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Management of Acid Tropical Soils for Sustainable Agriculture

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Management of Acid Tropical Soils for Sustainable Agriculture

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Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA)
Instituto Nacional de Investigación y Promoción Agropecuaria (INIPA)
North Carolina State University (NCSU)

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The International Board for Soil Research and Management, Inc. (IBSRAM) is a nonprofit international research support agency, with the primary objective of assisting national agricultural research programs in overcoming soil constraints to increase food production on a sustained basis. This is primarily accomplished through coordinated, multicountry networks for research and training. IBSRAM supplies backstopping support through assistance on experimental design, soil and statistical analyses, data processing, and information exchange.

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Foreword

Acid tropical soils—Oxisols and Ultisols—support an increasingly large proportion of the developing world's population, but technologies for their sustained production are at early stages of development.

Recognizing the urgency of this situation, IBSRAM organized the inaugural workshop on Management of Acid Tropical Soils for Sustained Production. The workshop was held in Peru under the auspices of INIPA and in Brazil under the auspices of EMBRAPA from April 24 to May 3, 1985.

Many donors supported the workshop, and IBSRAM is pleased to express its gratitude to the United States Agency for International Development (AID) through the Soil Management Support Services (SMSS); the Australian Centre for International Agricultural Research (ACIAR); and the Government of France. Thanks are also in order to the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) and the Instituto Nacional de Investigación y Promoción Agropecuaria (INIPA) for hosting the workshop and providing support for local expenditures. In addition, thanks are extended to North Carolina State University (NCSU) for organizing the workshop, and to the Centre International de Recherche Agronomique pour le Développement (CIRAD) and the Institut de Recherche pour le Développement en Coopération (ORSTOM), for providing special interest and support.

Twelve invited papers were presented during this workshop. They form the scientific synthesis for the network and provide a vast array of information based on geographic reviews of current soil management (Part 1), technologies and critical issues (Part 2), and suggestions on the process of formation of the network (Part 3). These papers have been scientifically edited by Pedro A. Sanchez, who has provided continuing support throughout the various stages of the workshop, Eric R. Stoner, and E. Pushparajah. The editors, however, did not attempt to reconcile different points of view expressed in various papers.

These proceedings, therefore, meet one of the first demands of the workshop participants: fundamental information on the management of acid tropical soils.

MARC LATHAM
Interim Director, IBSRAM

Opening Remarks

Victor Palma*

First I want to wish you a warm welcome and pleasant stay in Peru during this visit to Lima and Yurimaguas. In addition, let me give our thanks to both the Workshop Advisory Committee and the Workshop Organizing Committee, and especially to those persons and institutions that have made this workshop possible.

The importance of this meeting is quite evident from the following facts:

- Acid tropical soils account for about 1 billion ha of land around the world.
- Of this 1 billion, acid humid tropical ecosystems comprise about 700 million ha, while acid savannas occur on about 300 million ha. Both ecosystems are located primarily in the developing world.

Brazil and Peru, the host countries of the inaugural workshop of the Acid Tropical Soils Management Network, contain highly representative areas of both the humid tropics (Yurimaguas) and the acid savannas (Brasilia). Traditional farming systems on the acid soils of the tropics are mainly based on the slash-and-burn method of shifting cultivation. After a few years of cropping, this land is reverted to a bush fallow, and, over many years, may return to original forest. Population pressure, however, has forced many farmers to intensify cropping on these areas, which exposes many of the soils to chemical and physical degradation.

The most common constraints to agriculture on Oxisols and Ultisols are high soil acidity, associated secondary and micronutrient disorders, and low available phosphorus. In addition, nitrogen and sulfur deficiencies and a high susceptibility to compaction and erosion may occur in varying degrees. Some national research institutions, such as EMBRAPA in the *Cerrado* region and INIPA in the Amazon region, have had considerable success in developing technologies to solve the above-

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mentioned constraints. Moreover, two of the international agricultural research centers (IITA and CIAT) are located and work in agroecological zones in which acid tropical soils occur. The lack of coordination in international efforts to alleviate soil constraints to increase food production in the tropics, however, is evident.

In the case of Peru, there is an enormous need for internally increasing food production. With only about 3 million ha presently used for agricultural production, the agricultural sector is producing food, fiber, and wood for a rapidly growing population that very soon will be reaching 20 million people. Over time, however, the total supply of food in Peru has been decreasing. This situation was observed from 1970 to 1983. In 1984, due to beneficial growing conditions and a full set of sound agricultural practices, internal food production finally increased: food imports were reduced by 40%. In 1985, prospects are also good for considerable agricultural production.

However, these efforts are not sufficient for sustained agriculture. Food production must increase much more than that for a greater and more permanent reduction of agricultural imports, as well as lower consumer prices and thus reduced inflation. This will also result in greater food security, a lower external debt, and a greater loan repayment capacity. In developed countries, consumers spend about 20% of their income on food; in developing countries, however, they spend more than 50%. The 20% figure ought to be a main goal in any developing country, so that 80% of our income could be used for other purposes: clothing, education, health, and savings, for instance.

There are two ways for augmenting agricultural and food production: increasing yields in areas of traditional agriculture, and expanding the agricultural frontier. Because of several economic, political, and strategic reasons, we believe that in the short run in Peru we have to put greater emphasis on increasing yields on traditional agricultural areas. But it is evident that the extremely low land/labor ratio of 1:5 cannot be maintained in the long run. Thus, the agricultural frontier of the country has to grow. However, its growing process cannot follow the old traditional path of those large irrigation projects, which were costly and which intensively used modern inputs.

The conquest of the agricultural frontier has to be made at a very low cost on a per-hectare basis. To achieve this goal, research, knowledge, and management will play a fundamental role in removing constraints to agricultural production in the humid tropics, especially in areas such as:

- Soil fertility evaluation
- Availability of germplasm tolerant to soil stresses
- Management of soil acidity
- Nitrogen fertilizer efficiency
- Phosphorus fertilizer management
- Biological nitrogen fixation
- Land-clearing methods

- Improved farming systems, including:
  - Sustained production in Oxisols and Ultisols
  - Continuous and/or multiple cropping systems
  - Agroforestry
  - Low-input systems
- Probably even more important is the area of technology transfer through:
  - Validation and adaptation of research results
  - Developing fertilizer recommendations
  - Training in information services.

Through the above-mentioned areas of research, knowledge generation, and management conducted, as much as possible, on a network basis throughout the developing world, we are sure that we will be making an economically feasible agriculture in the tropics, while preventing deterioration of the ecosystem.

To achieve this, however, cooperation is *the* fundamental word. From our point of view cooperation is *the* reason and the main objective of the network.

As far as Peru is concerned, you can be sure that any individual research project, research result, or knowledge generated at our low jungle experiment station in Yurimaguas will be fully available to the participating institutions of the network. We really believe that the constraints to international technology transfer are becoming less and less important over time, and, thus, as long as we offer you our knowledge, we also invite you to collaborate with us in those areas of knowledge in which you have already developed a comparative advantage.

I formally declare open this Inaugural Workshop of the Acid Tropical Soils Management Network.

Opening Remarks

Ralph J. McCracken*

On behalf of the International Board for Soil Research and Management (IBSRAM) and its chairman, Professor Fred Bentley, I express appreciation for your presence and participation in this important workshop. We extend special appreciation and thanks to our Brazilian hosts—the leaders and staff of EMBRAPA—and to our hosts in Peru—the leaders and staff of INIPA.

Also, we wish to express public appreciation to the members of the Workshop Organizing Committee for their hard and efficient work in preparing for this week's activities:

Pedro Sanchez, chair
Manuel Arca
Hari Eswaran
Wenceslau Goedert
Douglas Lathwell
Alain J. Perraud
E. Pushparajah
Eric R. Stoner

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North Carolina State University (NCSU)
Soil Management Support Services (SMSS) of the USDA Soil Conservation Service
United States Agency for International Development (USAID).

First, a few words of explanation about IBSRAM—what it is and is not.

It is a truly international board, designated by an international selection committee. The present Board membership has a wide range of geographic representation, experience, and background:

C. Fred Bentley, Canada, Chairman
Marc Latham, France, Interim Director
Roger Fauck, France
Wenceslau J. Goedert, Brazil
Dennis J. Greenland, UK
Ralph J. McCracken, USA
Richard J. Millington, Australia
Achman Osman, Syria
Chris R. Panabokke, Sri Lanka
Samarn Panichapong, Thailand
F.J. Wang'ati, Kenya
Guy Gresford, Australia, Interim Administrator

IBSRAM is not responsible to any one agency or country—only to the developing countries that it is delegated to assist, and to its donors for wise and effective use of their funds.

It is a facilitating body formed for the specific purposes of conducting and coordinating multicountry workshops and soil management networks. These networks are for the purpose of overcoming soil-related constraints to increases in the quantity, quality, and economic efficiency of food and fiber production in developing countries.

IBSRAM is not a political entity or tool. It conducts scientific and technical programs without regard to politics or ideology. It is also not blessed with large amounts of funds or "new money" to present to participating countries.

It is a venture in faith and a reflection of the concerns, dreams, and hopes of a dedicated group of forward-looking, internationally minded soil scientists responsible for its founding.

IBSRAM is a partial counterpart of the international agricultural research centers. But it is not intended that IBSRAM build a large bricks-and-mortar center with rows of neat plots. It will emphasize field research and supporting labora-

tory analyses within the developing countries. IBSRAM is now in office space graciously provided by the Government of Thailand in Bangkok.

The general objectives of IBSRAM are to:

- Identify soil-research priorities;
- Promote national soil research and management programs;
- Promote training activities;
- Develop and implement soil data systems;
- Promote soil and water research;
- Promote development of farm-management-oriented research methods for removing soil constraints;
- Stimulate tropical soil characterization and classification.

IBSRAM is organized as follows:

- Board of Trustees (9 members) and Chairman
- Interim director, Marc Latham, seconded from ORSTOM
- Interim administering agency, ACIAR, Australia
- Funded by contributions from donors, chiefly various developed-country, international organizations.

Our expectations from this workshop are that priorities will be set for the six activity areas identified in the workshop brochure distributed before the conference (pedology-fertility interactions, soil acidity, efficient use of phosphate fertilizers, management of the soil surface, rehabilitation of degraded lands, soil dynamics under different management systems); that existing knowledge about acid tropical soils will be shared; and that the extent of interest of developing countries in participating in the Soil Management Network, implementation of which is to follow this workshop, will be determined.

Much has been learned about soil acidity in the past 25 years, but there is much more still to learn. We have an excellent, almost unparalleled opportunity to work together in a multidisciplinary, multinational program to solve one of the most pressing problems in agricultural science. The opportunity is here through an Acid Tropical Soils Management Network—let us seize it.

Part 1. Regional Reviews

Management of Acid Tropical Soils in Southeast Asia

E. Pushparajah and A.T. Bachik*

Summary

Ultisols and Oxisols account for over 50% of the total land area in Southeast Asia. These soils are acidic, high in iron and aluminum, and low in fertility. Clearing these areas for agriculture may lead to rapid leaching and erosion losses, especially under the intense rainfall that occurs in most locations. This review indicates that phosphorus is a major nutrient limitation. Appropriate use of lime, phosphate, and cultural practices leads to relatively high and sustained crop yields. Tree-crop agriculture is found to be very successful. Management systems not only sustain but also improve soil productivity. The paper also briefly identifies future research needs.

Introduction

Under the hot and humid tropical environment, weathering of soils has been rapid; thus, there occur large areas of Ultisols and Oxisols in the Southeast Asian region. It is estimated that Ultisols cover about 197 million ha and account for more than 50% of the land area in the region (FAO-UNESCO 1979), while Oxisols with about 15 million ha account for 4% (Dent 1980).

With population pressure and the demand for more food, there is greater demand for land. As a result, the newer areas being brought under cultivation are often less fertile and require greater inputs to maintain a sustained yield. Hence, the need for a better understanding to manage these soils cannot be overemphasized.

The inherent poor chemical properties of Ultisols and Oxisols pose problems for agriculture. This paper reviews such problems and considers measures to be implemented for successful agriculture in the Southeast Asian region.

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Table 1. Some physical and chemical properties of selected Oxisols and Ultisols in Malaysia.

Soil order	Soil series	Depth (cm)	Bulk density[1] (Mg m^{-3})	Clay mineralogy[2]	Total porosity[1] (%)	Available moisture[1] (%)	Fe_2O_3 (%)	O.C. (%)	ECEC (cmol kg^{-1})	Base sat. (%)	Al sat. (%)	CEC (NH_4OAc) (cmol kg^{-1})
Oxisols	Segamat[3]	4-33	—	K, Gi, Go	—	—	17.5	1.45	3.83	55	45	5.7
		33-66	0.94		65	86	18.6	0.66	1.70	58	42	4.7
		66-115	1.01		62	122	16.8	0.41	0.96	59	41	4.1
	Malacca[3]	0-10	—	K, Gi, Go	—	—	13.7	1.01	1.97	13	87	3.8
		10-110	—		—	—	18.4	0.53	2.12	14	86	3.0
	Prang[4]	0-8	1.00	K, Gi, Go	62	81	4.6	2.02	2.78	42	58	13.5
		8-38	1.03		61	65	5.6	0.86	2.23	56	24	8.7
		38-69	0.97		63	73	5.2	0.50	1.76	76	26	8.4
	Jerangau[3]	0-25	—	K, Gi, Go	—	—	11.4	1.80	3.56	69	31	13.8
		25-57	—		—	—	12.1	0.90	1.23	33	67	8.5
		57-89	—		—	—	12.2	0.48	0.50	36	64	8.5
	Tai Tak[5]	0-8	0.78	K	66	52	—	2.43	2.41	14	86	8.9
		8-20	0.96		63	67	3.2	1.11	1.85	7	93	5.7
		20-71	1.04		58	64	4.1	0.51	1.38	7	93	4.2
Ultisols	Rengam[5]	0-21	—	K	53	—	2.5	2.12	2.43	55	45	6.7
		21-49	1.07		50	109	2.4	0.79	1.47	17	83	4.4
		49-89	1.17		50	80	2.2	0.70	1.62	16	84	4.2
	Durian[4]	0-12	1.07	K, M, M-V, Q	60	80	1.6	1.06	6.11	6	94	9.2
		12-40	1.15		57	46	1.7	0.43	6.45	4	96	10.2
		40-64	1.19		55	28	1.8	0.48	7.69	3	97	9.2
	Serdang[6]	0-13	—	K, M, F, V	—	—	—	1.17	—	—	—	4.5
		13-30	—		—	—	—	0.43	1.43	8	92	3.3
		30-79	—		—	—	—	0.27	1.65	4	96	2.9

1. Dashes = not determined.
2. F = feldspar; Gi = gibbsite; Go = goethite; K = kaolinite; M = mica; M-V = interlayered mica-vermiculite; Q = quartz; V = vermiculite.
3. Dept. of Agric. Malaya (1978).
4. Zainol (1984). 5. Wong (1981). 6. Yew (1977).

