage legume cultivar development. To date, no collecting mission aimed specifically at tropical legumes for green manure and green leaf manure has been carried out. Programs to evaluate tropical legume germplasm are aimed at developing cultivars for forage; they focus on plant characteristics related to legume persistence and for age quality. A three-stage program for agronomic evaluation is briefly discussed and a list of legume species well-adapted to the acid, low-fertility soils of subhumid and humid tropical America is presented. A program to build and evaluate a gene pool of tropical legumes for green manure is proposed.

Tropical legumes are among the most interesting and useful of the world's plant genetic resources. They are used for such diverse purposes as ground cover in plantation agriculture, food production, green manure, forage, ornamental and medicinal plants, firewood, erosion control, and timber. But in spite of a long-known multipurpose potential, systematic efforts to collect, maintain, explore, and exploit the wide range of germplasm of tropical legumes are relatively recent and, for most genera, are still in an incipient stage.

Taxonomic and geographic diversity

The Leguminosae family

Legumes are considered here as the family Leguminosae, which includes three subfamilies: Caesalpinioideae, Mimosoideae, and Papilionoideae (Hutchinson 1964, Polhill and Raven 1981). They comprise 686 genera with about 17,000 species

Table 1. Tropical genera and species in the Leguminosae family (adapted from Williams 1983).

Subfamily	Genera (no.)	Species (no.)	Tropical species(%)
Caesalpinioideae	174	2,900	Almost 100
Mimosoideae	56	2,800	Almost 100
Papilionoideae	456	11,300	62
Total	686	17,000	

(Table 1). Almost 100% of the Caesalpinioideae and Mimosoideae and 62% of the Papilionoideae are tropical species (Williams 1983).

It is significant, particularly when considering their potential as green manure, that most of the Caesalpinioideae and Mimosoideae are trees and most of the Papilionoideae are shrubs and herbs. This is the principal reason the Papilionoideae received particular attention in early germplasm collecting missions that aimed at potential pasture legumes.

In his review of the potential of tropical legumes as pasture and forage plants, Williams (1983) reduced the numbers of species with forage potential to 700 within the Caesalpinioideae, 600 within the Mimosoideae, and 2,600 within the Papilionoideae. This reduction considered characteristics that make the species unsuitable for forage purposes (i.e., excluding trees and species with such known antiforage factors as spines and toxin content). No study that examines the green manure and green leaf manure potential of tropical legumes exists. But since spines and toxin content would be no impediment, the number of potentially useful species is probably considerably higher.

In view of the large number of species, taxonomic uncertainties probably will not greatly affect total species counts. It should, however, be pointed out that the taxonomy of many tropical legume genera, including even well-known genera such as *Desmodium* and *Zornia*, is unsatisfactory. Updated taxonomic descriptions of many genera would contribute to better research planning and communication among scientists.

Geographical distribution

Legumes are distributed throughout the tropics. Williams (1983) gives a rather comprehensive and, in part, quite detailed account of diversification at the tribal and even generic level within each subfamily. He points out that, although the Caesalpinioideae are more numerous in tropical America, at the genus level more diversity is found in Africa. The Mimosoideae also are found more frequently in tropical America. With respect to the tropical Papilionoideae, more diversification has occurred in America, particularly in the tribes Aeschynomeneae, Desmodieae, and Phaseoleae (which comprise especially valuable genera). Some of the better-known genera (Table 2) are examples of the wide species diversification and broad geographic distribution.

Table 2. Species and distribution of selected tropical legume genera (adapted from Polhill and Raven 1981 and Williams 1983).

Genus	Species (no.)	Distribution
	Subfamily Caesalpinioideae	
Bauhinia	250-570	Pantropical
Cassia	30	Pantropical
Chamaecrista	250	Pantropical, esp. America
Senna	240	Pantropical
	Subfamily Mimosoideae	
Acacia	900-1200	Pantropical, esp. Africa and Australia
Albizia	150	Pantropical
Calliandra	200	Pantropical, esp. America
Desmanthus	25	America
Inga	350	America
Leucaena	40-50	America
Mimosa	400-600	Pantropical, esp. America
	Subfamily Papilionoideae	
Aeschynomene	150-250	Pantropical, esp. America
Cajanus	35	Africa, Asia
Calopogonium	4-8	America
Canavalia	40-50	Pantropical
Centrosema	35	America
Crotalaria	350-600	Pantropical
Desmodium	300-350	Pantropical
Flemingia	30	Africa, Asia
Gliricidia	4-8	America
Indigofera	700-800	Pantropical
Lablab	1-2	Africa, Asia
Macroptilium	20	America
Macrotyloma	15-25	Africa
Mucuna	100-160	Pantropical
Neonotonia	1	Africa, Asia
Phaseolus	50	America
Pueraria	15	Asia
Rhynchosia	150-200	Pantropical
Sesbania	50	Pantropical
Stylosanthes	25-30	Pantropical, esp. America
Tephrosia	400	Pantropical
Vigna	100-150	Pantropical
Zornia	40-80	Pantropical

Collection of germplasm

History and overview

Systematic collection of the germplasm of tropical nongrain legumes (i.e., potential forage legumes) is of relatively recent history. The first Australian collecting mission by the Commonwealth Scientific and Industrial Research Organization (CSIRO) was carried out in subtropical and tropical South America in 1947-48 (Hartley 1949). That was the beginning of a series of major and minor Australian collection activities, in the 1950s in subtropical and tropical Africa, in the 1960s and 1970s in Central and South America as well as in Africa, and in recent years in Mexico.

Colombia, Venezuela, India, Indonesia, and Papua New Guinea (Broué and Grace 1976; Neal-Smith and Johns 1967,1971; Williams 1986). With parallel introductions from existing plant collections, these collecting efforts have resulted in one of the world's major collections of tropical and subtropical legume germplasm (about 13,000 accessions) held by the Australian Tropical Forage Genetic Resources Centre at CSIRO, Brisbane.

CIAT took up systematic and intensive collection of tropical legume germplasm, in collaboration with national research institutions, in 1973. By August 1986, more than 15,000 accessions of tropical legumes had been collected and, to a small extent, introduced from other institutions (Schultze-Kraft 1986).

The following are additional significant endeavors to collect tropical legume genetic resources:

- 1962-67 and 1973-78, lnstituto de Pesquisas IRI, in Brazil (Hymowitz 1971, Shock et al 1979);
- since 1968, University of Florida, ARC Fort Pierce, in Central America, the Caribbean, and Brazil (A. E. Kretschmer, pers. comm.);
- since 1973, the IDRC/University of West Indies/Belize Forage Legume and Pasture Research Programme, in Belize and the Caribbean (International Development Research Centre-Belize Forage Legume and Pasture Research Programme 1984);
- 1974-82, FAO/National Agriculture Research Station, Kitale, in Kenya/Ibrahim 1984);
- since 1975, the Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA), in Brazil (Coradin and Schultze-Kraft 1987);
- 1984-85, the International Board for Plant Genetic Resources (IBPGR), in Indonesia (Mehra 1986);
- since 1984, the International Livestock Centre for Africa (ILCA), and collaborating national institutions, in Africa (J. K. Lazier, pers. comm.).

Objectives, strategy, and methodology

All these endeavors are aimed at broadening the genetic base of tropical legume germplasm that will be useful in developing cultivars for pastures, browse, or cut-and-carry forage. With the noteworthy exception of a 1983 ILCA/CATIE mission in Costa Rica to collect *Gliricidia sepium* germplasm for alley cropping purposes (Sumberg 1986), no efforts as yet have had as their primary objective collecting germplasm for use in the development of green manure and green leaf manure cultivars. There is no doubt, however, that potential as green manure has often been thought of, particularly when a collector finds especially vigorous plants belonging to species that, because of known toxin content, probably do not have potential as forage plants.

Target areas for collecting are sometimes determined by administrative boundaries: an important example is the *Stylosanthes* collections by the Empresa de Pesquisa Agropecuaria de Minas Gerais (EPAMIG) in the state of Minas Gerais, Brazil (Costa and Ferreira 1982). In most cases however, regions for legume collecting are chosen on the basis of their climatic or edaphic similarities with the

target region of cultivar development; examples are recent Australian collections in dry regions of Mexico (Reid 1983) and the CIAT collections in acid soil areas (Schultze-Kraft 1985).

This approach sometimes underestimates the broad adaptability of tropical legumes. A striking example is *Leucaena leucocephala,* a species that is outstandingly adapted to humid environments, in considerable contrast with its dry natural habitat in Central America. Another example is *Centrosema macrocarpum,* of which ecotypes from non-acid, fertile soils grow very well on low fertility soils with pH 4.0 and 90% A1 saturation (Schultze-Kraft et a1 1985).

The priorities regarding target species are, of course, determined by a collector's interest and research program. The strategy for a given region may be a collecting survey that aims at sampling the broadest possible range of genera. This can be a most convenient approach, particularly when a region has not been sampled before. It was successfully applied during the early IRI collections in Brazil (Hymowitz 1971).

The specific search for genetic variation within a promising genus or species is at the other extreme. An example of this approach is the recent Australian *Stylosanthes hamata* collection in Venezuela and Colombia (Edye 1986). Very good results also have been obtained with an intermediate approach—survey sampling in a given region, while at the same time emphasizing particular high-priority genera. Examples are recent collections in Southeast Asia, where 72% of 600 collected samples were high-priority Desmodium (and allied genera) and Purraria (Pattanavibul and Schultze-Kraft 1985). In Mexico, 20% of 400 collected samples belonged to high-priority genus *Centrosema* (Peralta et al 1987).

Regardless of their use, the particular value of legumes is their potential nitrogen contribution through effective symbiosis with *Rhizobium.* Although the ideal legume nodulates freely with effective native *Rhizobium* strains and needs no inoculation, on many soils and with many legumes an effective legume-*Rhizobium* symbiosis depends on previous inoculation (Sylvester-Bradley and Munevar 1987). *Rhizobium,* therefore, should be considered an important complementary plant genetic resource that also warrants collection.

Appropriate methodologies for 1) optimum sampling of legume seed and vegetative material, as well as *Rhizobium* nodules in the field, 2) data recording, and 3) sample and data processing have been developed (Clements and Cameron 1980, Mott 1979).

The major collections

A wide range of germplasm of tropical legume genera is now available as a result of the collection endeavors mentioned. The largest and most comprehensive collections are held by CSIRO, ILCA, and CIAT; they include considerable portions of the materials gathered by other collecting institutions. The University of Hawaii holds a significant shrub collection specialized in *Leucaena* and *Sesbania* (J. L. Brewbaker, pers. comm.).

Inventories of the major genera in the CSIRO, ILCA, and CIAT collections are presented in Table 3. The estimated total inventory is 15,000-20,000 distinct

Table 3. Tropical forage legume collections at CSIRO, CIAT, and ILCA.

Genus	Accessions[a] (no.)		
	CSIRO (August 1986)	CIAT (February 1987)	ILCA (May 1987)
Acacia	50	-	150
Aeschynomene	450	850	100
Alysicarpus	250	250	150
Cajanus	300	50	100
Calopogonium	150	500	50
Canavalia	100	200	-
Cassia	250	300	100
Centrosema	1,200	1,900	300
Clitoria	100	150	50
Crotalaria	300	250	150
Desmanthus	200	150	100
Desmodium	1,500	2,550	150
Dioclea	-	2 00	-
Dolichos	50	-	-
Eriosema	-	100	-
Erythrina	-	-	50
Flemingia	-	50	-
Galactia	100	550	-
Gliricidia	-	-	50
Glycine	100	-	-
Indigofera	450	200	150
Lablab	150	-	150
Leucaena	600	150	150
Lotononis	100	-	-
Lotus	200	-	-
Macroptilium/Vigna/Phaseolus	1,300	1,250	750
Macrotyloma	150	50	50
Mucuna	-	50	-
Neonotonia	250	100	200
Phyllodium	-	50	-
Pseudarthria	50	50	-
Pueraria	100	200	-
Rhynchosia	300	400	150
Sesbania	150	50	100
Stylosanthes	2,000	3,250	900
Tephrosia	250	150	100
Teramnus	100	300	50
Trifolium	1,200	50	1,450
Uraria	100	150	-
Vicia	100	-	-
Zornia	100	950	250
Total	12,750	15,500	5,950

[a]Rounded figures. Dashes (-) indicate fewer than 50 accessions. Sources for CSIRO collection: Williams (1986); for ILCA collection: J. R. Lazier, pers. comm.

materials, after duplicates within each collection and accessions common to the three collections are sorted out. CIAT also holds a major *Rhizobium* collection. It comprises 3,000 strains and is fully characterized; a computerized catalogue is available (Franco et al 1986).

Although the figures look encouraging when one takes into account that they are the result of a relatively few years' work, it must be emphasized that they represent only a very small fraction of the genetic diversity among tropical legumes in nature. In spite of intensive sampling, collection of the world's genetic resources of tropical legumes has only begun.

Germplasm evaluation

Objectives, strategy, and methodology

Germplasm evaluation is aimed at identifying adapted genotypes for direct use as cultivars or for plant breeding projects. For tropical legumes, evaluation of larger germplasm collections has aimed at pasture plants for grazing and, to a lesser extent, at cut-and-carry forages. Evaluations of large collections specifically for their potential as green manure are not numerous. Important examples are the work of Ghai et a1 (1985) with a 38-accession collection of *Sesbania* spp. in Karnal, India, and the evaluation of 49 *Gliricidia sepium* at ILCA, Nigeria (Sumberg 1986).

The major difference between the two uses seems to lie in the fact that plant persistence and forage quality (including the absence of antiquality factors) are among the screening and selection criteria for forages that have a significant role at early evaluation stages. Those will be of little or no importance for green manure plants.

Characteristics that contribute to legume persistence under grazing are considerably more important criteria in developing pasture plants for more extensive production systems than are rapid early growth and high dry matter production potential (which seem to be important traits for green manure legumes). Among the important characteristics influencing legume persistence are 1) adaptation to the marginal soil fertility that often prevails in the extensive production systems of the tropics, 2) tolerance for diseases and insect pests, 3) adequate growth habit and competitiveness in association with grasses, 4) drought tolerance, 5) adequate self-regeneration mechanisms, and 6) absence of excessive palatability.

In general, the evaluation strategy consists of testing large collections at a few major screening sites representative of the agroecological conditions of a given region. Smaller subsets of adapted materials selected from the larger collections are then tested at a range of sites within the same agroecosystem, but under the range of prevailing climatic and edaphic conditions.

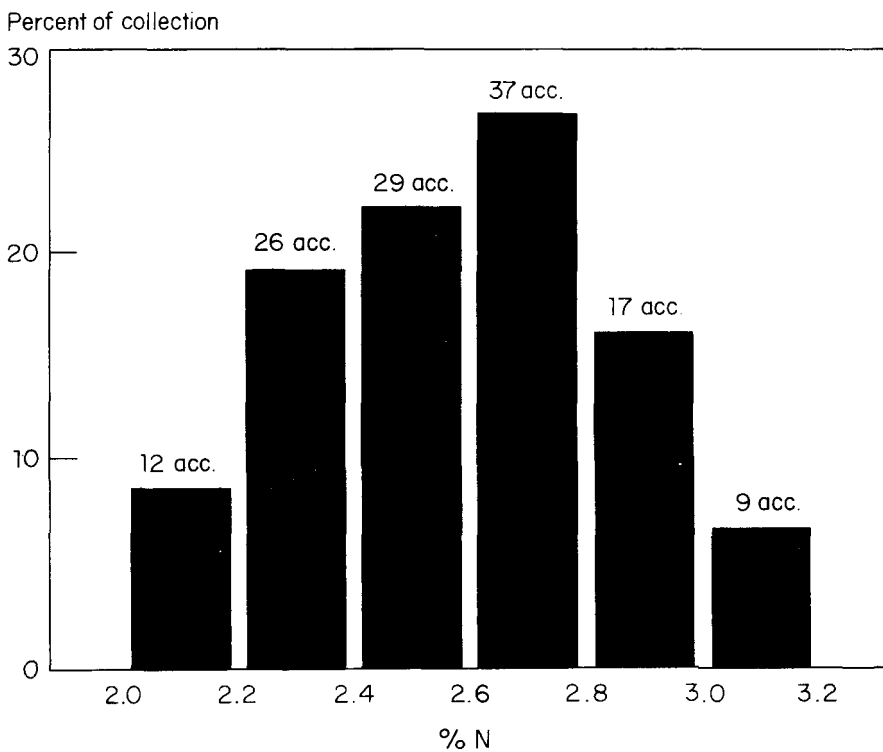
These evaluations are carried out by a multidisciplinary team of scientists, in which the plant nutritionist and the plant pathologist play key roles. Mineral deficiency and toxicity symptoms must be interpreted and separated from disease symptoms. Diseases of tropical legumes have become increasingly important. Largely unknown 1-2 decades ago, they are now the major constraint in tropical legume evaluation and selection.