Properties of Ultisols and Oxisols

Some of the physical and chemical characteristics of selected soil series in the orders Ultisols and Oxisols are given in Table 1.

Physical Properties

Due to their iron and aluminum oxide contents, Oxisols are normally well aggregated to the extent that clay fractions may be present as pseudosilts and clayballs (Paramananthan and Eswaran 1984). This causes clayey soils to behave like loams or sands. As a consequence, the soils become porous with excessive drainage and low available moisture content. In some cases, severe drought stress in crops was observed when a dry spell continued for more than 3 weeks (Sudjadi 1984, Tawonmas et al. 1984).

The high iron content sometimes reflects the formation of ironstone and gibbsite concretions or nodules, which may occupy as much as 60% of the volume in one horizon (Paramananthan and Eswaran 1984) and cause a low available moisture-storage capacity (Tawonmas et al. 1984). The presence of such skeletal material also inhibits root penetration, causing poor root establishment and anchorage.

The high clay and iron contents, combined with the low amount of organic matter, render the same Ultisols susceptible to compaction and erosion (Uexkull 1984). Crust formation after tillage and sheet erosion commonly occur within a short period after such soils are left exposed.

Chemical Properties

The fertility of these soils is limited by the properties brought about by the high iron and aluminum contents, low activity clay, and low organic-matter content. These limitations are reflected in the following properties:

- low pH (less than 5.0) and high exchangeable Al;
- low CEC and low base saturation;
- high phosphate-fixing capacity.

Low pH and high exchangeable Al. With intense weathering and leaching, the soils are depleted of many of their exchangeable bases; thus, H^+ and exchangeable Al dominate the exchange sites and the soil solution (Coleman and Thomas 1967). Hence, Ultisols and Oxisols generally have low pH values (less than 5.0) as well as high Al saturation that often exceeds 60% (Paramananthan and Eswaran 1984, Sudjadi 1984); both result in tremendous problems for crop production, especially for annuals (Tawonmas et al. 1983, Sudjadi 1984). The low pH of the soils also mobilizes some elements (such as Mn, Ni, Cr, and Co) to an amount that may cause toxicity to the plants (Bachik et al. 1985, Paramananthan and Eswaran 1984).

One of the main reasons for applying lime is to decrease the content of exchangeable Al. This is normally accomplished by raising the pH value to 5.5 or 6.0 instead of to a pH near 7.0. Besides being uneconomical, the amount of lime required to raise the reaction to pH 7.0 will also cause several nutrient imbalances in the soils that will affect the crops (Sanchez 1976).

Low CEC and low exchangeable bases. Since most Oxisols and Ultisols of Southeast Asia are dominated by low-activity kaolinite clay and have low organic-matter content, the CEC is normally less than 10 cmol kg^{-1} soil. In addition, due to severe leaching and high Al saturation, the base saturation hardly reaches 5%. Therefore, the inherent fertility of the soils is low. This is further complicated by the zero or positive net charge of some subsoils brought about by the variable-charge Fe and Al oxide/hydroxide colloids and also the broken edges of kaolinite (Uehara and Gillman 1981, Tessens and Zauyah 1982, Shamshuddin et al. 1984), which results in high losses of applied nutrients by leaching.

Low organic-matter content. Under the intense hot and humid tropical conditions, both Ultisols and Oxisols have low organic-matter content. This is worsened by clearing the land from its native forest vegetation for conversion into agricultural purposes. Several factors are affected when natural forests are cleared. A drastic decrease in the organic-matter content is one of the most significant changes that can be detected. Lost with the organic matter are its beneficial effects, such as good physical soil structure, cation-exchange sites, water-holding capacity, and some plant nutrients, such as N, S, and P.

High phosphate-fixing capacity. The high phosphate-fixing capacity of clayey soils rich in Fe and Al is well documented. It is generally accepted that the oxides of iron and aluminum are able to sorb phosphate in great amounts. The amorphous forms of these oxides are most active in this respect (Harter 1969, Syers et al. 1971, Biermans and Baert 1977, Bachik and Baert 1981b, Norrish 1981). Applied phosphates are converted from the soluble into the unavailable forms probably through mechanisms such as (1) rearragements of the sorbed phosphate ions on the Fe- and Al-hydroxy surfaces, transforming them from being physically sorbed to chemically sorbed (Perrot et al. 1974, Ryden et al. 1977); (2) formation of multidentate bonding of phosphate (Hingston et al. 1974); or (3) multilayering of phosphated surfaces by Al- and Fe-hydroxides (Bachik and Baert 1981a).

Due to this high P-fixing capacity, coupled with the inherent low native P status of these soils, phosphate availability is one of the major problems in the management of Ultisols and Oxisols. Most of these soils responded to phosphate fertilizer for crops such as rubber (Pushparajah et al. 1976, Pushparajah 1977, Mahmud 1978), oil palm (Corley and Mok 1972, Chan 1981), cocoa (Wessel 1970, Wyrley-Birch 1972, Mainstone et al. 1977, Siregar et al. 1980, Ling and Mainstone 1981), maize (Tawonmas et al. 1984, Sudjadi 1984), cassava (Chan et al. 1981), and some pasture species (Wan Mohammad and Kamaruddin 1977, Kerridge 1978).

Effect of Clearing

Erosion

Even with some conservation measures, the A- layer of the soil is often eroded away within 2 years after jungle clearing (Soepadmo 1979) due to the intense rainfall and reduction of rain-interception capacity by clearing. Even cultivated tree crops show a 15–20% reduction in rain-interception capacity. Such reduction results in an increase in runoff by 10 to 15%, which leads to increased soil erosion from about 30 to 100 kg ha^{-1} per year to over 2800 kg ha^{-1} per year. The total sediment load in the streams increases from 6 to 1350 m^3 km^{-2} per year. Such erosion leads to further reduction in the already poor inherent fertility status.

Table 2. Major nutrients[1] in bulk samples from the upper 2 cm of Xanthic Ferralsols in a 20-year upland rice/bush fallow cycle in Sarawak, Malaysia. (After Andriesse 1980.)

	Nutrient					
Period	C (%)	N (%)	Ca (mg kg^{-1})	Mg (mg kg^{-1})	K (mg kg^{-1})	P (mg kg^{-1})
After felling*	1.81	0.13	133	90	63	3.7
After burning*	2.38	0.24	1104	579	721	139
After harvest*	1.16	0.10	307	75	46	7.5
Year of fallow						
1	1.95	0.16	563	96	91	3.2
2*	2.40	0.22	550	112	78	5.4
3	2.37	0.22	438	145	109	3.1
4	2.21	0.21	440	114	84	2.6
5	2.49	0.24	276	114	115	3.3
6	2.95	0.26	534	132	119	2.7
7	2.41	0.25	553	157	131	3.1
8	2.34	0.20	383	115	92	2.7
9[2]	2.67	0.23	816	157	116	3.1
10[2]	2.92	0.28	800	187	139	3.3
11*	2.23	0.21	335	85	97	4.1
12	2.48	0.21	313	115	85	2.6
13*	2.15	0.19	300	95	73	3.0
15*[2]	2.41	0.22	555	180	116	4.3
20*[2]	3.12	0.29	402	202	119	4.4
C.V. (%) for within site	2-30	5-40	20-50	10-20	20-50	5-50

1. For all periods, except where indicated by (*), the value is the mean of six subsamples: i.e., two sites × three positions (upper, mid, and lower slopes). For periods indicated by (*), sampling was only from one site: i.e., three subsamples. For years 13, 15, and 20, the area was on slopes 12-20°, whereas for the other years, it was 8-10°. Each cropping for 8 months is rice followed by cassava.
2. Sites for years 9, 10, 15, and 20 had only undergone one cropping period. All other sites had undergone two to three cycles of cropping/fallow.

Clearing and Burning

On felling and burning, there is an increase in the nutrients in the surface soil, but this drops to relatively low levels within 8 months (Table 2). Allowing the land to fallow for a period of 20 years did not enhance the fertility (Andriesse 1980), although such fallows can possibly enhance the organic-matter buildup, as suggested in Table 2. More importantly, the bush-fallow cycle allows the remaining nutrients in the soil to be accumulated in the growing vegetation and to be recycled in the next cropping period.

Even when a primary or virgin forest is cleared for agriculture, there is a rapid loss of carbon and nitrogen. Such changes as observed in Malaysia are given in Table 3. The dramatic reduction in organic carbon observed after land clearing was seen to persist even after 7 years of cultivation (Uexkull 1984): the depletion of organic carbon was evident even to a depth of more than 50 cm (Fig. 1). In Ultisols and Oxisols, CEC is more related to carbon content; hence, with a depletion of the percentage of carbon, there is also a rapid decline in CEC (see Fig. 1). Such changes would lead to reduction in crop productivity, so the need to maintain the organic-matter content is critical. These factors must be taken into consideration when cultivating soils.

Arable Cropping

Liming

Aluminum in the soil is one of the main factors limiting production of grain and legume cereals in the tropics. Based on experience in Malaysia, it was estimated that Al saturation must be below 65% for reasonable growth of groundnut, 45% for soybean, 25% for maize, and 15% for mungbean (Foster et al. 1980).

In Indonesia, on a soil with 71% Al saturation, application of lime at 2 t ha^{-1} (1.5 cmol kg^{-1} exchangeable Al) increased yield of soybean from 200 to 700 kg ha^{-1} (Sudjadi 1984). In the same trial, application of 48.5 kg P ha^{-1} in the absence of lime increased yields to 1500 kg ha^{-1}. The increase of 1300 kg P ha^{-1} over the control plot was more than double that obtained by liming. Application of lime

Table 3. Effect of clearing of virgin forest soil, Malaysia. (After Ling et al. 1979.)

	At soil depth (cm):					
	0-10		10-20		20-30	
Fertility parameter	Under forest	3 mo. after clearing	Under forest	3 mo. after clearing	Under forest	3 mo. after clearing
pH (H_2O)	4.0	6.0	3.9	5.6	4.0	5.5
C (%)	2.5	1.2	2.3	1.0	1.6	0.5
N (%)	0.35	0.30	0.21	0.17	0.17	0.14
CEC (cmol kg^{-1})	14.0	8.9	11.3	7.6	10.5	5.4

and P gave a yield of about 1800 kg ha^{-1}. In the residual cropping with maize, a yield of only about 60 kg ha^{-1} was obtained in the control, while the residual lime gave a yield of about 320 kg ha^{-1}. With residual P alone (48.5 kg P), the yield was over 700 kg ha^{-1}, while both residual P and lime gave a yield of 950 kg ha^{-1}.

This poses the question of the possible role of P in reducing Al saturation; it also suggests that in some Ultisols, low P may be a greater limitation than excess Al. In such areas, economic considerations may dictate that when money is limited only P be applied.

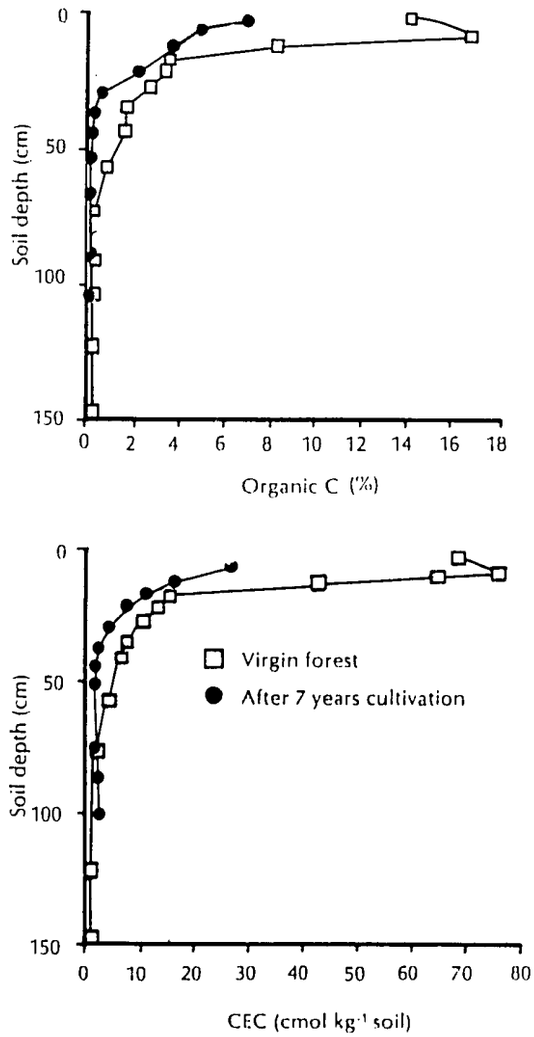

Fig. 1. Changes in organic carbon and cation-exchange capacity after land clearing and cultivation. (Uexkull 1984.)