Appropriate methodologies have been developed for agronomic evaluation of tropical forage legumes (i.e., initial evaluation without animals) (Clements and Cameron 1980, Mott 1979, Toledo 1982). The stages, starting when new material is received from field collections or donations, are essentially as follows:

Table 4. Principal descriptors used for characterization and preliminary evaluation of tropical forage legume germplasm.

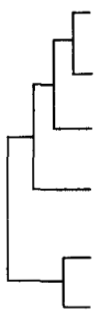
Genus, species	Self-seeding capacity
Life form (herb, subshrub, shrub, tree)	Seed production potential
Growth habit	Drought tolerance
Annuality	Nutritional disorders
Regrowth capacity and mechanism	Tolerance for insect pests and diseases

- Seed increase using potted plants in the greenhouse. This phase is often obligatory because of plant quarantine restrictions on imported seeds. These plants are also used for initial observations and characterization.
- Planting the entire collection of a given genus or species in spaced rows or plots in the field for the first preliminary evaluation. In general, seed is still very scarce, so that field establishment may be in the form of transplants from the greenhouse. Depending on the size of the collection and the field labor available, replications, although highly desirable, may sometimes be impossible. This planting usually is used for further seed multiplication. Depending on the size of the collection and availability of field labor, plants might be cut to determine the comparative green



1. Classification of a 130-accession collection of *Centrosema brasilianum* into 6% N groups (Schultze-Kraft and Belalcazar 1987).

Table 5. Classification of a *Centrosema macrocarpum* collection (105 accessions) into 6 cluster groups, based on dry matter production, number of rooted stolon nodes, and seed production (adapted from CIAT 1987).

Dendrogram	Cluster no.	Accessions no.	Accessions %	Mean dry matter yield (kg/plot)	Mean rooted nodes (no./m^2)	Mean seed yield (g/plot)
	1	12	11	9.0	668	440
	2	27	26	7.3	571	196
	3	3	3	7.5	3681	60
	4	10	0	11.3	1139	430
	5	26	25	5.0	297	369
	6	27	26	2.3	118	53

or dry matter production potential and to observe regrowth after defoliation. This is a decisive first-selection stage, during which relatively large collections are reduced to smaller, more manageable sizes. The parameters most commonly determined during this evaluation phase are presented in Table 4.

- Variety comparison trials of selected, pure legume stands for cutting or of grass or legume swards for grazing. The choice will depend on the intensity of evaluation that was possible during the previous stage and on the availability of seed. At this stage, plants are established from directly sown seed. Plot size must be considerably larger for the grazing than for the cutting option. Among the principal parameters to be determined are dry matter production potential and nutritive value. The need to inoculate with *Rhizobium* strains should also be determined during this phase. With grazing trials, the first observations and measurements related to legume persistence also can be made.

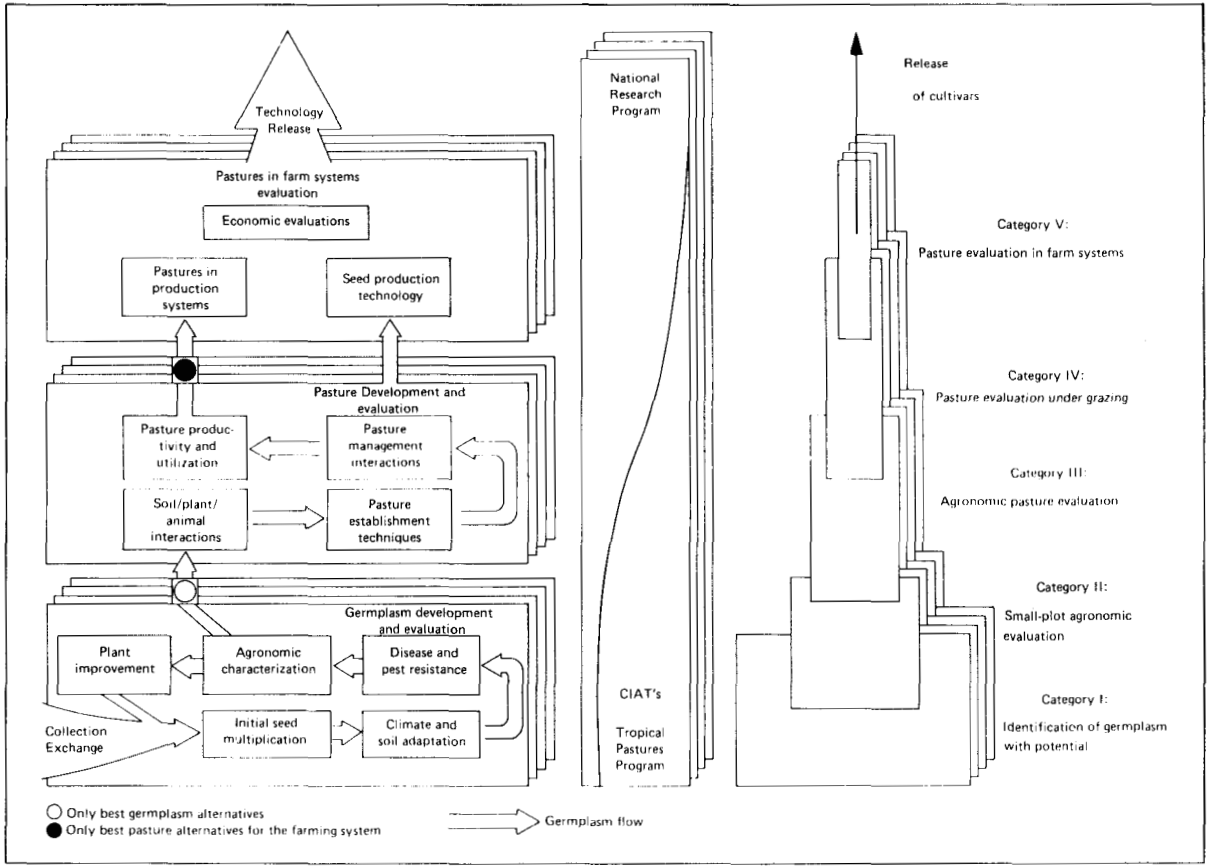
An important aspect of preliminary evaluations of large collections is documentation of results. Handbooks describe several options (Clements and Cameron 1980, Mott 1979, Toledo 1982). A simple computerized data management system has been developed and used with a large legume collection in Indonesia (Ivory et a1 1985). At CIAT, Ward's cluster analysis (1963) considers a limited number of variables to classify collections into groups of similar performance. Table 5 presents the classification of 105 accessions of *Centrosema macrocarpum* into 6 cluster groups. The variables used were dry matter yield, number of rooted stolon nodes, and seed yield.

A simple but informative description of the variation of a plant character in a large collection is the distribution frequency. Figure 1 presents the classification of a 130-accession collection of *Centrosema brasilianum* into 6 N content groups. Both examples show how extremely variable tropical legume germplasm can be within a given species.

Tropical legumes for acid soils

One of the objectives of the CIAT Tropical Pastures Program is to develop pasture cultivars, particularly legumes. adapted to the acid, low-fertility soils of the subhumid and humid savanna and forest environments of tropical America. A large legume germplasm collection was systematically screened and evaluated according to the scheme presented in Figure 2. A series of previously unknown or little-known legume species with good potential for acid soils were identified (CIAT 1981-87). The evaluations were done not only at major screening sites, but also throughout a network of regional trials within the Red Internacional de Evaluacion de Pastos Tropicales (RIEPT). The following list is of outstanding new legumes, some of which have been released by national institutions:

- *Centrosema acutifolium.* A trailing-climbing species very closely related to *C. pubescens,* agronomically unknown until recently, with very broad adaptability. Outstanding characteristics are low soil fertility requirements, good dry season performance, and competitiveness with grasses. Accession CIAT 5277 released in Colombia as cultivar Vichada.
- *C. brasilianum.* A trailing-climbing species with high potential in savanna climates with a 3-6 mo dry season. Very high seed production and very low soil fertility requirements. Accession CIAT 5234 among the most widely tested and most promising.
- *C. macrocarpum.* A vigorously climbing species closely related to *C. pubescens,* with somewhat higher soil fertility requirements but also higher productivity, particularly in the humid tropics. High tolerance for *Centrosema* diseases. Accessions CIAT 5452 and 5713 in advanced testing stages.
- *Desmodium ovalifolium.* A rather well-known prostrate and stoloniferous legume cover crop for plantation agriculture. Slow to establish, forms a dense mat. Particularly well adapted to humid tropics. Very competitive with stoloniferous, mat-forming grasses. Commercial lines susceptible to stem gall nematode and false rust. Selected CIAT 13089 highly productive and disease-tolerant.
- *Stylosanthes capitata.* A medium-productive subshrub with potential limited to savanna climates. Very low soil fertility requirements, resistance to fungal disease anthracnose outside Brazil, high seed production potential, and good dry season performance. Blend of CIAT accessions released in Colombia as cultivar Capica.
- *S. guianensis* (common). A well-known subshrub legume. Susceptibility to anthracnose a major limitation. Accessions CIAT 136 and 184 highly productive and disease tolerant in the humid tropics. CIAT 184 released in Peru as cultivar Pucallpa.
- *S. guianensis* var. *pauciflora.* A productive shrubby legume with potential for higher rainfall areas. Same positive features as *S. capitata,* but with very low seed production potential. Accession CIAT 2243 released in Brazil as cultivar Bandeirante.
- *S. macrocephala.* Very similar to *S. capitata,* but with lower dry matter productivity. Accession CIAT 1281 released in Brazil as cultivar Pioneiro.



2. Germplasm evaluation scheme of the CIAT Tropical Pastures Program (CIAT 1984).

- *Zornia glabra.* A herbaceous, little-known species with broad adaptability. Medium-productive, low nutrient requirements. Disease resistant, particularly to *Sphaceloma* scab. CIAT 7847 and 8279 among most promising accessions.
- *Z. latifolia.* A herbaceous, leafy species. Very similar to *Z. glabra,* but susceptible to *Sphaceloma* scab and *Drechslera* leaf spot. Outstanding performance at some humid tropics sites. CIAT 728 and 9199 among best accessions.

In addition, accessions of several other species are showing promise, with vigorous growth in very acid, low fertility soils. These include *Aeschynomene histrix, Dioclea guianensis* and *D. virgata, Flemingia macrophylla,* and *Pueraria montana* var. *chinensis.*

With the exception of an exploratory trial in which *Z. latifolia* CIAT 728 was included as green manure for cassava (CIAT 1985), the potential of these legumes for green manure has not been studied. It seems worthwhile to test that potential in rice farming systems, not only because these new legumes grow well on less acid soils and respond to higher soil fertility, but also because recent advances in rice research seem to indicate a good potential for this crop in acid soils (CIAT 1987). They probably have a high potential for legume fallows in shifting agriculture.

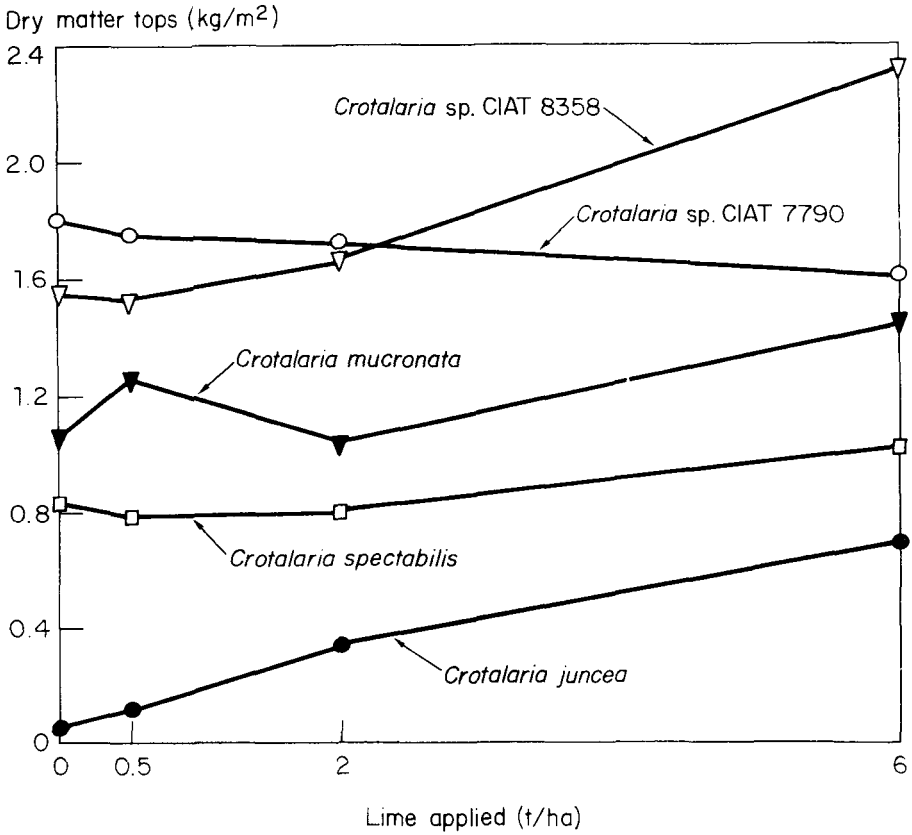
Conclusions and proposed research strategy

Although only a very small portion of the naturally available genetic diversity of tropical legumes is represented in the existing germplasm collections, these collections seem to contain very diverse material at the genus. species, and ecotype levels. The presently available collections have practically never been looked at as potential green manure legumes; however, they represent a valuable resource. It can be expected that, in a manner similar to the identification of successful forage species, systematic evaluation will lead to the identification of new, promising green manure legumes or to superior lines within already known genera or species. Figure 3 shows the variation in a small *Crotalaria* collection of 5 accessions—including commercial *C. juncea*—growing on a very acid Ultisol with 80% Al saturation, and their response to lime applications. The highest level of lime reduced A1 saturation to 40%. The new accessions were superior to *C. juncea* at all lime levels; some of them were apparently insensitive to high Al saturation.

If using tropical legumes for green manure is economically attractive, justifying research intensification, the following strategy might be used, at least as far as germplasm collection and evaluation are concerned.

Build a gene pool

It would seem important 1) to define the various agroecological conditions for which green manure crops in rice farming systems are required (e.g., cracking clays, acid soils, seasonally flooded conditions, cool temperatures during the growing season), and 2) to define the most important characteristics required of a tropical legume for use as green manure (e.g., fast early growth, drought tolerance, absence of specific *Rhizobium* requirements, low self-seeding potential). Curators of major germplasm collections could then be asked to scan their collection site and evaluation files for suitable germplasm.



3. Dry matter response of 5 *Crotalaria* accessions to lime application on Ultisol (pH 4.1, 80% A1 saturation) (CIAT 1987).

The resulting collection of tropical legumes with green manure potential should have as broad a genetic base as possible. If existing collections are too restricted to forage species, with too narrow a green manure potential, collecting missions aiming specifically at species with green manure potential could be considered. In this case, the advice and support of the International Board for Plant Genetic Resources should be sought.

Germplasm evaluation

Once an institution has been assigned the responsibility to maintain a germplasm collection of tropical green manure legumes, systematic and intensive seed multiplication at the greenhouse or plant nursery level should precede any regional testing under agroecological and farming system conditions. Existing rice variety testing networks could be used for such regional evaluation of green manure germplasm.

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Notes

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Seed production and management of mungbean and soybean

S. Shanmugasundaram

The seed requirement to plant the world mungbean area is estimated to be around 68,000t; for soybean, it is 3,156,000t. Current seed supplies cannot meet that demand. The need to produce sufficient quality seeds in mungbean and soybean is emphasized and preharvest and postharvest seed production problems discussed. Future directions for seed production are examined in the context of innovative concepts and procedures in plant breeding.

In early agriculture, people grew crops primarily for food. Each season, they saved some grain as seed for the next crop. Today, farmers in many countries still follow that age-old practice. In choosing seeds for the next planting, farmers select only the best (Chin 1969).

Mungbean *Vigna radiata* (L.) Wilczek and soybean *Glycine max* (L.) Merr. form important constituents of human food and animal feed. It is estimated that worldwide mungbean production amounts to about 1.4 million t harvested from about 3.4 million ha (Shanmugasundaram and Poehlman 1988). Seed rate for planting varies with seed size, percentage of germination, and desired plant population density (Morton et a1 1982). However, 68,000 t of seeds are required to satisfy the need of 3.4 million ha of mungbean production. Assuming an average seed rate of 20 kg/ha, about 113,333 ha of land is needed to produce 600 kg good quality seed ha.

In 1985, 52.6 million ha were planted to soybean (Table 1), about 49% of the area in North and Central America, 27% in South America, and 20% in Asia. With an average seed rate of 60 kg/ ha, it is estimated that 3,156,000 t of seeds are needed. About 2,104,000 ha of land is required to produce an average 1.5 t good quality seed/ha.

The objective in seed production is to maximize the production of seed with suitable germination capacity (Bowring et al 1978). In the United States in 1983, certified soybean seed was produced on 387,445 ha, 36% of the total soybean area. The soybean seed requirement in Thailand was 7,000 t in 1983, but the government produced only 980 t (Potan 1987). In Indonesia, only 30% of the total area is planted with seeds of improved cultivars (Djauhari et al 1984).