Organic Matter

In Thailand, in addition to lime, the use of composts alleviated the problem of high Al and Mn on a Paleustult (Table 4). The use of lime and/or compost over time increased both pH and Ca and reduced levels of Al and Fe in the soil. In six croppings (from 1977 to 1982), the yield from plots where compost was applied was about 2.6 times that of the control and was also about 34% more than where liming was the only treatment. There was no difference in yields between compost applications alone and compost plus lime applications. The benefit of the compost need not have been due to the influence on pH, Al, and Fe alone, as will be noted later. Furthermore, the need for such large quantities of compost (50 t ha^{-1}) could be a deterrent. However, this dramatically demonstrates the useful role of organic-matter additions.

Phosphate

A review of the management of P deficiency on Ultisols in Indonesia indicated two strategies used in P fertilization (Sudjadi 1984). One is to use a high enough rate to saturate the P-fixation capacity, while the second is to apply moderate rates but applied in rows. Trial data showed a continuing rise in yield with increasing P levels from 30 to 240 kg ha^{-1} (Sudjadi 1984). In the first crop with maize, yields ranging from 5 to 6 t ha^{-1} were obtained when sufficient P was applied. The control yield was 2 t ha^{-1}. The second cropping gave yields of 3 to 4 t ha^{-1} with residual P and 1 t ha^{-1} in the control. The results show that rates of 30 kg ha^{-1} banded could be an optimal rate. On the same soil, application of 5 to 30 kg P ha^{-1} increased yields of upland rice by 70 to 145%, respectively, with a base yield of 1.3 t ha^{-1} in the unfertilized plots (Sudjadi 1984).

Rock phosphate is also a useful source of P even for annual crops (Table 5), although the beneficial effect of rock phosphate is most evident in residual cropping. The use of rock phosphate (often with lower concentrations of P) would be governed by transportation cost.

Cultural Practices

Cultivation of the soil sometimes results in deterioration of soil physical properties, such as aggregation of soil particles, which, in turn, affects soil water-holding capacity (RRIM 1972). Effects of cultivation on soil aggregation are shown for three cropping systems (Table 6).

Minimum tillage may provide a solution to the problem, as illustrated by work on an Oxic Paleustult (Table 7). Zero tillage over a period of four croppings gave a cumulative yield of 16.5 t ha^{-1}, which was about 19% more than that obtained with conventional tillage. The beneficial effect of minimal or zero tillage was more evident in the fourth year, and the differences observed are likely to be larger. Unfortunately, data on soil properties are not available.

The use of organic mulch would help maintain the organic-carbon content, and this, in turn, could beneficially influence the soil physical properties. At the same

Table 4. Effects of liming and compost (50 t ha^{-1}) applications on changes in topsoil properties and soybean yields in a kaolinitic Paleustult of Thailand. (After Tawonmas et al. 1984.)

Fertility parameter	Treatments							
	Control		Lime		Compost[1]		Lime + Compost	
	1977	1981	1977	1981	1977	1981	1977	1981
pH (H_2O)	4.5	4.3	4.5	4.9	4.5	4.7	4.5	5.1
P (mg kg^{-1})	22	16	23	9	21	21	23	16
Ca (mg kg^{-1})	88	140	96	460	68	310	84	890
Mg (mg kg^{-1})	16	26	17	30	14	42	15	45
Al (mg kg^{-1})	284	248	295	168	303	216	264	104
Mn (mg kg^{-1})	24	125	21	10	22	9	22	10
	Yield (t ha^{-1})*							
1977	0.32 c		0.85 c		1.75 a		1.60 a	
1978	0.65 c		0.87 b		1.20 a		1.25 a	
1979	0.07 c		0.46 b		0.52 ab		0.65 a	
1980	0.90 c		1.42 b		1.70 ab		1.85 a	
1981	0.30 b		0.85 a		1.00 a		1.05 a	
1982	0.55 b		1.10 a		1.27 a		1.35 a	
Total (5 yrs)	2.79		5.55		7.44		7.75	

*Yields followed by different letters are significantly different.
1. 50 tons of compost.

Table 5. Effect of sources of P on yields of rice and maize on an Ultisol in Indonesia. (After Sudjadi 1984.)

P (140 kg P ha^{-1}) applied as:	Grain yield (t ha^{-1})					
	No. 1 Rice	No. 2 Maize	No. 3 Rice	No. 4 Maize	Total rice crop	Total maize crop
Triple superphosphate	2.56	4.27	1.94	1.22	4.50	5.49
Florida rock phosphate	2.57	3.50	2.12	1.69	4.69	5.19
Christown rock phosphate	2.17	3.79	2.66	1.21	4.83	5.00
Bone meal	2.04	3.92	2.10	1.51	4.14	5.43
Ciluar rock phosphate	2.12	4.17	2.26	1.36	4.38	5.53
L.S.D. .05	0.45	0.53	0.46	0.43	—[2]	—[2]

1. Applied at 140 kg P ha^{-1}.
2. Not determined.

Table 6. Effect of cultivation on aggregation of surface (0-15 cm) on a Typic Paleudult in Malaysia. (After RRIM 1972.)

Crop sequence	Aggregation (%)	Mean weight diameter (mm)
Peanut-maize-peanut relay	67	1.08
Cassava	74	1.16
Creeping legume	76	1.50

Table 7. Effect of tillage on yield of maize (Suwan 1) on an Oxic Paleustult.[1] (After Tawonmas et al. 1984.)

	Yield (t ha^{-1})				
Method of tillage	1979[2]	1980	1981	1982	Total
Conventional	3.0	4.3	3.9	2.7	13.9
Fine tillage	2.6	4.5	4.9	2.8	14.8
No tillage	3.1	5.2	4.2	4.0	16.5

1. Nutrients applied: N at 95 kg ha^{-1} y^{-1} and P as rock phosphate at 164 kg P_2O_5 in 1979 and 1981.
2. In 1979 there was considerable weed stubble mulch.

Table 8. Effect of mulching on yield of cowpea on a Paleudult in Serdang, Malaysia.[1]

	Grain yield (t ha^{-1})		
Crop no.	Control	Mulched[2]	Increase (%)
1	0.69	1.31	90
2	0.70	1.17	67

1. Fertilizer applied = 60 kg P_2O_5 ha^{-1}.
2. 3 t ha^{-1} of cut *Imperata cylindrica.*

time, organic mulching would conserve soil moisture (Lim and Maesschalck 1980). The use of 3 t ha^{-1} of cut lalang (*Imperata cylindrica*), a weed, helped conserve soil water and resulted in higher water content throughout the growing season (Fig. 2). In addition, surface soils in the mulched treatments had maximum temperatures of 31°C, while temperatures in nonmulched soil were as high as 39°C.

The yield of cowpea was about 67 to 90% higher with mulching in an experiment in Malaysia (Table 8). In addition, the favorable environment under mulching allowed better nodulation: 2.6 nodules per plant in the control and 4.8 in mulched.

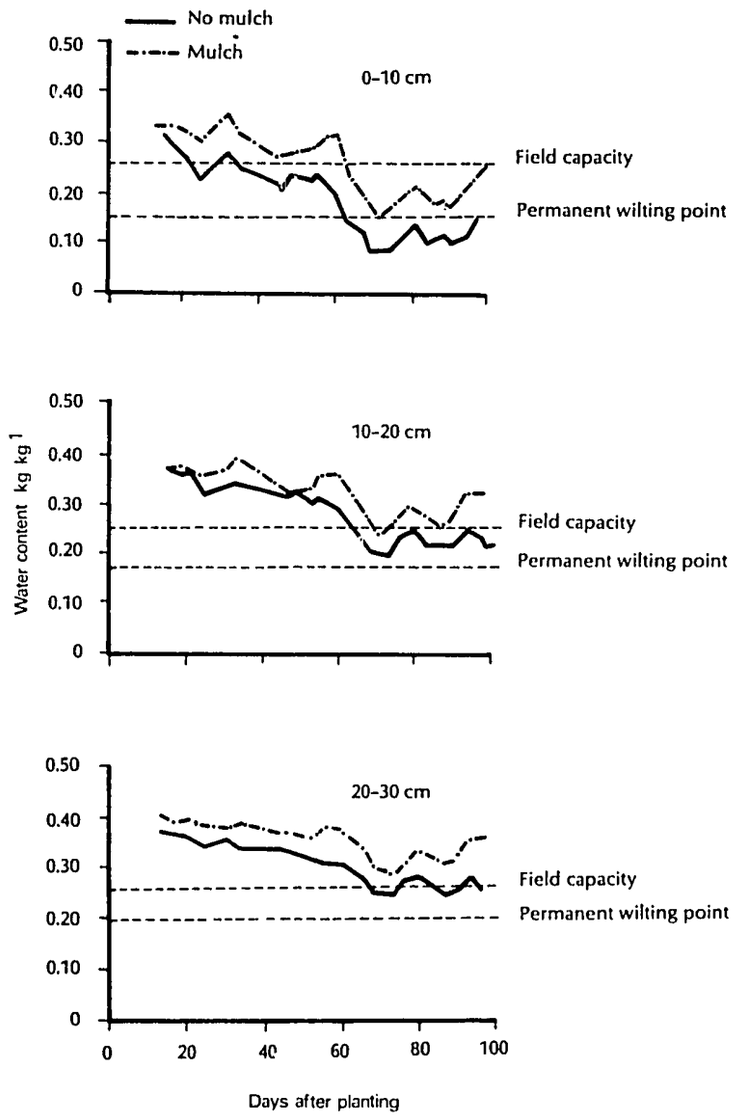

Fig. 2. Soil-water distribution at various soil depths during the second planting period, with and without organic mulching with *Imperata*, on a Paleudult in Malaysia.

Table 9. Effect of cumulative ammonium sulfate applications on pH, carbon, and exchangeable cations in the surface soil of an Oxisol and an Ultisol of Malaysia. (Pushparajah 1975.)

Ammonium sulfate[1] applied (t ha^{-1})	pH (H_2O)	C (%)	Exchangeable cations (cmol kg^{-1})		
			K^+	Mg^{2+}	Ca^{2+}
		Oxisol[2]			
0	4.6	1.66	0.33	0.17	0.56
3.23	4.2	1.75	0.28	0.14	0.49
6.26	4.1	1.81	0.27	0.11	0.30
P (<0.05)	0.07	0.19	0.03	0.03	0.22
		Ultisol[3]			
0	4.8	1.15	0.14	0.24	0.50
1.88	4.4	1.14	0.11	0.10	0.09
3.75	4.2	1.29	0.12	0.08	0.13
P (<0.05)	0.09	0.19	0.03	0.04	0.08

1. The total amount of ammonium sulfate used ranged from 6.25 to 10.8 kg per tree. This was applied on tree rows only, which account for about a third of the land area. Hence, effective rate = three times the rates shown above.
2. Fertilizer applied over a 12-year period.
3. Fertilizer applied over an 8-year period.

There is an apparent lack of data on the long-term effect of cultivation of arable crops on soil properties in Southeast Asia. There is an urgent need to obtain such basic data to enhance a better understanding of the problem and hence improve productivity.

Perennial Tree Crops

Food-bearing tree crops such as coconut and oil palm, and the nonfood tree crop *Hevea brasiliensis* (rubber), also play a predominant role in Southeast Asian agriculture. Generally, these crops are tolerant to acid soils and thrive well in soils with a pH of 4.2 to 5.5. These crops are normally established in rows or in triangular plantings with a tree density of 150 to 600 trees ha^{-1}, the density depending on the crop. During the early stages of development of tree crops, sufficient light reaches the interrow spaces, and these areas are intercropped with food crops or are planted with a semipermanent cover of creeping legumes. Often when these areas are intercropped with food crops, they revert to a cover of grasses or other mixed dicots and monocots. The effect of such initial intercropping on the soils or the fertilizer needs of the intercrops might be similar to that observed for the conventional arable cropping. However, where the interrow vegetation is a permanent creeping "green-manuring type" legume cover or a permanent nonlegume cover, the effect on soil would be different. With fertilizer application to the tree

crops, changes in fertility would be evident. This section therefore examines the impact of management practices on soil both in the "tree rows" and "interrows."

Effect of Fertilizer Practices

The need for N, P, and K fertilizer applications for tree crops has been reviewed by De Geus (1973). Depending on various levels of management, different levels and/or types of inorganic fertilizers are used. Investigations of the long-term effects of fertilizers on the different soils under rubber in Malaysia (Pushparajah et al. 1976) are summarized below.

Nitrogen. The application of N fertilizers, particularly as ammonium sulfate, decreased pH and levels of exchangeable K, Ca, and Mg in Oxisols and Ultisols

Table 10. Effect of rock phosphate on pH, P, and Ca in the surface soil of an Oxisol and an Ultisol of Malaysia. (Based on Pushparajah 1977.)