Table 1. Total area, average yield, and production of soybean in 1985 (FAO 1986).

Region	Area (thousand ha)	Average yield (t/ha)	Production (thousand t)
Africa	404	0.97	392
North and Central America	25,853	2.29	59,099
South America	14,300	1.81	25,805
Asia	10,611	1.32	14,023
Europe	600	1.55	929
Oceania	63	1.74	110
USSR	738	0.65	480
World	52,569	1.92	100,839

Table 2. Mungbean or soybean seed production and management by various institutions in different countries (FAO 1977).

Country	Institution handling production and management
Africa	
Cameroon	Limited amount by crop improvement institutions
Zambia	Rural Development Cooperation Ltd. Zambian Seed Producer's Association
North & Central America	
Canada	Basic and certified seed companies, about 5,000 ha
Trinidad-Tobago	Chaguaramas Agricultural Development Project
South America	
Argentina	More than 70 private seed companies, cooperative growers and government institutions, 10,800 ha commercial seed production
Bolivia	Three official institutions, about 400 ha
Brazil	National seed plan, PLANASEM, 288,000 ha
Chile	Instituto Nacional de Investigaciones Agropecuarias
Colombia	Instituto Agropecuaria Colombiano, 4,400 t
Ecuador	Empresa Mixta Semillas, private seed company with state participation
Paraguay	SENASE, 2,800 ha
Asia	
India	National seed cooperatives, state seed farmers, private seed companies
Indonesia	Central Research Institute for Food Crops Extension seed farms, village seed farms
Korea	Experimental stations, seed growers, 4,000 ha
Philippines	Farmers' cooperatives
Sri Lanka	Department of Agriculture
Thailand	Field crop experiment station and Department of Agricultural Extension, 1,700 ha
Oceania	
Australia	Seed processors, official seed increase committee

The primary objective of seed certification is to maintain genetic purity, varietal identity, and good seed quality during seed production and distribution (Fehr 1978). Seed certification is required in Western Europe, Canada, and Australia for seed marketing within the country and for imported seed (Weimortz 1985).

In the developing countries, the frequently mentioned problems and constraints to mungbean and soybean production are "little use of improved varieties" (India); "shortage of supply of good seeds, high-yielding varieties not available" (Pakistan); "seeds of recommended varieties cannot be supplied in sufficient quantity, distribution of seeds among farmers still inadequate, no storage facilities" (Indonesia); "sufficient supply of seeds yet remains to be secured" (Philippines) (Suzuki and Konno 1982). Although governments encourage the use of improved varieties and good quality seed, the erratic availability of quality seed impedes that realization.

In many developing countries, both public and private institutions are involved in mungbean and soybean seed production and management (Table 2). The major goal of plant breeders is to develop improved cultivars which can increase crop production and improve human nutrition. As more and more farmers become interested in growing recommended improved varieties, in many instances the supply of quality seed cannot meet the demand.

Production of the good quality seed that is a prerequisite to obtain good grain yields (Hebblethwaite 1978) is a specialized operation requiring skill, care, and training. Invariably, seed quality is reflected in the price. For improved cultivars to reach farmers, an efficient production system to provide adequate quality seed of improved cultivars at reasonable prices is essential (McDonald and Pardee 1985).

Seed production and management of soybean have been well reviewed (Naik 1985, Nangju et al 1978, Popinigis 1985, Sinclair and Jackobs 1982, Scott and Aldrich 1970, Tekronyet al 1978, Wannapee et al 1985). However, little information is available on mungbean seed production. The basic principles and requirements for seed production and management are discussed below, with examples where data are available on mungbean and soybean.

Seed production

Soybean seeds are large and bulky and have high oil content. Their storage life under ambient room temperature is short. Annual seed production is essential to obtain a continuous supply of good quality seed (Tekrony et al 1978).

Mungbean seeds are relatively small, but are readily attacked by seed weevil *Callosobruchus chinensis.* Seed quality and viability are serious problems in the tropics. Overplanting to alleviate poor seed quality is unreliable and expensive. Poor quality seeds have less germination vigor.

In planning a seed production program, private or public, it is necessary to know seed demand, estimated quality seed yield, multiplication rates, storage needs, transportation needs, and marketing strategies (Douglas 1980).

Varietal development

Varietal development precedes seed production. Soybean and mungbean varieties that have high yield potential, adaptability to environments, and resistance to diseases and insects have been developed and breeding for good seed quality in the

tropics and subtropics has received attention (Dassou and Kueneman 1984, Kueneman 1983, Opeña et al 1987, Shanmugasundaram 1976, Shanmugasundaram and Poehlman 1988).

Successful quality seed production will depend on incorporation of genetically controlled quality traits with desirable agronomic ones. Hard seededness is known to improve seed resistance to detrimental environmental influences (Potts et al 1978). Other characters with similar influences are seed coat thickness (Caviness and Simpson 1974), pod thickness or composition (Hartwig and Edwards 1970), and resistance to seedborne diseases (Wilcox et al 1975).

In the past decade, a number of new mungbean and soybean varieties were released to farmers. But seed quality characters have yet to be incorporated into new varieties.

Seed categories

Genetic improvement must be associated with good seed certification. Farmers should have access to good, relatively affordable seed (Walker 1980). But seed production, inspection, certification, processing, distribution, and marketing vary widely among countries.

The steps to produce the various categories of seeds described here apply to mungbean and soybean. Seed multiplication rates vary with the crop.

The plant breeder carefully selects for various traits (with adaptability and high yield considered essential) and identifies a line as suitable for release. The identified line is unique in a number of qualitative and quantitative traits. However, certain distinct traits are uniform and stable. These distinguishing characters are consistent and relatively easy to use for a specified region of adaptation.

For example, when a new soybean variety is released in the USA, characters such as seed coat color, hilum color, flower color, pubescence color, stem termination, leaf type, USA maturity group classification, pertinent disease resistance or susceptibility, and protein and oil content are described. Foundation seed is produced from the basic breeder seed. Registered and certified seeds are produced by selected farmers. Methods of seed production by the plant breeder, maintainer, seed merchant, and progressive farmer depend on the crop species and on the breeding system (Bowring et al 1978).

The plant breeder's responsibility is to maintain the pedigree seed (Fehr 1978) or the prebasic seed (Bowring et al 1978). Basic seed is produced from pedigree seed. A plant breeder supervises production of these two seed categories of seed, making sure that the variety is pure and free from variations that are not described as part of the variety. Pedigree and basic seed also should be free from weed seeds and extraneous materials.

A variant is defined as plants or seeds described as part of the variety, but different from the norm for the variety (Otto 1985). In soybean, natural mutation can cause changes in plant or seed characteristics. Brown and black seed coat mutants are common in yellow seeded soybean; these offtypes should be removed during purification (Fehr 1978).

Mungbean and soybean are self-pollinated, annual species reproduced by normal fertilization. In mungbean, natural outcrossing varies from 0.0 to 13% (Shanmugasundaram and Poehlman 1988). A high level of outcrossing can cause considerable variation in the seed produced. In India, when mungbean seed was produced, a 1.5-m border was left unharvested between adjacent varieties (Kernick 1961). Considering the large extent of outcrossing in some genotypes, the isolation requirement has been increased to 3 m.

Usually, a plant breeder maintains a variety by planting single plant progeny and checking characteristics against the variety's official description. If the rows are uniform, they are bulked. In soybean, 30-50 kg of pedigree seed normally is reserved. In mungbean, 10-15 kg of pedigree seed is reserved. In temperate and tropical countries, seed production rates vary because of the length of growing seasons and the yield potential of varieties. Pedigree seed is planted on 0.5-1.5 ha to produce 1-3 t soybean and 0.3-1 t mungbean basic seed.

Basic seed is used to produce the subsequent categories of seeds (Shanmugasundaram 1982). At each stage, care is exercised to remove variants. In countries with official seed certification programs, designated agencies supervise and regulate seed certification.

In India, a parastatal national seed corporation coordinates the production of certified seed through a series of state seed farms that are profit-responsible. They were set up and funded by World Bank (Walker 1980). The All-India Coordinated Research Project on Soybean, in its annual meeting, allocates to each breeder the quantity of seed to be produced. For example, in 1985-86 breeders produced about 92 t of basic seed of 20 new soybean varieties (P. S. Bhatnagar, pers. comm.).

Factors to consider in seed production

Seed production is a specialized activity. Preharvest and postharvest factors must be considered (Nangju et al 1978): field environment, cultural practices, genetic influence, and harvest time (Tekrony et al 1978) and biotic and abiotic factors (Roberts 1972b, Sinclair and Jackobs 1982).

Basic constraints in seed production can be varietal (genetic characteristics), environmental, biological, and socioeconomic, alone or in combination. Vagaries of climate and soils must not be used as excuses for deficiencies in plant genetics, selection procedures, isolation distances, good crop management, and quality control (Walker 1980).

Constraints such as photoperiod, temperature, soil properties, and rainfall cannot be controlled by the seed producer (Shanmugasundaram and Tsou 1987). Land preparation, organic or inorganic fertilizer applications, pest and disease control, and weed control and management are factors that can be regulated. A sufficient knowledge pool is available (for a review see Morton et al 1982, Nangju et al 1978, Scott and Aldrich 1970, Shanmugasundaram 1982, Shanmugasundaram and Tsou 1987, Sinclair and Jackobs 1982, Tekrony et al 1978). Although obtaining a high yield is a consideration, the most important criterion is producing good

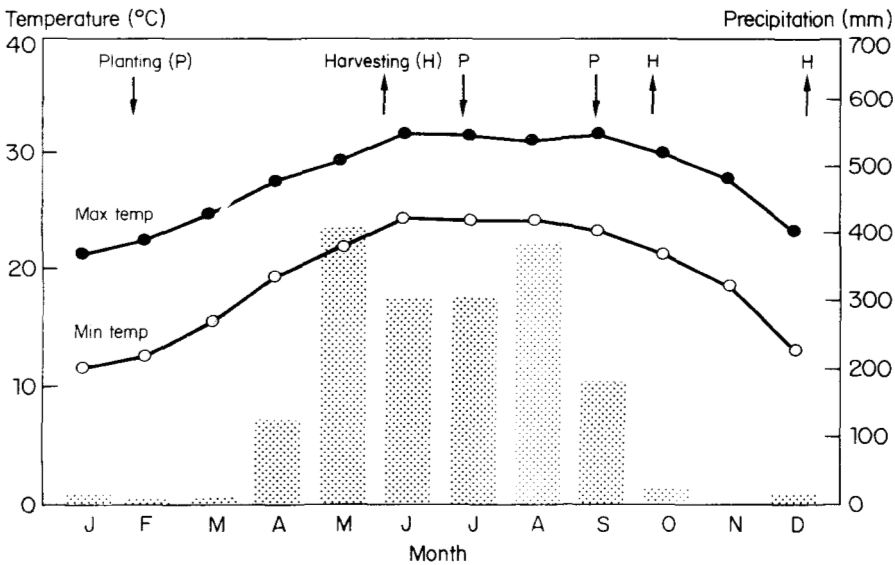
quality seed. Since the price of seed is generally higher than the price of grain, extra management inputs are justified.

Preharvest factors

Seed longevity and field weathering. At the Asian Vegetable Research and Development Center (AVRDC), soybean can be planted in the February, July, and September seasons. The February crop encounters rain at harvest (Fig. 1). The July rainy season crop may be exposed to typhoons. Field weathering of seed is a common problem in both seasons. Therefore, the seed quality of February and July season crops generally is not dependable. The September season crop produces the best quality seed (Shanmugasundaram and Tsou 1987). The seed quality of rainy season crops, in general, is poor in Indonesia, Thailand, Philippines, Sri Lanka, and Nigeria (Arulnandhy 1987, Nangju et al 1978, Potan 1987, Sumarno 1987).

One of the best ways to prolong seed longevity and combat field weathering of soybean is through genetics. At the International Institute of Tropical Agriculture (IITA) and at AVRDC, obtaining good seed quality is a key breeding objective.

Varietal differences in seed deterioration in storage was observed in soybean (Wien and Kueneman 1981). Freshly harvested seeds of AGS 2, a pure line from an Indonesian introduction; Pb-1 from India; and AGS 29 from AVRDC maintained about 80% germination for about 6 mo at ambient room temperature in Bangladesh. Locally grown variety Bragg and AGS 66 from AVRDC can be stored for only 2-3 mo (Fig. 2). Small-seeded varieties from Indonesia and black seed coat varieties deteriorate more slowly than large-seeded varieties. However, reports on the role of large and small seeds in seed longevity, germination, emergence, and yields have

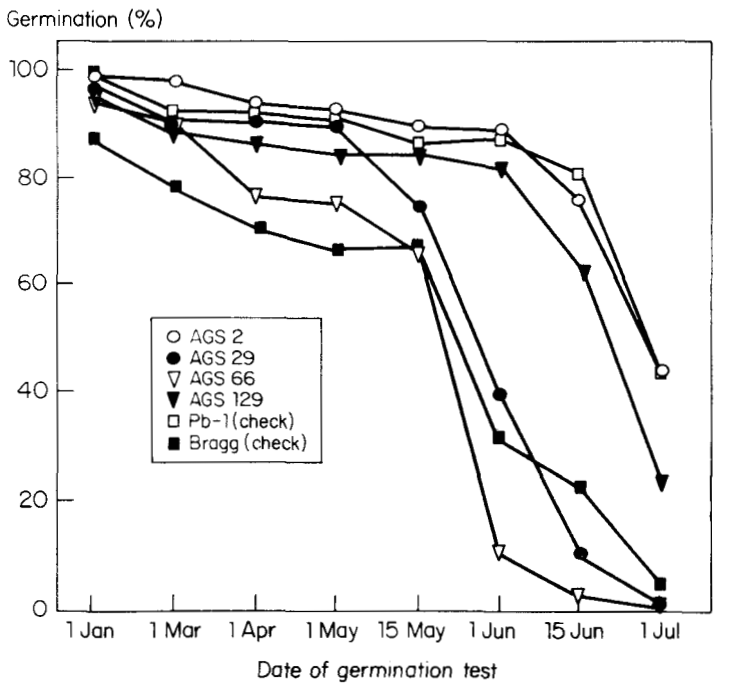


1. Maximum and minimum temperature and rainfall pattern at AVRDC in 1984 and time of planting and harvest.

been contradictory (Edwards and Hartwig 1971, Fontes and Ohlrogge 1972, Green et al 1965, Johnson and Luedders 1974, Ndunguru and Summerfield 1975). Some changes associated with seed deterioration are reduced protein synthesis, reduced ability to utilize labeled glucose, reduced respiration, and increased respiration quotient (A. Knapp, pers. comm.). Although small seeds are associated with better seed longevity, the reasons are not yet understood.

Seed vigor is an elusive and complex concept.Vigorous seeds are "likely to . . . perform particularly well in the field, better than others which may be equally satisfactory in the laboratory test" (Heydecker 1972). Loss of seed vigor due to weathering precedes loss of seed viability. Assessing seed vigor is problematic for seedmen (Kueneman 1982). The concept of seed vigor and its importance to seed production were described by Heydecker (1972) and Perry (1978). A modified accelerated aging and hot water stress test were used to screen for seed longevity and vigor.

In the accelerated aging stress test, seeds are kept at 42 °C and 100% relative humidity (RH) for 48 h, followed by a laboratory germination test (Byrd and Delouche 1971). To distinguish cultivars with good and poor seed storability, Wien and Kueneman (1981) used a modified accelerated aging stress technique. After pods dried, they threshed the seeds and subjected them to 75% RH at 40 °C for 6 wk, followed by a laboratory germination test.



2. Germination percentage of 6 soybean varieties evaluated at different intervals after storage at ambient temperature. Bangladesh, 1985.

Hot water pregermination stress includes soaking seeds for 70 s in 75 °C water and rinsing in tap water prior to determining germination or emergence (Kueneman 1982).

Kueneman (1983) evaluated the F_1 seeds of reciprocal crosses between soybean genotypes with good and poor seed longevity using the accelerated aging method. He found significant reciprocal differences, and suggested the possible influence of the maternal plant genome on seed longevity. The pooled F_2 variances were larger than pooled parental variances, which indicated the influence of the genotypes. Differences between reciprocals of the F_2 seed, although relatively small compared to those between F_1 reciprocals, were significant, indicating that cytoplasmic gene action for seed longevity may also be involved, but its effects are probably small. Because of the influence of the maternal plant, expression of segregation is delayed one generation (Kueneman 1983).

Dassou and Kueneman (1984) subjected physiologically mature pods to a weathering technique in an incubator at 30 °C and 90-95% relative humidity (RH) for 10 d. They identified several genotypes resistant to both seed weathering and deterioration in storage (Table 3). Paschal and Ellis (1978) reported that genotypes PI 205912, PI 205907, PI 341249, PI 279088, and PI 219653 could be used for breeding soybean with resistance to field weathering and to seed deterioration in storage.