Fertilizer applied[1] ($t\ ha^{-1}$)	pH (H_2O)	Total P[2] ($mg\ kg^{-1}$)	Available P[3] ($mg\ kg^{-1}$)	Exch. Ca ($cmol\ kg^{-1}$)
			Oxisol [4]	
No P	4.2	465	5	0.16
1.61 RP	4.3	647	49	0.52
3.23 RP	4.4	781	91	0.66
$P < 0.05$	0.1	139	21	0.22
No N or P	4.6	507	6	0.23
3.23 RP	4.6	788	84	0.88
6.26 A/S	4.0	506	5	0.12
3.23 RP + 6.26 AS	4.1	713	111	0.54
$P < 0.05$	0.1	241	37	0.38
			Ultisol [5]	
No P	4.4	121	11	0.13
1.40 RP	4.4	210	38	0.27
2.80 RP	4.5	309	108	0.42
$P < 0.05$	0.1	54	25	0.08
No N or P	4.5	123	6	0.23
2.80 RP	4.9	324	149	0.76
3.75 A/S	4.3	130	6	0.07
2.8 RP + 3.75 A/S	4.3	331	94	0.20
$P < 0.05$	0.2	94	14	0.62

1. The fertilizer was applied on tree rows, which account for about a third of the land area. Hence, effective rate = three times the rates shown above. A/S = ammonium sulfate and RP = rock phosphate.
2. Sulfuric/perchloric extraction.
3. Bray II.
4. Fertilizer applied over a period of 12 years.
5. Fertilizer applied over a period of 8 years.

Table 11. pH phosphate fractions, Ca, and P uptake by *Pueraria phaseoloides* in pots in a Typic Paleudult of Malaysia. (Based on Pushparajah et al. 1977.)

Treatment	Soil depth (cm)	pH (H_2O)	Phosphorus (mg kg^{-1} soil)						Calcium (cmol kg^{-1})	
			Al-P	Fe-P	Ca-P	Soluble p[1]	Total p[2]	Uptake by plant	Total Ca	Uptake by plant
No P	0-2	4.0	11.2	21.5	2.8	11.0	150	2.4	96	8.0
	2-8	4.2	7.6	21.8	2.8	11.0	150	1.7	26	5.0
	8-15	4.4	3.6	12.4	1.4	6.0	128	2.0	36	6.8
	15-30	4.5	2.8	9.3	1.4	5.0	117	1.7	14	0.6
	30-45	4.6	2.0	7.9	1.1	4.0	117	1.2	26	4.5
	45-60	4.6	1.4	7.3	1.2	5.0	122	1.2	14	4.5
Double super phosphate[3]	0-2	4.5	248.2	105.2	65.9	307.0	689	60.8	122	68.6
	2-8	4.6	244.9	115.2	62.6	307.0	606	42.5	60	28.9
	8-15	4.4	183.8	75.0	31.6	149.1	350	30.6	34	38.3
	15-30	4.4	107.6	27.8	35.9	16.0	183	14.1	18	19.7
	30-45	4.6	3.5	12.7	2.9	6.0	139	2.7	15	9.0
	45-60	4.6	3.5	12.0	2.8	6.0	133	2.3	14	9.0
Christmas Island rock phosphate[4]	0-2	4.8	103.4	227.2	357.5	158.0	939	66.8	1416	147.5
	2-8	4.6	52.8	151.0	99.2	132.0	528	46.3	404	88.8
	8-15	4.6	16.0	57.0	14.2	33.0	267	30.4	134	47.0
	15-30	4.6	5.4	20.8	3.5	10.0	162	13.9	106	14.5
	30-45	4.6	5.4	16.0	2.5	8.0	161	3.2	57	10.7
	45-60	4.6	2.5	16.6	1.8	7.0	144	2.8	40	9.9

1. By Bray II method.
2. $HClO_4/H_2SO_4$ digestion.
3. Double superphosphate = 1785 kg ha^{-1} applied.
4. Christmas Island rock phosphate (36% P_2O_5 + 40% CaO) = 1925 kg ha^{-1} applied.

under rubber in Malaysia (Table 9). There was also an indication that application of N fertilizers led to increased topsoil organic-matter content. This could be due to the fertilizer promoting higher vigor of the rubber trees and hence higher leaf-litter inputs into the soil.

Phosphorus. Applications of P for 8 to 10 years led to buildup of P at depths up to 45 cm in the same soil. In addition, the use of rock phosphate resulted in a slight increase in pH and a buildup in levels of Ca (Table 10). The concurrent use of rock phosphate and ammonium sulfate reduced the adverse effect of the latter on soil pH and Ca.

Although most of the P applied as rock phosphate was in the sand fraction (63%), with time the residual P (ammonium fluoride extractable; Bray II) was in the silt and clay fraction (80 to 90% of residual P) (Pushparajah et al. 1977). Over 30% of the residual P was recovered by cropping with a creeping legume, *Pueraria phaseoloides*.

Later, in work with a Typic Paleudult, the P fractions in the soil were evaluated to assess the fate of P applied as rock phosphate and soluble phosphate (Table 11). When superphosphate was used, a large portion was retained in the soil as Al-P, whereas when rock phosphate was used, a large portion was in the Fe-P and Ca-P fractions (Pushparajah et al. 1977). Phosphorus movement down to at least the 30-cm depth was evident. A residual cropping experiment indicated that with rock phosphate, over 35% of the soluble P in the soil (Bray II method) could be taken up, but with superphosphate, the amount of residual P taken up was only 14 to 20% of this fraction.

These findings indicated a strong residual effect of using rock phosphate. An added advantage of the rock phosphate would be the calcium that it supplies. Hence, in considering unit cost of P fertilizer, there may be a need to consider the cost of Ca present in the fertilizer.

Effects of Covers

An early evaluation (Watson et al. 1964) showed that legume interrow covers return considerable amounts of leaf litter during the initial 4 years. More recently, a shade-tolerant legume, *Calopogonium caeruleum*, was introduced as a cover for rubber and was able to survive for periods of up to 8 years. The leaf-litter turnover and N return are given in Table 12.

Various workers (Mainstone 1969, Pushparajah and Chellapah 1969, Pushparajah and Tan 1979) showed the influence of such legume covers on growth and yield of *Hevea*. Others (Grey and Hew 1968, Tan and Ng 1977) showed that legume covers also enhance the yield of oil palm. Work with Ultisols and Oxisols showed that the beneficial effects of legumes on yield of rubber continued to persist for well over 13 years after establishment of rubber and covers (Pushparajah and Tan 1979), while in oil palm the residual effects persisted for up to at least 10 years after establishment (Yeow et al. 1982).

Table 12. Leaf-litter turnover and N returns from a legume cover mixture of *Pueraria phaseoloides* and *Calopogonium caeruleum* on rubber in Malaysia.

Year after establishment[1]	Dry weight of litter (t ha^{-1})[2]	Total N in litter (kg ha^{-1})[2]
0-2	10.5	284
3	9.6	267
4	6.0	163
5	4.5	123
6	2.9	83
7	1.6	46
8	0.4	13
Total	35.5	979

1. Data for years 0-2 from Pushparajah (1981); data for the other years from Tan et al. (1976).
2. *Pueraria* accounted for 30% of the total returns, with most of it being in the first 3 years. The returns from roots are not accounted for.

Table 13. Effect of legume cover on runoff and soil loss after 1 year on a Typic Haplothox of Malaysia. (After Ling et al. 1979.)

		Stage of growth[1]		
Parameter	Cover	30% cover	30-90% cover	90-100% cover
Runoff (mm)	Bare	57	71	64
	Legume	47	19	3
Soil loss (t ha^{-1})	Bare	13.5	30.2	11.2
	Legume	9.0	1.8	0.01

1. Average of 289 mm rainfall.

Table 14. Effect of legume cover on nutrient loss in runoff water on a Typic Haplothox. (After Ling et al. 1979.)

	Nutrient loss (kg ha^{-1} y^{-1})				
Vegetation	N	P	K	Mg	Ca
Forest	1.4	0.1	0.7	1.8	4.7
Legume	11	1	1	13	46
Bare	44	4	129	51	129

Table 15. Residual effects of different cover plants on soil physical properties of surface soil (0-15 cm) of an Ultisol in Malaysia. (After Soong and Yap 1976.)

Cover	C (%)[1]	Aggregation (%)	Mean weight diameter of stable aggregates (mm)	Bulk density (Mg m^{-3})	Permeability (cm h^{-1})
Clean cultivation	1.1	66.2	0.95	1.21	8.4
Grass cover	1.4	73.8	3.39	1.13	13.2
Legume cover	1.4	69.4	1.98	1.13	12.4
Weed cover	1.3	72.4	2.20	1.16	2.0
L.S.D. ($P<0.05$)	—	2.0	0.18	0.05	3.1

1. Dash indicates data not determined.

Hevea trees grown in association with grass covers required 1000 kg N ha^{-1} more than those grown in association with legumes (Pushparajah and Tan 1979), but only 800 kg more N was required for oil palm (Yeow et al. 1982). Such beneficial effects of covers cannot be due to the returns of N alone.

Effect on soil loss. Although legume covers reduce runoff and hence soil loss (Table 13), soil losses in 1 year after clearing and planting with tree crops on a Typic Haplorthox was 55 t ha^{-1} when the ground was bare and 11 t ha^{-1} when a legume cover was established (Ling et al. 1979). Nutrient losses in runoff water were also reduced by legume covers (Table 14).

Effect on soil physical properties. An assessment was made of the residual effect of different covers at 14 to 15 years after establishment of covers and rubber (Table 15). Clean cultivation led to deterioration of soil by reducing the percentage of aggregation of the finer soil particles, decreasing aggregate size, and increasing bulk density. In the absence of covers, even with the leaf-litter turnover (estimated at about 2 to 3 t ha^{-1} y^{-1} from the rubber), crust formation on soil surfaces was evident (Soong and Yap 1976). Thus there was also a reduction in infiltration.

A summary of the effects of covers in six trials on Ultisols and Oxisols showed highly significant correlation between organic carbon and some soil properties (Soong and Yap 1976). These were percentage of aggregation, 0.39; mean weight diameter, 0.84; and bulk density, -0.70. This clearly implies that the beneficial effects of covers on physical properties was through the large returns of organic residues, which in turn increased topsoil organic-carbon contents.

Effect on soil water. Even as early as 2 years after establishment of covers, consistently higher water contents were observed in the soil under legume cover (Watson et al. 1964). The lowest water content was under clean cultivation (Fig. 3).

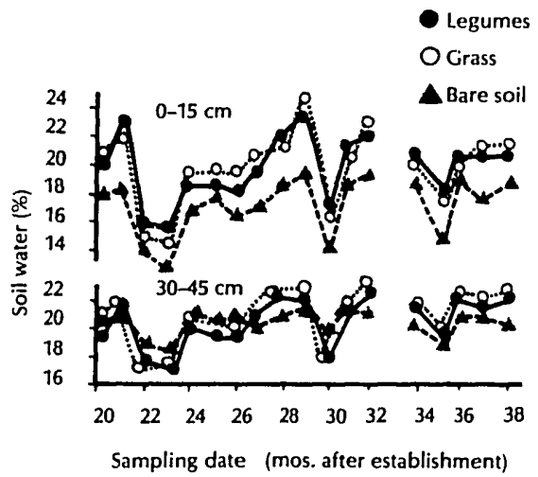

Fig. 3. Effect of covers on soil moisture. (After Watson et al. 1964.)

Effect on nutrient status. The effects of covers on nutrient status of soils over a long-term period are reported in Table 16. By the third year of cover establishment, the legume covers led to an increase in percentage of carbon in relation to the level after burning. By the 16th year, the carbon content had dropped to 1.3%, but this was a higher percentage than that observed under clean cultivation. Similar beneficial long-term effects on percentage of N and on exchangeable Ca, Mg, and K were also evident.

The lower N content in the absence of covers could be due to the rapid mineralization of organic matter (Watson et al. 1964). A detailed investigation from the 20th to 38th month after establishment of covers showed that the level of nitrate under clean cultivation was much higher than that observed under any of the covers. This was evident not only in the 0 to 15-cm depth, but also in the 30 to 45-cm depth. Conversely, ammonium levels were lower under clean cultivation (Fig. 4).

A sampling at 4 years after establishment clearly demonstrated that the lower level of N observed under clean cultivation was due to the nitrate being leached away to lower depths beyond the rooting zone (Fig. 5). Similarly, differences in exchangeable cations were also evident.

Maximizing beneficial effects of covers and fertilizer. An early study showed that application of rock phosphate to legume covers and thus cycling it to the trees through the litter return was more beneficial to tree growth than applying it directly to the trees (Table 17). Later, it was demonstrated that the application of fertilizers to covers enhanced N return from the covers (Table 18); similar beneficial effects were obtained when K and Mg were applied to the covers. This implies that cycling P, K, and Mg through the interrow covers is desirable.

Table 16. Changes in soil (0-15 cm depth) on a Typic Paleudult of Malaysia under different covers with time.[1]

Covers[2]	pH (H_2O) at year: 3	6	10	Organic carbon (%) at year: 3	6	10	16	Total nitrogen (%) at year: 3	6	10	16
Control: year 0		4.73				1.39				0.13	
: under forest		4.40				1.86				0.16	
Legume	4.70	4.50	4.63	1.73	1.55	1.39	1.31	0.14	0.14	0.12	0.14
Grass	4.75	4.62	4.65	1.64	1.47	1.44	1.31	0.12	0.12	0.12	0.13
Naturals	4.73	4.62	4.63	1.55	1.35	1.20	1.11	0.13	0.12	0.11	0.13
Clean cultivation	4.28	4.50	4.57	1.36	1.32	1.16	1.01	0.11	0.11	0.09	0.11
Min. 5% sig. diff.	0.23	0.17	0.05	0.25	0.24	0.20	0.23	0.02	0.03	0.02	0.02

	Exch. Ca at year: (cmol kg^{-1}) 3	6	10	Exch. Mg at year: (cmol kg^{-1}) 3	6	10	16	Exch. K at year: (cmol kg^{-1}) 3	6	10	16
Control: year 0		0.24				0.18				0.11	
: under forest		0.44				0.13 (0.65)[3]				0.10 (0.41)[3]	
Legume	0.43	0.12	0.08	0.21	0.09	0.06	0.31	0.17	0.07	0.06	0.18
Grass	0.56	0.20	0.10	0.24	0.10	0.06	0.31	0.12	0.06	0.06	0.18
Naturals	0.62	0.17	0.11	0.30	0.15	0.07	0.34	0.20	0.09	0.05	0.18
Clean cultivation	0.28	0.10	0.07	0.08	0.08	0.04	0.28	0.06	0.05	0.04	0.16
Min. 5% sig. diff.	0.23	0.18	0.04	0.11	0.10	0.01	0.06	0.05	0.04	0.01	0.04

1. The values 3, 6, 10, and 16 refer to the year after inception of the trial. Data for year 3 from Watson et al. (1964); for years 6, 10, and 16 from Pushparajah (1984).
2. Legumes—mainly *Pueraria phaseoloides* and *Centrosema pubescens*; grass—mainly *Ischaemum timorense* and some *Ottochloa nodosa*; naturals—*Tremma, Hornstedtia, Solanum, Macaranga,* etc.
3. 6*N* HCl extractable values.