An early-maturing variety can be used to avoid weathering damage. In Taiwan, for example, spring soybean is planted in February-March and harvested in mid-May. However, early maturity is not a dependable alternative. In some years, rains may come early and spoil the crop.

Manipulating the cropping pattern also can be used to avoid field weathering in the rainy season. In Pakistan, soybean for seed is planted July-August and harvested October-November (Beg 1987). In East Java, Indonesia, lowland and upland soybeans are planted year-round. Seed for the lowland rainy season and dry season

Table 3. Genotypes resistant to seed weathering and to deterioration in storage.

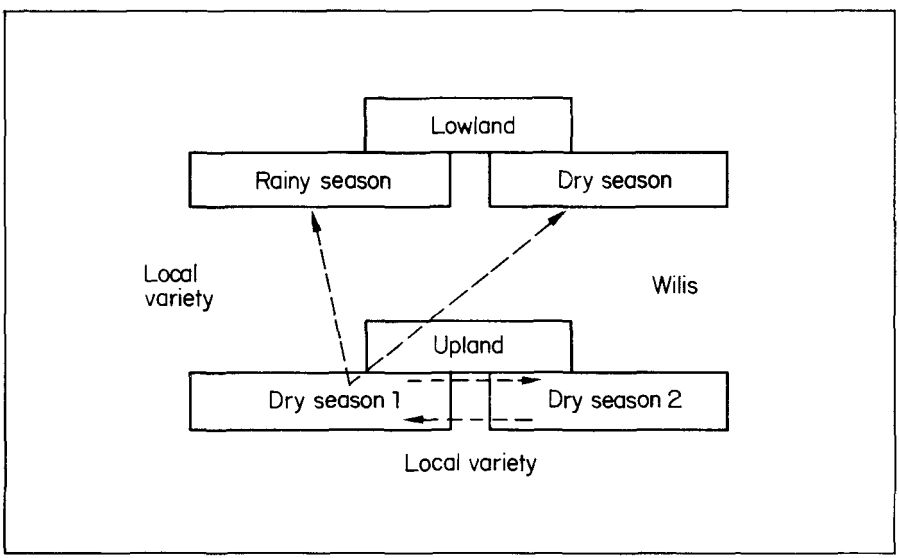
Genotype	Origin	100-seed wt (g)	Seed color	Hard seed[a] (%)	After incubator weathering (%)	After ambient storage[b] (%)
INDO 153	Indonesia	9.7	Black	36.0	54.2	87
INDO 131	Indonesia	10.2	Black	24.6	35.4	92
INDO 243P	Indonesia	8.9	Black	17.2	42.9	90
INDO 226	Indonesia	9.3	Black	27.2	46.2	80
INDO 255	Indonesia	10.1	Black	30.6	32.6	91
INDO 173A	Indonesia	10.8	Black	52.6	32.9	81
Fort Lamy	USA	10.5	Black	46.6	56.2	80
Lee A	USA	9.0	Black	62.0	58.5	88
Biloxi 3	China	10.5	Black	37.2	50.4	71
AVRDC 8457	Taiwan	6.1	Black	64.0	58.7	77

Source: Dassou and Kueneman 1984.
[a]Nonimbibing seed after 1 h soaking in water. [b]Stored for 8 mo at 25°C and 50 to 95% relative humidity.

crops comes from the second upland dry season crop. Seed for the second dry season crop comes from the first dry season crop. Only the grain of the rainy season crop is used (Fig. 3). Similar seed production strategies are used in other countries (Potan 1987, Sumarno 1987).

Water management. Water management is closely associated with field weathering in both soybean and mungbean seed production (Huck and Davis 1976, Morton et al 1982). Soybean that undergoes alternate wetting and drying in the field has poor seed quality caused by rapid differential absorption of water by localized tissues in the seed coat (Moore 1971, 1972). Plasmolysis and deplasmolysis at different stages of seed development can result in external and internal seed injuries (Iljin 1957). Damage caused by on-and-off excess moisture also has been observed in mungbean (B. C. Imrie, pers. comm.). Overhead sprinkler irrigation and rain at harvest can cause wetting and drying of pods. Therefore, from the R_5 growth stage on, either flood or furrow irrigation is suggested to obtain good quality seeds. During the dry season, when good quality seeds can be produced, adequate soil moisture at flowering (R_1 and R_2) and seed filling (R_5 and R_6) (Fehr and Caviness 1977) is essential.

Location. Some locations are more suitable for good quality seed production than others. Low relative humidity and cooler temperatures are the two key factors to consider in selecting a location for soybean seed production (Harrington 1963). Mungbean is a hot weather crop, but humidity and rainfall should be low for good quality seed production (Morton et al 1982). Locations with a cool, dry season are excellent for soybean seed production. In Pakistan, the cooler foothills of Hazara, Swat, and Parachinar are excellent sites for soybean seed production. Seed



3. Flow of soybean seed between locations in different seasons in East Java, Indonesia (source: personal discussions with fanners, extension staff, and researchers). The arrows show seed flow.

produced in those areas is distributed to other areas (Beg 1987). In Indonesia, soybean seed is produced during the dry season in Sumatra and transported to Java for planting. Distance, mode of transportation, type of packing material, and handling are important considerations in seed quality.

Pest management. Because seed is a high value crop, seed quality is an important consideration. In seed production, weed, insect, and disease control using recommended management practices is mandatory. Weeds can compete with a crop and restrict the use of nutrients, reducing crop quality. Weeds can also harbor insect vectors that may transmit various virus diseases and can serve as hosts for various fungal and bacterial diseases. Many leguminous weeds are hosts for soybean rust *Phakopsora pachyrhizi* and can serve as a reservoir of initial inoculum to create epidemics on soybean. If the field is weedy, the seeds can be contaminated with weed seeds during harvest (Nangju et al 1978).

The stink bug *Nezara viridula* in soybean and various pod borers in mungbean and soybean can reduce seed quality (Morton et al 1982, Todd 1982). The beanfly *Melanagronomyza* sp. and others can reduce seedling vigor and impair seed quality. It is imperative to monitor insect pest incidence and adopt appropriate, timely control measures.

Christensen (1972) tested thousands of soybean and seed samples over 20 yr to determine storage fungi invasion of seeds prior to harvest. He concluded that there is no significant invasion of seeds by storage fungi.

Fungal pathogens that can cause a reduction in seed quality in soybean are pod and stem blight and seed decay *Phomopsis* spp. = *Diaporthe phaseolorum* var. *sojae;* anthracnose *Colletotrichum dematium* var. *truncata;* and purple seed stain *Cercospora kikuchii* (Sinclair 1982). In the absence of genetic resistance, chemical control of these diseases is important.

Among the soybean viruses, soybean mosaic virus (SMV), tobacco ringspot virus (TRSV), and tobacco streak virus (TSV) may be important (Sinclair and Shurtleff 1975). In mungbean, yellow mosaic virus (YMV) is the most important virus disease. Vector control and planting resistant varieties are the only means of controlling virus diseases.

Postharvest factors

A seed begins its existence well before it is harvested. Preharvest conditions can cause varying amounts of seed deterioration even before harvest (Roberts 1972a).

Harvesting and drying

Within a season, the time of harvest can affect seed viability (Roberts 1972a). Harvesting should be done promptly on maturity. Harvesting seed with excessive moisture or too low moisture content can also damage quality. If the crop has to be harvested before full maturity, but after physiological maturity, it should be dried slowly under moderate temperature. Slow drying prevents shriveling due to rapid loss of moisture. After physiological maturity, seeds of both soybean and mungbean may begin to sprout during the rainy season while the plants are still in the field.

Under those circumstances, it is better to harvest at the onset of rain and dry the plants in a well-ventilated area. They can be air-dried slowly to enable threshing later.

Threshing and cleaning

High cylinder speeds of combines or threshers will result in multiple fractures and deep-seated bruises, especially in large-seeded soybean or mungbean and in seeds with lower moisture content (Moore 1957,1972; Roberts 1972a). A 700 rpm cylinder speed is better than 1155 rpm. Soybean seeds impacted at 12-16% seed moisture germinated satisfactorily; those impacted at 8- 10% and 18-20% moisture germinated poorly (Bunch 1960).

In developing countries, soybean and mungbean usually are threshed by hand, either by beating pods inside a bag with sticks or by trampling with animals or small tractors. Such harsh treatment can result in mutilated seeds. Studies at IITA showed that combine threshing is inferior to hand threshing and beating pods inside a bag (Nangju et a1 1978). Possibly the cylinder speed was not set properly or the seed moisture content at threshing was too low.