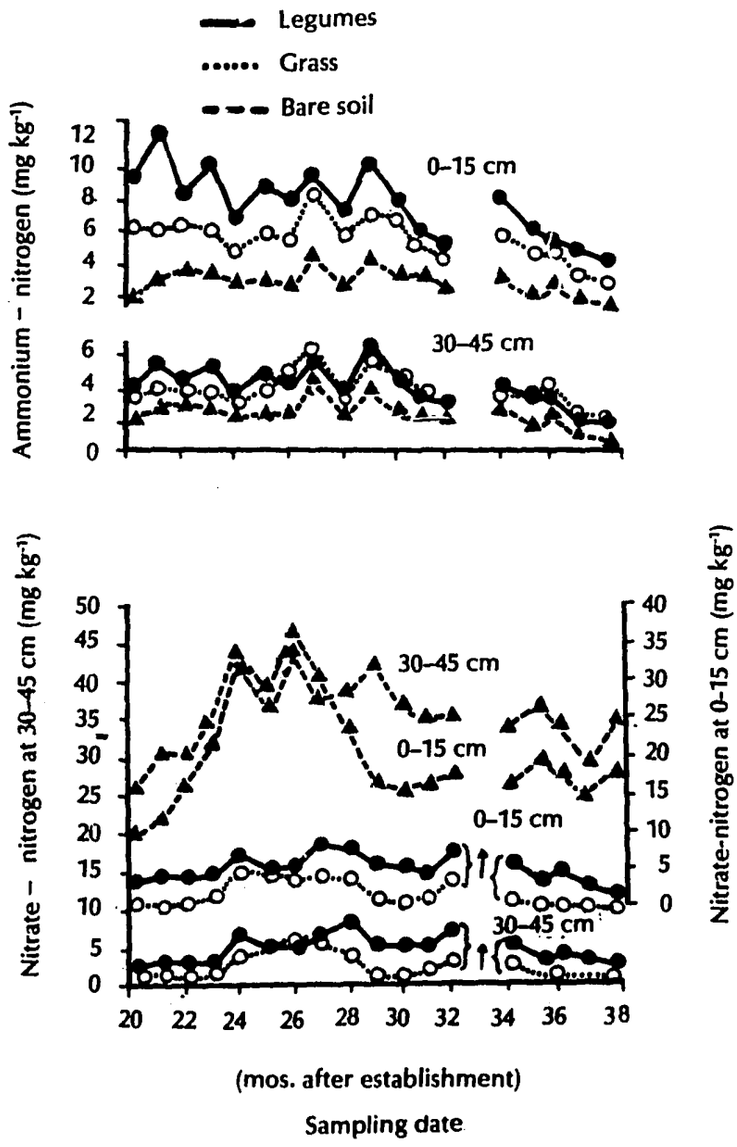

Fig. 4. Effect of covers on ammonia and nitrate nitrogen. (After Watson et al. 1964.)

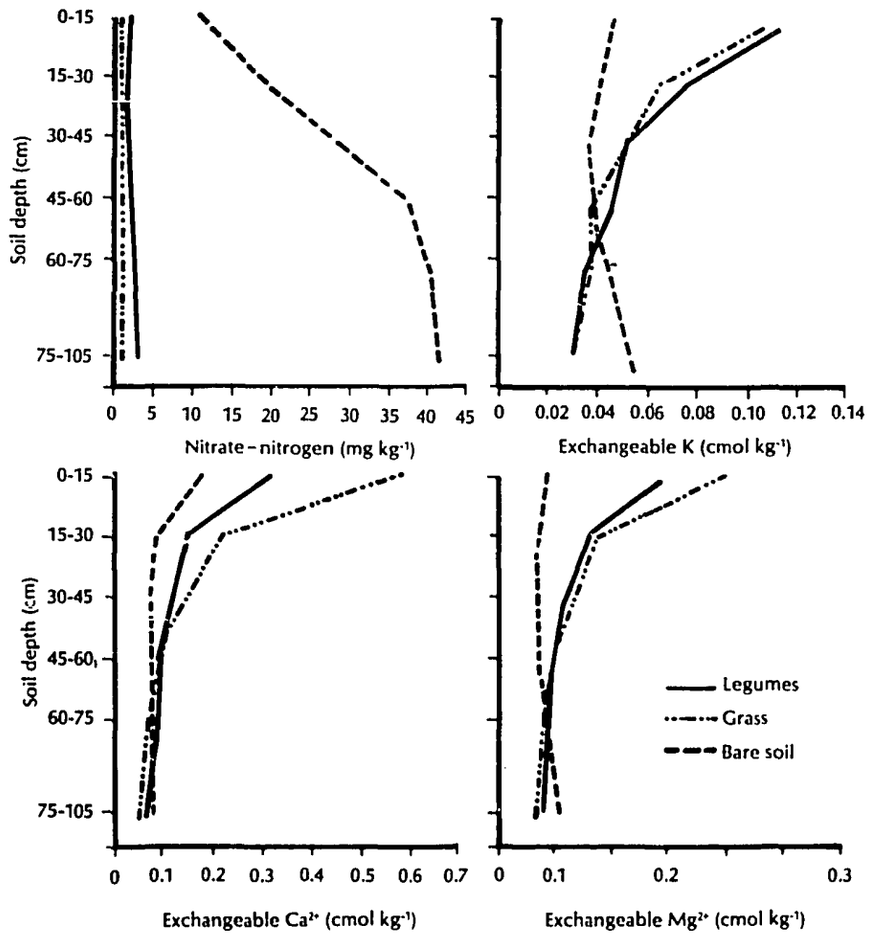

Fig. 5. Effect of covers on NO_3^--N and exchangeable cations in the soil profile at the fourth year. (After Watson et al. 1964.)

Table 17. Effect of application of P to trees or covers on a Paleudult in Malaysia. (After Pushparajah and Chellapah 1969.)

Treatment	Tree girth (cm)	Rubber leaf nutrient content (%)	
		N	P
No P	46.2	3.14	0.18
P to trees only	47.9	3.21	0.22
P to covers only	49.5	3.24	0.23

Table 18. Economic returns from legume covers through use of fertilizers. (After Tajuddin et al. 1980.)

Nutrient	Application rates (kg ha^{-1})	Extra N returned[1] (kg ha^{-1})	Extra economic returns[2] ($1000/ha)
P_2O_5 as rock phosphate	45	117	316
	135	313	520
	225	366	559
P_2O_5 as superphosphate	45	145	229
	135	345	511
	225	356	420
K_2O	75	133	219
	150	170	248
	225	176	218
MgO	50	90	108
	100	117	92
	150	129	47

1. No P returned 280 kg N; no K returned 216 kg N; and no Mg returned 252 kg N.
2. Returns = Gross value of N as ammonium sulfate minus cost of fertilizers used.

Fertilizer Practices

In most Asian countries, fertilizer usage has developed in the following stages (Uexkull 1984):

1. Usage limited to a few commercial crops, mainly grown for export; the NPK used is often balanced.
2. Fertilizer use extends to food crops; nitrogen consumption is larger than that of other nutrients; there is a consequent depletion of the limited P and K in soils.

3. With increasing use of N, demand for P increases and need for K develops.
4. N usage reaches economic optimum; P usage levels off, and K demand grows.
5. Consumption of N and K stagnates and, with time, P rates decline.

In this assessment, the Philippines and Thailand are at a point between stages 1 and 2, and Indonesia is at the end of stage 2. It is evident that in these countries, large responses to P and K can be expected.

Prospects for Improving Productivity on Ultisols and Oxisols

The available data, although limited, suggest that there are practices, which, if implemented, can lead to improved productivity on the Ultisols and Oxisols in Southeast Asia. The lack of adoption of these practices is probably due to the fact that these data are from limited sites and crops. Further, a considerable amount of the published work on arable cropping appears to be piecemeal and based on the interest of individual researchers. Until recently, there was no apparent effort to consolidate research findings to provide a comprehensive picture, linking the findings in soil chemistry, physics, plant nutrition, fertilizer and cultural practices, and crop adaptation. On the other hand, research on soil management for perennial crops seems to have followed a more systematic approach. Even in this, the research findings are limited to only a few sites. These practices have been implemented in the more progressive farms and, in fact, high yields of both rubber and oil palm are being obtained and sustained on Ultisols and Oxisols. The experience with tree crops and the limited experimental findings on arable crops indicate the potential of Ultisols and Oxisols with proper management. However, to achieve this objective, a multidisciplinary approach with emphasis on the following is needed:

1. Identifying factors that limit productivity;
2. Management and/or overcoming problems of soil acidity;
3. Efficient use of P fertilizers and, to a limited extent, K and Mg;
4. Management of soil surface and conservation of soil moisture;
5. Evaluation of appropriate cropping systems for different soil conditions.

These studies should be of a long-term nature, and technologies developed should be practical and within the means of the farming community toward which the evolving technology is aimed.

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Management of Acid Tropical Soils in Africa

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Summary

Acid soils cover large areas of Africa and have low productivity due to their low native fertility. Research conducted for many years has proved that such productivity can be markedly increased. However, it is necessary to consider two different cases: the acid soils in the humid tropics and savannas, and the acidified cultivated soils common in western Africa that cover humid, subhumid, and semiarid zones.

Application of initial corrective fertilization—using heavy rates of N, P, K—and lime, drastically increases the productivity of the acid soils from Africa. This productivity can be maintained under continuous cropping through annual fertilizer applications that match crop nutrient requirements. This technology—called "investment fertilization" or "maintenance fertilization"—although agronomically sound, is generally not adapted to African conditions, due to the high risks it induces for the small farmer in terms of erosion and potential nonprofitability.

This paper presents some low-input technologies and indicates the need for more research on evaluation of lime requirements, availability of P fertilizer in high P-fixing soils, crop tolerance to Al in soil solution, and physical properties of the acid soils.

Low fertility sandy soils of western Africa are highly sensitive to acidification, as a consequence of current farming practices that induce nutrient imbalance in the soils. The low levels of fertilization, erosion, leaching, and intense organic-matter mineralization that occur in the semiarid zones are

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the main causes of soil degradation and acidification. Due to the predominant economic situation, recommended cropping and soil management systems must rely upon intensive use of local resources (crop residues, manures, rock phosphates, nitrogen-fixing legumes) and efficient use of mineral fertilizers, but they must also promote deep socioeconomic changes.

Introduction

Since the 1970s, many countries in Africa are facing major shortages of food production. Suffering from many economic and environmental constraints—among them a severe and persistant drought—agricultural production is slowing while the population growth rate is becoming the highest in the world (2.6% per year). Food production per capita is decreasing at the rate of 1% less per year since the 1970s (FAO 1984). A large increase in food production is required to match the consumption needs of these countries, and experts agree that increased yields cannot be achieved by expanding the cultivated area or by increasing crop intensity (the number of harvests per year).

Acid soils in the humid tropical zones of Africa cover several hundred million hectares and most often support a marginal agriculture due to their natural low fertility. The coastal zone of the Benin Gulf, the Adamaoua Plateau of Cameroon, the Congo Basin, the high plateaus of Madagascar, and the highlands dividing the Congo and Nile basins support mainly shifting agriculture, although some areas (such as the Ivory Coast and Cameroon) also support large and intensive agroindustrial farms of perennial crops (oil palm, coffee, rubber, and pineapple, among others). These crops are more tolerant to acid soils than the majority of the staple food crops.

In West Africa, however, acidified Alfisols are more frequent than naturally acid soils (Oxisols and Ultisols). The process of soil acidification is common in the humid zone as well as in the semiarid zone of West Africa where sandy soils with low organic-matter content are dominant. Management of these low-buffered soils differs from that suitable for the acid soils.

Different technologies adapted to acid and acidified soils of Africa have been studied for many years by various research organizations. A review of what has been done for the last 20 years in the Francophone countries is partially presented in this paper, with emphasis on the management of soils under subsistence agriculture. The paper addresses the management of (1) acid soils in the humid tropics, (2) acid soils in the savannas, and (3) acidified soils.

Management of Acid Soils in the Humid Tropics

A Practical Distinction among Acid Soils in the Humid Tropics

These acid soils belong, in the French system of soil classification, to the "unsaturated" and the "partially saturated" groups of Ferralitic soils. In terms of capabilities, however, agronomists conveniently distinquish between two types of soil environments (IRAT 1975):

1. Acid soils located at less than 600 m elevation, receiving more than 2000 mm annual rainfall, whose native vegetation is forest. Although these soils were formed by ancient ferrallitization processes, in the Quaternary Era many of them suffered transformations such as lateral displacement, which have induced redistribution of the pedons and, as a consequence, moderate acidity of the surface layer (pH 5.0 to 5.5). When cultivated, these soils are usually devoted to perennial crops and, to some extent, to staple root crops such as yam, cassava, macabo (*Xanthosoma sagittifolium)*, and sweet potato.
2. Acid soils located in high-altitude zones (from 600 to 2000 m and more), with well-defined dry and wet seasons, moderate temperatures most of the year, and annual rainfall ranging from 1400 to 2600 mm. These soils, often less affected by morphological movements, have been intensively leached for a long time, are very acidic (pH below 5.0), and bear a sparse, savanna-type vegetation.

The first type of acid soil is typical of the forest zone surrounding the Gulf of Benin, from Guinea to the Congo Basin. The second type of acid soil is well represented by the high plateaus of Madagascar, Cameroon, Rwanda, and Burundi, where in most cases agricultural activities are either very extensive or nonexistent due to the extreme low chemical fertility of this environment.

Management of Acid Soils Located in Low Altitudes

Management of acid soils in low altitudes for food crop production has been intensively studied in southern Nigeria and to a lesser extent in the forest environment of the Ivory Coast.

Greenland (1962) and more recently IITA researchers (Okigbo 1985) demonstrated that, under extensive farming systems, the traditional shifting cultivation system has many agronomic and economic advantages. Because of the favorable physical properties (such as porosity and structure) of these soils, intensive management systems after clearing should maintain the upper organic layer of soil as undisturbed as possible by practicing no-tillage and cropping systems designed to allow an efficient recycling of nutrients, such as what occurs in the forest. Alley-cropping, which seems to be spreading around Ibadan, is a soil and crop management system inspired by this principle.

Although zero-tillage is well adapted to recently cleared forest environments, it is not always advisable for all acid soils located in low altitudes, especially if the land has been cleared for a long period or has been used for intensive perennial crop production. In these cases, soils become more acid and/or more depleted of nutrients and physically degraded. It is thus necessary to rehabilitate the land beforehand. Two examples are given below.

The southern parts of Benin and Togo are characterized by coarse surface textured unsaturated Ferrallitic soils (Fauck 1970) that have been cultivated for a long time under a farming system that associates extensive oil palm crops with maize-

Table 1. Effect of different soil surface management practices on maize yield in relation to soil degradation, a *Terre de Barre*,[1] south Togo. (After Nicou 1981.)

Soil			Maize yields (t ha^{-1})		
Type locality	Clay (%)	Carbon (%)	No tillage	Manual hoe cultivation	Conventional plowing
Nondegraded (Davie)	8.1	6.1	2.1	2.3	3.2
Degraded (Glope)	5.0	4.6	0.6	1.3	1.7
Very degraded (Agbomedji)	6.5	3.5	0.6	1.4	2.0

1. *Terre de Barre*=Ferrallitic soil with A horizon impoverished in clay.

Table 2. Behavior of five food crops in relation to the quantity of lime applied after seven successive crops of pineapple on a Ferrallitic soil from Abengourou, Ivory Coast. (After Osseni 1994.)

	Cumulative lime application (7 crops) (t ha^{-1})			
	0	6.6	12.1	23.2
Soil characteristics (0-20 cm)				
pH (H_2O)	4.30	4.85	5.45	6.50
Al saturation (%)	74.4	24.4	0.1	0
Organic C (%)	0.98	0.90	0.85	0.85
Exch. Ca^{2+} (cmol kg^{-1})	0.29	1.17	2.50	5.01
Exch. Mg^{2+} (cmol kg^{-1})	0.12	0.26	0.40	0.46
Crop yields (t ha^{-1})				
Cassava	17.81	17.92	18.96	21.95
Yam	14.68	18.20	20.67	21.85
Sweet potato	4.30	12.58	13.58	13.92
Maize	0.91	2.17	2.18	2.70
Peanut	0.47	1.81	2.09	2.37

cassava, either intercropped or in sequence. It is assumed that these soils, acid at the present time and in a less humid environment, have been progressively depleted since the 16th century as cropping intensity is high (two crops of maize a year possible with a 1200-mm total bimodal rainfall distribution) and nutrient recycling is low. In this situation, it was demonstrated that even if chemical constraints were overcome by use of lime and mineral fertilizer, the physical constraints (low porosity, poor root development) were such that zero-tillage management was inappropriate (Table 1).

Another example is given related to soil acidification in pineapple plantations. In the Ferrallitic soils (pH = 4.3, 20% clay, 1.2% carbon) of the southern Ivory Coast, with an average rainfall of 2000 mm, the pH became very low after seven crop production cycles (Godefroy et al. 1976). However, lime requirements were low as the range of suitable pH for this crop was between 4.5 to 5.0, due to the high sensitivity of pineapple to *Phytophthora nicotianae* as soon as soil pH exceeds 5.0. If farmers want to use that land for staple food crop production, it is generally necessary to apply lime to increase pH and decrease the percentage of aluminum saturation. However, it is also possible to use more tolerant plants, the best ones thought to be cassava and yam. Yields of sweet potato, maize, and peanut were sharply decreased at a pH lower than 4.9 (Table 2).

It is now assumed that the best management for a humid forest environment must be based on no-tillage and mixed cropping with little need for lime. This management system is well documented by Nigerian and IITA researchers. However, in less humid zones or previously cleared forest zones, especially those with more sandy soils, rehabilitation of the degraded fertility must be based upon more conventional tillage (plowing) and more intensive use of lime.

Management of Acid Soils in Savanna Highlands

Acid soils in savanna highlands are the most typical of the unsaturated Ferrallitic group. Table 3 shows the major physical and chemical topsoil characteristics of some of these soils, sampled in Madagascar, Gabon, and Rwanda. They are very acid, with low base status, usually clayey or loamy texture, and low in available P. These oxic soils are understood to have high P fixation (IMPHOS-GERDAT 1980). It is worth noting that organic-matter content is frequently high, perhaps as a consequence of soil acidity (moderate rate of mineralization) and of the cool temperature regime prevailing in these highlands. Management of these acid soils has been intensively studied in the high plateaus of Madagascar, with major emphasis on fertilizer use.

Correction and maintenance fertilization approach. This approach was developed by IRAT (Institut de Recherches Agronomiques Tropicales et des Cultures Vivrières) and IRAM (Institut de Recherches Agronomiques de Madagascar) in the 1960s (Chaminade 1965) and is illustrated by results reported in a colloquium published by IRAT (1968). This approach is better suited to deeply leached old Ferrallitic soils without initial physical constraints.

The correction and maintenance approach aims to overcome the main mineral soil deficiencies, previously determined in pot experiments, using the missing nutrient technique and applying a one-time heavy rate of fertilizer or lime as determined by response-curve field experiments (Table 4). This is called "corrective" fertilization and it is intended to establish optimum fertility levels for high soil productivity. This high productivity is sustained by annual "maintenance" fertilizer applications at rates that match different crop uptake demands. Whereas maintenance fertilization is highly profitable and must be paid by the farmers themselves, corrective fertilization is considered a "national" investment. Its cost therefore is ideally supported by the government, or international aid agencies, and not by the individual farmer.

Very promising experimental results have been collected at the research station level by applying the corrective and maintenance fertilization approach. As a con-

Table 3. Main characteristics of the surface horizon (0-20 cm) of four different desaturated Ferrallitic soils in Africa.

	Madagascar		Gabon	Rwanda
	Ambohimandroso	Ampangabe	Boumango	Gakuta
Particle size (%)				
Clay	37.4	30.5	58.3	24.7
Fine silt	31.6	12.8	3.5	20.5
Coarse silt	9.2	5.3	1.2	9.2
Fine sand	11.2	25.0	9.2	16.3
Coarse sand	10.6	26.4	27.8	29.3
Organic matter				
C, total (% × 1.72)	6.13	2.43	5.49	5.57
N, total (%)	0.26	0.10	0.22	0.33
Phosphorus				
P_2O_5, total (mg kg^{-1})	782	700	—	861
P_2O_5, Olsen (mg kg^{-1})	22	17	22	122
Acidity				
pH, H_2O (1/2.5)	4.45	5.25	4.85	4.5
pH, KCl (1 *N*)	4.05	4.30	4.10	4.0
Exchangeable cations				
Ca (cmol kg^{-1})	0.40	0.10	0.22	0.72
Mg (cmol kg^{-1})	0.10	0.05	0.10	0.17
K (cmol kg^{-1})	0.14	0.06	0.16	0.11
Na (cmol kg^{-1})	0.07	0.01	0.01	0.04
Al (cmol kg^{-1})	2.00	0.60	2.85	1.99
Al saturation (%)	73.8	73.2	85.3	65.7

sequence, it was asserted that any sound policy for increasing soil productivity in tropical agriculture should include this approach (Chaminade 1971).

It should be recognized, however, that the transfer of this technology has not encountered striking success in the tropics during the last 15 years. Economic and human constraints prevailing in Africa have been underestimated and may explain

Table 4. Response of maize to N, P_2O_5, K_2O, and dolomite applications at two sites in Madagascar, 1965/66. (After Velly et al. 1968.)

Nutrient applied (kg ha^{-1})	Maize grain yield (t ha^{-1})	
	Ambohimandroso	Ampangabe
N		
0	3.27	5.78
80	4.98	8.28
120	5.60	9.18
160	6.10	8.12
200	6.56	9.30
300	7.39	8.98
C.V. (%)	6.7	11.6
P_2O_5		
0	1.90	1.34
100	2.80	2.61
200	3.46	3.67
300	3.88	3.85
400	4.66	3.89
1000	6.82	5.38
C.V. (%)	9.6	11.9
K_2O		
0	0.38	1.13
90	2.36	2.90
180	3.36	3.52
270	3.94	3.49
360	4.69	4.76
600	5.90	5.06
C.V. (%)	9.1	8.5
Dolomite		
0	1.08	2.66
550	2.40	3.25
1100	3.52	3.80
1650	4.28	4.01
2200	5.18	4.26
4200	6.04	5.07
C.V. (%)	10.5	8.0

Table 5. Erosion in the Madagascar highlands, Namisana to Ambatobe. (After de Vergnettes et al. 1968.)[1]

	Maize	Groundnut	Grass field
Runoff (1958-1963) (% of rainfall)			
Average	11.5	11.8	0.7
Extreme values	5.5	3.6	0
	17.1	16.0	1.2
Erosion (t $ha^{-1}y^{-1}$)			
Average	19.1	12.5	0.1
Extreme values	1.0	1.4	0.1
	67.8	26.4	0.1

1. Average annual rainfall = 1394 mm.

the limited applicability of this approach. The large amounts of fertilizers and lime required for "corrective" fertilization posed problems of pricing policy, supply, storage, marketing, distribution, and cash flow for the country as a whole and for each farmer as well. Most often, the research recommendations were not implemented. Due to the high level of capital investment, this technology has been applied by some national and private agroindustrial organizations seeking high food production levels and immediate profit, using mechanization, high-yielding varieties, and two crops a year if possible.

Such experiences failed in Cameroon and Madagascar for many reasons, including inadequate rate and timing of application of the "technical package," yields below expectations, the occurrence of devastating soil erosion (Table 5), and compaction by heavy implements.

More recently, new agricultural production projects located in the acid savanna zones of Gabon and Madagascar appear to be more successful in terms of controlling erosion and increasing profitability through product demand for industrial processing of crops such as sugarcane, barley, maize, and soybean.

Alternative approaches. Low-input technologies based upon farmers' experiences and traditional know-how often appear to be more adequate for African conditions, especially for the landlocked countries where any imported input carries a high cost of transportation.

To cope with these conditions, three approaches can be investigated by research and development organizations:

- Selecting specific sites of acid savanna soils with the best conditions for food production;
- Screening species and varieties for tolerance to an acid environment;

- Promoting soil and crop management to improve soil productivity in local areas through a gradual buildup of fertility.

Selecting more fertile sites within acid savanna zones can be a first alternative, particularly when low population densities allow this kind of selection. Raunet (1984) emphasizes the good natural productivity of the lowland alluvial soils (*bas fonds* in French, *várzeas* in Portuguese), which in many cases offer a good potential for crop production, whereas upland surroundings need more investment to reach the same productivity potential. It is thus recommended that soil surveys in the acid savannas pay more attention to mapping lowland units, in spite of their small extensions.

During the last few years, more research efforts have been focused on screening acid-tolerant species and varieties of crops. This subject is well documented in the international literature and will not be discussed in detail.

On the one hand it is necessary to stress that many so-called acid-tolerant cultivars—i.e., tolerant to aluminum toxicity, low phosphorus levels, low calcium levels, etc.—screened by using hydroponic solutions and various greenhouse devices, appear to be not so tolerant when grown in the field. This incorrect screening seems to be related to the fact that nutrient concentration in laboratory solutions is affected by many secondary reactions (Mattigod and Sposito 1979). As shown by Pavan et al. 1982, only ion activity in the soil solution may explain plant behavior.

On the other hand, it is true that good results can be achieved by using acid-tolerant cultivars in these soils. In the case of legumes, it appears that significant yield increases can be achieved by screening not only acid-tolerant cultivers but also acid-tolerant strains of *Rhizobium*. Some data are shown in Table 6 for soybean cultivars grown in Gabon with and without two different inoculant strains. By screening for the best cultivar-strain association, dry-matter yield and N uptake were increased fourfold. However, this kind of result is not common, and it must be emphasized that usually the best yield results are obtained when tolerant varieties are matched with a certain level of soil fertility improvement (which is the case in the Gabon experiment reported in Table 6 where a basal fertilization of 100 kg ha^{-1} DAP plus 100 kg ha^{-1} KCl was applied at planting time).

Transfer of fertility from a large area to a smaller one is still frequent. This is commonly used by farmers who accumulate crop residues or collect cattle dung from specific fields of their farm. In the acid highlands of Madagascar cattle manure is used; in Rwanda weeds are incorporated after planting pea or bean. These and other traditional management practices have proven their efficiency under current socioeconomic conditions and must be taken into consideration.