After threshing, the seeds should be cleaned to remove plant debris, weed seeds, dirt, and other extraneous materials that favor seed deterioration. The seeds should be examined for purity and variants should be removed. Seeds with mottling due to SMV should be removed.

Testing for viability and longevity

A number of factors can influence seed quality and viability during production. Poor seed with low viability will be even poorer after storage. Therefore, seed lots need to be examined before storage. A good-looking seed may not necessarily be good quality. Seed viability is usually measured when the seed is planted, but it is also measured for industrial purposes (MacKay 1978). Incubator germination, field emergence, tetrazolium, seedling growth rates, and seed leachates are some of the tests used to evaluate seed viability (Kueneman 1982, MacKay 1978).

Genotypic differences in seed longevity have been reported (Kueneman 1983, Paschal and Ellis 1978). Within a variety, a number of preharvest and postharvest factors can influence seed longevity. These tests of seed longevity have been proposed: seed storage (normal aging of seeds), accelerated aging stress, cold stress, hot water pregermination stress, osmotic stress, thermo stress during germination, and methanol stress (Kueneman 1982). Accelerated aging, pregermination, thermo, and methanol stress are recommended for use in breeding for seed longevity.

Seed storage

Factors to consider in storing seeds until planting are initial seed moisture content, genotype, temperature, RH, the container in which the seed is packed, and the method of packing. At AVRDC, seeds are sun- or air-dried to 8% moisture content for medium-term storage at 2-5 °C and 40-45% RH. Under these conditions, soybean seed can be stored for 20 yr (AVRDC 1985, Cromarty et a1 1982). With 8.1-9.4% seed moisture content, soybean seed can be stored at 10 °C for 10 yr; at 13%

Table 4. Equilibrium moisture content of soybean at 25°C at 30-95% relative humidity (RH) (Roberts and Roberts 1972).

Equilibrium moisture content at given RH					
10%	30%	45%	60%	75%	95%
4.3	6.5	7.4	9.3	13.1	18.8

moisture content, it can be stored for 3 yr. At 20-30 °C, seed with 13-18% moisture content will remain viable for less than a year (Toole and Toole 1946). Under tropical conditions, high initial quality soybean seeds at 9-9.5% moisture content can be safely stored 9 mo at 20-25 °C and 50-60% RH (Gregg 1982). Most AVRDC breeding materials with good initial seed quality and 9-10%, moisture content are stored at 20-24 °C and 55-60% RH. The majority of the entries stored under these conditions retained more than 80% viability for at least 2 yr. Similar storage conditions are suitable for mungbean.

If storage conditions have a higher RH, there is no need to dry the seed to less than equilibrium moisture content. At 45% RH or lower, seed should be dried to 7.4% moisture content or lower. At 60% RH, drying the seed to 9% moisture will suffice. Soybean seed moisture content at 25 °C with different relative humidity levels are given in Table 4.

The usual rule of thumb for storage conditions for the short term is percent RH and degrees Fahrenheit totaling 100 or less (James 1961).

The viability of soybean is determined using an age index concept.

$$\text{Age index (AI)} = \text{months in storage} \times 10^{0.143MC} \times 10^{0.0645T}$$

Where MC= moisture content (%), T= temperature (°C), and months in storage = Log AI-0.143MC-0.0645T.

Fungi activity during storage below 75% RH is very low; below 62% RH, all storage fungi are completely inactive (Roberts 1972a). Below 60% RH, storage insects are inactive. Because mungbean weevil is a serious storage pest, it is important to maintain RH below 60% and seed moisture content below 8% (Roberts 1972a).

The minimum germination required for seed certification varies among countries. For soybean, it is 80% in the US. but many seedmen demand 90% (Tekrony et al 1978). In India, it is 70%. For mungbean, minimum germination in India is 75% (Agrawal 1980).

Under ambient conditions, mungbean appears to be storable longer than soybean (Table 5). Traditional mungbean varieties appear to have a high proportion of hard seeds, but hard seededness decrease with age in storage. Mungbean seed loses hard seededness with a year (Pathwardhan 1927).

During domestication, the hard seededness character was selected out. It appears probable that this trait in mungbean can be used in breeding for good seed quality (B. C. Imrie, pers. comm.). Soon after harvest, hard-seeded mungbean germination is low, but it improves with storage (Rajasekara Mudaliar and

Table 5. Germination of quality seed tested after different durations in storage at ambient conditions in Delhi, India (Agrawal 1980).

Crop	Germination (%)							
	0	3mo	6mo	12mo	18mo	24mo	36mo	37
Mungbean cultivar P. S.-16	99	99	99	99	98			98
Soybean cultivar Bragg	94	93	81	43	14	0	0	0

Tabla 6. Germination of soybean seed stored in different containers at ambient room temperature and cold room for different durations in Sri Lanka (Arulnandhy 1987).

Storage period (mo.)	Storage condition	Germination (%)	
		Gunny bag	Polyethylene bag
0	Ambient	90	90
	Cold	90	90
3	Ambient	80	81
	Cold	88	80
6	Ambient	2	70
	Cold	79	81

Sundararaj 1954). Even after 11 yr of storage, hard-seeded mungbean had 70% germination (Sonavene 1928). In soybean, a certain proportion of hard seeds in a variety seems to improve seed longevity and germination (Potts et al 1978).

Because farmers in the tropics do not have sophisticated cold storage facilities, practical storage methods need to be developed. Harrington (1963) suggested using steel bins with steel lids, or steel drums with an aluminum foil layer and a gasket seal, sealed tin cans, hermetically sealed glass jars, sealed aluminized polyester pouches, or sealed highdensity polyethylene bags. Metal drums with gasket seals are common in Taiwan. Sealed polyethylene bags kept in a shaded area can safely store seed for 6-9 mo (Table 6). Vaporproof packages for storage protect seed from drastic fluctuations in RH. For a detailed review on this topic, see Delouche et al (1973), Delouche (1975), and Nangju et al (1978).

Although storage facilities, low RH, and temperature are known to ward off mungbean weevil, such facilities are unavailable in developing countries in the tropics. Asian villagers traditionally have used peanut oil to protect pulse grains against storage insects. Results at AVRDC suggest that peanut oil or soybean oil at 2-3 ml/kg of seed can effectively suppress weevil reproduction in stored mungbean for 3 mo (AVRDC 1976).

In India, treatment with neem oil, activated clay, and red earth is common. Asian farmers also mix seeds with ash to prevent moisture buildup.

If the integrity of the seed is violated before or after harvest, then the seed is vulnerable to damage by biotic factors. Almond moth *Ephestia cautella* can develop

on soybean in storage. An intact seed coat is an effective barrier to infestations. Soybean saponin extracts have been found to inhibit development of mungbean weevil and soybean almond moth. The saponins or their glucosides seem to produce typical antibiotic symptoms (Sirisingh and Kogan 1982).

Future of seed production

Rapid advances in innovative breeding concepts and procedures will surely modify concepts of crop varieties in the future (Jensen 1965). In soybean, there are blends, mixtures of two or more pure lines, multiline varieties, and short breeding cycle varieties (less uniform); there is a potential for hybrids and genetically engineered varieties. Some of these will not conform to the variety norm of purity, homogeneity, and distinctness. Seed production and certification of these new products will be a challenge (Jensen 1965, Lafever 1985). The products will have greater variability for plant type. The working philosophy of the future will emphasize performance over uniformity. In such cases, seed certification probably should monitor seed quality rather than distinctness.

Diagnostic tests for germination should include rapid vigor tests, disease tests, seed treatment tests, and variety identification tests (Voris 1985). A simple, inexpensive, and practical way to efficiently produce, harvest, thresh, clean, and store good quality seed for small farmers is needed. The mechanisms involved in protecting against insects using home remedies such as peanut oil need further exploration. Research also should focus on the reasons for good seed quality with small seeds and black seeds, with or without hard seededness. The role of the environment at different stages of seed development and its relevance to seed deterioration deserve further study. Because farmers are interested in storing seed at most for 6-9 mo, research with that objective should be distinguished from commercial concerns for longer term storage.

There is growing awareness, even in developing countries, of the need to obtain quality seed for planting. Farmers consider it an important single investment that is a prerequisite if all other management inputs are to pay off. But both government and private industry are unable to meet the demand or provide good quality seed. The price of certified seed is almost double the price of regular seed (in Thailand, regular seed costs US$1.40/kg; certified seed costs $3.0/kg)(Potan 1987). However, the government offers subsidies or other means of obtaining quality seed. Governments also should encourage the private seed industry to meet local demand without unduly exploiting the farmers.

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