Better results are obtained, however, by promoting localized and/or gradual buildup of soil fertility. This kind of technology relies upon a better understanding of the specific effect of soil acidity on each crop, the sensitivity of which may differ widely during different crop growth stages.

Usually early growth stages are the more sensitive: pea, for instance, cannot stand high acidity except during the first days after planting (Lie 1969), and upland rice

Table 6. Effect of inoculation on yield of three varieties of soybean cultivated in acid soil, Gabon. (After Wey 1984).

Varieties	Soybean (grain) Dry-matter (t ha^{-1})	Soybean (grain) N (kg ha^{-1})
Without inoculation		
Standard G	0.54	35
IRAT/ISRA 26/72	1.14	72
IRAT/ISRA 44A/73	1.14	71
With inoculation		
Strain G3 (USDA)	1.09	69
Standard G		
IRAT/ISRA 26/72	1.77	113
IRAT/ISRA 44A/73	1.61	101
Strain Fa3 (IRAT)	1.29	84
Standard G		
IRAT/ISRA 26/72	1.98	128
IRAT/ISRA 44A/73	2.02	130

1. Uniform fertilizer application: 100 kg ha^{-1} DAP and 100 kg ha^{-1} KCl.

Table 7. Effect of various types of dolomite applications on soybean production, Madagascar. (After Samson and Fetiarison 1984.)

Lime application: Placement	Lime application: Rate (kg ha^{-1})	Soybean grain yield (t ha^{-1})
Check	0	1.31
Broadcast	1000	1.52
	2000	2.29
Furrow	130	1.69
Seed coating	30	2.35

has the apparent same behavior (Thawornwong and Van Diest 1974). In a recent sand pot experiment with a circulating nutrient solution device in Madagascar, soybean was maintained for 12 weeks after seeding in a solution of pH 6.5, then the same solution then was acidified to pH 4.0 (Samson et al. 1986). Soybeans produced the same dry-matter yield and the same number of nodules as did soybean maintained in a 6.5 pH solution during the entire growth period (Fig. 1). Subsequently, the effect of a small quantity of lime (dolomite) coating each seed of soybean (30 kg ha^{-1}) versus the effect of different rates of broadcast and furrow localized lime applications was tested at field level. Seed coating and a broadcast application with 2 t ha^{-1} of dolomite provided the same yield of soybean (Table 7).

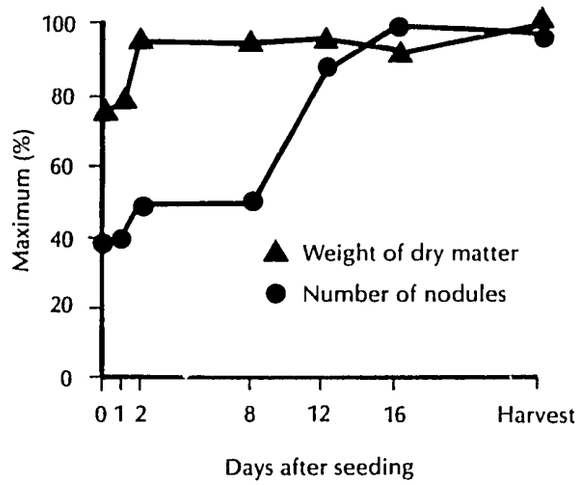


Fig. 1. Influence of pH on dry-matter production and nodule formation on soybean. (From Samson and Fetiarison 1984.)

It is also possible to recommend gradual buildup of soil fertility. This approach was explored by Arrivets et al. (1978) in Madagascar. For P fertilization the experimental data presented in Table 8 confirm that under high plateau conditions, the highest maize production is reached using the "correction plus maintenance" fertilization approach. However, after 4 or 5 years of annual P applications, at a rate slightly higher than crop uptake (45 kg P_2O_5 $ha^{-1}y^{-1}$), 80% of the maximum cumulative yield was attained, when compared with one-time applications of P (180 kg ha^{-1} or 360 kg ha^{-1}). Even with a lower productivity, this progressive fertility build-up approach appears to be better adapted to the local socioeconomic situation.

It must be emphasized that much research has been conducted (Pichot et al. 1978, Truong et al. 1974) to promote the use of rock phosphate ores, which are rather numerous in Africa, lime, and organic materials (crop residues, cattle manure), which are able to increase P availability (Raharinosy 1983). All these studies cannot be cited here; however, one fact is worth mentioning. Acid Ferrallitic soils, as encountered in the high plateaus of Madagascar, have a very high P-fixing capability, according to laboratory measurements (IMPHOS-GERDAT 1980, Fardeau and Jappe 1976). However, more than often, field data indicate that low rates of P fertilizer have direct and residual effects, which may appear in-consistent with the high P-fixing capacity of the soils. In many laboratory determinations, the P-sorption energy evaluation is overlooked, and even if sorption occurs, phosphate ions can remain partially available to the roots of many crops (Truong et al. 1974).

Table 8. Effect of one-time and annual applications of P[1] on maize yields in Madagascar, Ampangabe 1973/74 to 1977/78. (After Arrivets et al. 1978.)

Annual quantity of P_2O_5 (TSP) applied (kg ha^{-1})	Year 1	90	45	180	180	360
	Year 2	0	45	0	45	0
	Year 3	0	45	0	45	0
	Year 4	0	45	0	45	0
	Year 5	—	—	—	45	0
Total quantity P_2O_5 (kg ha^{-1})		90	180	180	360	360
Cumulative yields (t ha^{-1})		7.75	9.25	11.45	16.00	18.40
Average yield (t ha^{-1} y^{-1})		1.94	2.31	2.86	3.20	3.68
Yield ratio (annual/one-time application) (%)			(81%)	(100%)	(87%)	(100%)

1. P_2O_5 applied as rock phosphate (Hyper reno 30% P_2O_5; citric acid solubility: 44%).

Research Needs

Acid soils in the African tropics offer a large potential for increasing food production. Management of these soils may differ according to the corresponding environments. Under forest climate, management must be based on a zero-tillage system and crop associations (as promoted by the alley-cropping system) that do not disturb the surface layer and that maintain, to a certain extent, the natural nutrient cycling prevailing in that environment. There is general agreement on the high agricultural potential of the acid savanna soils, but they suffer from severe mineral deficiencies. These deficiencies can be overcome by using more or less intensive technology according to the local socioeconomics.

The typically poor economic conditions prevailing in Africa induce scientists to promote low-input technology but also emphasize the need for a more specific understanding of the constraints prevailing in the acid soils. Four lines of research could be emphasized in a network of acid soils:

1. To more precisely evaluate lime requirements, it would be valuable to develop a routine procedure of Al, Ca, and Mg measurements in soil solution, and to model the relationships between ion activity and more classical soil analysis (exchangeable cations, percentage of aluminum saturation, etc.). At the field level, it is necessary to increase our knowledge about ion dynamics in cultivated soils in such a way that lime and other nutrient rates required for fertility maintenance under continuous cropping patterns may be better evaluated. To meet this objective, additional research on variable-charge colloids is desirable.

2. Basic research on efficient use of P fertilization in tropical acid soils should be strengthened to arrive at practical recommendations in relation to realistic P-fixing capacity, as well as direct and residual P effects on crops.
3. Crop tolerance to soil acidity and minimum acid soil improvement techniques should be developed by increasing current knowledge about the main critical stages of acid growth in relation to sensitivity for each crop, and on the interactions between soil solution and rhizosphere, including nitrogen fixation by legumes.
4. Soil compaction and erosion, being severe constraints to maintaining the productivity of limed and fertilized acid soils, it appears that the rheology and physical properties of these soils should be better understood to promote more efficient soil surface management. More attention should be placed on the relationships between the forms of aluminum and liming on the one hand and porosity and aggregate stability on the other.

Management of Low Fertility Acidified Soils

Soil acidification is a process closely related to all aspects of crop production. The development of new technology, the use of mineral fertilizer, the introduction of tillage, the increase of cropping intensity, and the reduction of fallow systems increase acidification of the low-buffered sandy soils of western Africa to the point that soil acidity has become an increasingly limiting factor to crop productivity in the semiarid tropics. To cope with this degradation process and to recommend adequate management, it is necessary to briefly review the main causes of soil acidification as they have been identified through the last 20 years by IRAT and IRCT (Cotton Institute) in collaborative work with national West African research organizations from Senegal (ISRA), Mali (IER), Ivory Coast (IDESSA), Burkina Faso (IBRAZ), Niger (INRAN), Cameroon (IRA), Togo, Benin, and Chad.

Main Causes of Soil Acidification in Semiarid Western Africa

The large majority of soils in sub-Saharan western Africa belong to the Ferruginous tropical soils group, according to the French classification system and Alfisols in Soil Taxonomy. These kaolinitic soils are characterized by a surface horizon that is usually coarse textured, poorly buffered, and low in organic matter.

According to a recent review on this subject, soil acidification results as a side effect of widespread nutrient imbalance in West African cultivated soils (Pieri 1983). It has been shown that a correct evaluation of nutrient balance cannot rely upon the comparison of the total mineral uptake by crops on one hand and quantity of mineral and/or organic fertilization on the other.

Nutrient losses by erosion and runoff are commonly underestimated in western Africa. Roose (cited in Pieri 1983) reported annual average loses of 5 to 15 kg N ha^{-1}, 8 kg K ha^{-1}, 28 kg Ca ha^{-1}, and 6 to 15 kg Mg ha^{-1}, by runoff and erosion.

Table 9. Nutrient losses by leaching under the rooting zone of different crops in Ferruginous soils of Senegal, Cameroon, and the Ivory Coast.

Locality (Country)	Year	Rainfall (mm)	Crop	Drainage (mm)	Nutrient losses (kg ha^{-1} y^{-1})				
					N	CaO	MgO	K_2O	P_2O_5
Bambey, Senegal[1]	1981	507	Pearl millett	10	0.3	0.8	0.4	0.3	Tr
			Peanut	101	25.1	54.1	13.6	5.2	Tr
Mauoua, Cameroon[2]	1975	705	Sorghum	2	Tr	0.1	0.1	Tr	Tr
	1977	683	Cotton	83	2.1	43.7	12.3	1.7	Tr
Bouaké, Ivory Coast[3]	1981	633	Maize	210	6.1	36.4	26.2	2.4	Tr
	1981	532	Cotton	260	7.1	18.0	6.6	2.0	Tr

1. Piere (1983).
2. Gigou (1982).
3. Chabalier (1983).

Due to the sandy textures and the highly variable rainfall distribution, leaching is also an important cause of soil impoverishment in this zone. This process is strengthened by the introduction of new crops or varieties, the roots of which are more superficial than the traditional African cereals such as pearl millet and sorghum. Different leaching losses between these traditional crops and peanut, maize, and cotton are shown in Table 9.

These two processes of soil degradation are highly dependent on the soil organic-matter dynamics. In the semiarid western African zone, many authors have shown that soil organic-matter mineralization is very intense during the rainy season (Chabalier 1976, Gigou 1982, Wetselaar and Ganry 1982) under continuous cropping systems and that organic colloids do not sufficiently protect the soil's structure or aggregate stability. Furthermore, the leaching of nitrates induces more intense losses of calcium and magnesium with the drainage flux (Pieri 1979, Chabalier 1984). The effects of nitrate content on calcium are shown in Figure 2.

When fertilization is related to nutrient balance, two additional considerations must be put forward. Due to the high cost of transportation and distribution, the

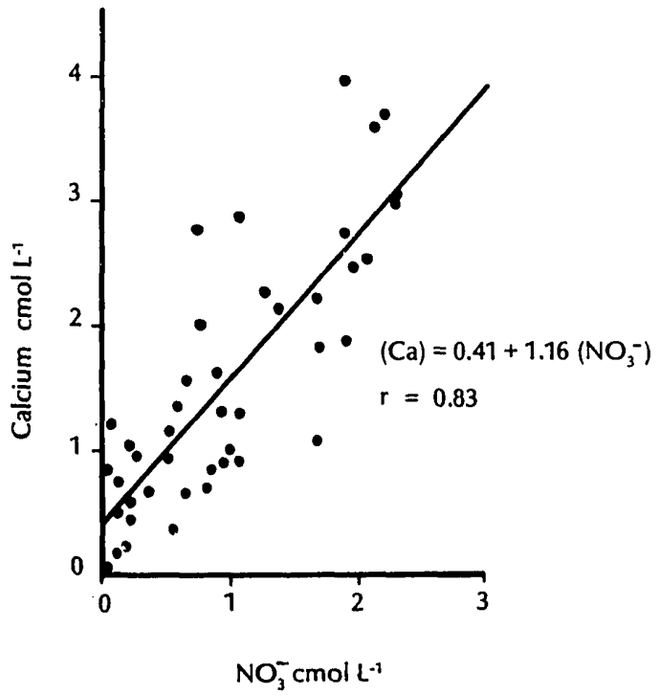


Fig. 2. Relationship between calcium and nitrate concentrations in soil solution (From Pieri 1979.)

most common mineral fertilizers recommended in Africa are diammonium phosphate (DAP), muriate of potash (KCl), and urea. These three concentrated fertilizer sources do not contain calcium, and although they produce initial increases of yields, they often increase leaching, and consequently a negative Ca and Mg balance (Pieri 1979, Chabalier 1984). Manure, when available, is usually a good source of nutrients and also provides an increase of soil buffering ability. However, one must never forget that organic residues and traditional cattle manure have a highly variable nutrient content, which reflects the soil's fertility on which the animals grazed (Table 10).

Thus, soil acidification has become a degradation process spreading over more and more cultivated land in the semiarid zone of Africa. An example of Senegal has been given by Ange (1984). Decreasing pH is only a consequence of a more worrisome soil fertility degradation process that results in a decrease of the soil humus content, effective cation-exchange capacity, and soil pH (Table 11). The latter value, pH, often appears to be a poor indicator of this process of degradation (Siband 1972, Pieri 1983).

Management of Low Fertility Acidified Soils

The suitable technology for dealing with acidified soils is not much different from that suitable for naturally acid soils. Liming is required to decrease aluminum saturation, which is responsible for poor germination of sorghum in Burkina Faso

Table 10. Mineral content of farmyard manure in the cotton zone of Mali. (Pieri 1983.)

Element	Dry-matter content (%)		
	Average	Extreme values	Standard error
N	1.18	0 -2.05	0.64
P_2O_5	0.74	0.31-1.45	0.35
K_2O	1.83	0.31-5.02	1.17
S	0.15	0.05-0.23	0.06
CaO	1.24	0.28-2.73	0.59
MgO	0.69	0.18-1.33	0.36

Table 11. Evolution of soil surface (0-20 cm) characteristics in a Ferruginous tropical sandy soil of central Senegal. (After Pieri 1982.)

Parameter	1973	1977[1]
CEC (cmol kg^{-1})	1.23 ± 0.16	0.92 ± 0.12
Organic C (%)	2.09 ± 0.13	1.59 ± 0.28
Total N (%)	0.18 ± 0.02	0.14 ± 0.02
Soil pH (H_2O)	5.82 ± 0.08	5.34 ± 0.16

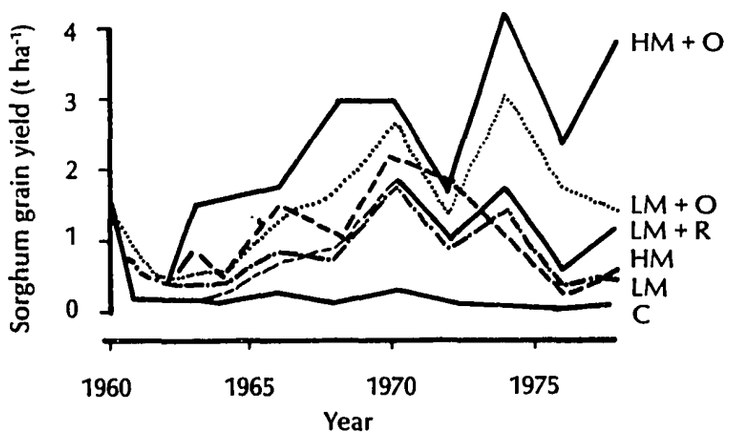
1. After 5 years of millet and peanut cultivation.

(Pichot et al. 1981), growth limitation and decrease of peanut yields in Senegal (Pieri 1974), and poor root development and low sugarcane yields under irrigation in Burkina Faso (Namoro 1983).

All experimental data gathered in that semiarid zone, however, emphasize the key role of organic-matter restitution. Long-term experiments in Burkina Faso (Pichot et al. 1981), in central Ivory Coast (Chabalier, cited in IRAT 1983), and in many other countries confirm that even in the presence of a high level of mineral fertilizers, soil productivity cannot be maintained except with organic matter. The results of the Burkina Faso plots are shown in Figure 3. Indeed, maintaining productivity in sandy Ferruginous soils under continuous cropping results from the combination of plowing and mineral and organic fertilization, as shown in the Thilmakha experiment in Senegal (Table 12).

Final Considerations

In the semiarid zone of Africa, beyond the acidification problem, there is a much more serious problem of maintenance of soil productivity during severe dry spells and under severe economic limitations. Soil management should take into account



Legend:

C	=	control without fertilizer
LM	=	low rate of mineral fertilizer
LM + R	=	low rate of mineral fertilizer + sorghum residue return
LM+ O	=	low rate of mineral fertilizer + 5 t ha^{-1} y_r^{-1} cattle manure
HM	=	high rate of mineral fertilizer
HM+O	=	high rate of mineral fertilizer + 40 t ha^{-1} y_r^{-1} cattle manure

Fig. 3. Effect of mineral and organic fertilizers on sorghum grain yield over time, Saria, Burkina Faso. (From Pichot et al. 1981.)

these constraints, which cannot be overcome simply by combining several inputs. Long-term fallows no longer are an alternative to the maintenance of soil fertility in that region where human and cattle densities have been increasing over the last 20 years.

The crucial requirement of organic-matter return in a region where biomass is limited implies fundamental changes in the traditional relationships between nomadic herders and farmers, as well as in the use of the land for fuelwood produc-

Table 12. Effect of some soil management practices on yields of peanut and pearl millet, Thilmakha, Senegal, 1972-1981. (After Pieri 1985.)

Treatment	Peanut kernel yields (t ha^{-1})	Pearl millet grain yields (t ha^{-1})
Control	0.75	0.30
Plowing only	0.87	0.39
Plowing + manure	1.45	1.11
Lime only	1.08	0.32
Plowing + lime	1.23	0.35
Plowing + manure + lime	1.34	1.08

Table 13. Comparison of different forms of phosphates. (From Truong 1984.)

	Cotton (47 experiments)		Maize (21 experiments)	
Treatment	(t ha^{-1})	(%)	(t ha^{-1})	(%)
TOGO. IRCT-IRAT-DRA experiments in Togo (1983).				
Control NKS	0.78	53	0.44	51
NPKS (rock phosphate[1])	1.13	77	0.74	85
NPKS (partial acidulation 61%)	1.26	86	0.82	93
NPKS (TSP)	1.48	100	0.88	100

	Sorghum	
	(t ha^{-1})	(%)
BURKINA. IRAT-IBRAZ experiments (1983).		
Control NKS	0.85	69
NPKS (rock phosphate[2])	0.93	76
NPKS (partial acidulation 29%)	1.13	92
NPKS (TSP)	1.22	100

1. Togo rock phosphate: total P_2O_5 = 35%, 21% citric acid soluble.
2. Burkina rock phosphate: total P_2O_5 = 30%, 24% citric acid soluble.

tion. These considerations have been reviewed elsewhere (Tourte 1974, Norman et al. 1982).

From the specific point of view of soil chemical fertility maintenance, the local socioeconomic conditions emphasize the need for more research not only on soil acidity as mentioned above, but also on the feasibility of the maintenance of nitrogen and organic-matter balance and other nutrient balance at the farmer's level (Pieri 1985). This can be achieved by:

- Promoting a more efficient recycling of crop residues,
- Increasing the nitrogen-fixation efficiency of legume crops,
- Improving the efficiency of mineral nitrogen fertilizers and local sources of rock phosphates through mixtures with compost or partial acidulation, as shown in Table 13.

Even so, little will be achieved if agricultural policies are not consistently implemented in these countries where, most often, food crop production is limited by the weakness of marketing and credit organizations.

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Management of Acid Soils in the Humid Tropics of Latin America

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Summary

The humid tropics of Latin America are caught between the need to expand agricultural production and the need to preserve an ecosystem of extreme diversity. Soils are acknowledged as a crucial factor for a balanced approach to solving this problem. The Latin American humid tropics have a higher proportion of acid soils than their counterparts in Asia and Africa, with 81% of the land area covered by Oxisols, Ultisols, and Dystropepts. The most widespread soil constraints in the Amazon are phosphorus deficiency (90% of the area), aluminum toxicity (73%), drought stress (53%), and low nutrient reserves (50%). Concerns about laterite formation and low soil organic-matter contents are not supported by published data. Traditional slash-and-burn clearing or bulldozing with a shear blade are the recommended land-clearing methods. Long-term research suggests a series of soil management options for specific soils, landscape positions, and levels of infrastructure development. These options include paddy rice cultivation on alluvial soils; intensive, mechanized crop rotations on acid soils with suitable topography; low-input cropping systems for the same locations if they have poor infrastructure; legume-based pastures; and agroforestry. Without appropriate soil management technology, development of the humid tropics will fail in both economic and ecological terms. With appropriate technology and market infrastructure, development is feasible and may produce a rational balance between cleared areas and rainforests.

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Introduction

The humid tropics encompass those areas of the world with high and nearly constant temperature, a dry season of less than 4 consecutive months, and a tropical rainforest or seasonal, tropical forest as native vegetation. About 45% of the world's humid tropics are located in tropical America (Table 1), and three-fourths of that are in the Amazon Basin. The humid tropics are one of the world's crucial ecosystems: it is here that the need to expand agricultural land to relieve population pressure is in direct conflict with the need to preserve an ecosystem of extreme faunal and floral diversity. Soil constraints are acknowledged as a major limitation

Table 1. Geographical distribution of soils of the humid tropics based on dominant soil in FAO maps at a scale of 1:5 million.

	Total land area (million ha)				
Soil orders and suborders	Humid tropical America[1]	Humid tropical Africa[2]	Humid tropical Asia and Pacific[3]	Total land area of world's humid tropics (million ha)	Percentage of region or country
Oxisols	332	179	14	525	35
Ultisols	213	69	131	413	28
Inceptisols:					
Aquepts	42	55	23	120	8
Andepts	2	1	9	12	1
Tropepts	17	19	58	94	6
Subtotal	61	75	90	226	15
Entisols:					
Fluvents	6	10	34	50	3
Psamments	6	67	17	90	6
Lithic subgroups	19	14	39	72	5
Subtotal	31	91	90	212	14
Alfisols	18	20	15	53	4
Histosols	4	4	23	31	2
Spodosols	10	3	6	19	1
Mollisols	—	—	7	7	<1
Vertisols	1	2	2	5	<1
Aridisols (saline only)	3	1	1	5	<1
Total	673	444	379	1496	100

1. Sanchez and Cochrane (1980) plus recent adjustments.
2. FAO-UNESCO (1975) and Dudal (1980).
3. FAO-UNESCO (1977, 1978). Includes 46 million ha of the humid tropics of Australia and the Pacific Islands.

of the region; thus knowledge of soils and their management is crucial for a balanced approach between the opposing forces.

During the last 2 decades, significant advances have been made in the characterization and management of soils of the Latin American humid tropics. Individual soil survey reports, many of them listed in this paper's bibliography, have been brought together under a common legend, along with comparable data on climate, topography, and vegetation (Cochrane 1984, Cochrane et al. 1985). Research to find sound soil management systems for the rational use of the humid tropics has also advanced in the region.

This paper summarizes some of the available information about the geographical distribution of soils, common misconceptions about them, soil constraints, land-clearing methods, and soil management options for the American humid tropics. Emphasis is given to the Amazon Basin because of its size, the preponderance of acid soils, and the level of research effort already expended in the area.

Soil Geography

The geographical extent of soils of the humid tropics is given in Table 1 using Soil Taxonomy terminology (Soil Survey Staff 1975). The translation of this terminology into the FAO Legend, 1938 USDA, French, and Brazilian soil classification systems is shown in Table 2. Acid soils, classified as Oxisols, Ultisols, and Dystropepts, cover large areas of the humid tropics, but their relative importance is greater in Latin America (81%) than in Africa (56%) or Asia (38%) (Table 3). The inverse occurs with moderately fertile, high base status soils, which cover as much as 33% of humid tropical Asia and 12% of humid tropical Africa but only 7% of humid tropical America (National Research Council 1982). Most of these moderately fertile soils in Asia are already under intensive cultivation; therefore, the potential for area expansion into such soils is limited. This is not the case in humid tropical America and Africa where considerable areas of poorly drained, alluvial soils or well-drained high base status soils occur within vast areas of acid soils. Representative soil profile data of experiment stations or key areas are described in Table 4.

Common Misconceptions

Three common misconceptions about soils in the humid tropics deserve clarification. They relate to laterization, organic-matter content, and proportion of nutrients stored in the plant biomass and the soil under tropical rainforests.

Laterite Formation

It is often stated that tropical soils when cleared of native vegetation will harden irreversibly into laterite. However, the dangers of laterite formation after clearing tropical forests are limited (Buol and Sanchez 1978, Moormann and Van Wambeke 1978). In the Amazon Basin, only 4% of the region has soft plinthite in the sub-

Table 2. Translation of Soil Taxonomy terminology used in the humid tropics into other classification systems.

Soil Taxonomy	FAO Legend	1938 USDA system	French classification	Brazilian classification
Oxisols	Ferralsols	Laterite soils	Sols ferraltiques, fortement désaturés, typiques ou humiferes	Latossolos, Terra Roxa Legítima
Ultisols	Acrisols and Dystric Nitosols	Red and yellow Podzolics Reddish-Brown Laterite Yellowish-Brown Laterite	Sols ferralitiques, lessivés	Podzólico Vermelho-Amarelo distrófico
Inceptisols: Aquepts Andepts Tropepts	*various* Gleysols Andosols Cambisols	*various* Half Bog soils Andosols Brown Forest soils	Sols peu évolués Sols hydromorphes Andosols Sols brunifies tropicaux	Solos com horizonte B Solos hidromórficos Solos com horizonte B, incipiente
Entisols: Fluvents Psamments	*various* Fluvisols Arenosols and Regosols	*various* Alluvial sands (dry)	Sols minéraux bruts Regosols	Regossolos, Areias e Quartzisosas
Lithic subgroups	Lithosols	Lithosols	Sols lithiques	Litossolos
Alfisols	Luvisols, Eutric Nitosols, and Planosols	Grey-Brown Podzolics, Planosols	Sols ferrigineaux tropicaux lessivés	Podzólico Vermelho-Amarelo equivalente eutrófico, Terra Roxa Estruturada, Planossolos
Histosols	Histosols	Bog soils	Sols organiques	Solos orgânicos

Spodosols	Podzols	Podzols	Podsols	Podzcls
Mollisols	Rendzinas, Phaeozems	Rendzinas, Chernozems		Brunizens
Vertisols	Vertisols	Grumusols	Vertisols	Grumusols
Aridisols (saline only)	Solonchaks	Solonchaks	Sols halomorphes	Solonchak

Table 3. General distribution of main kinds of soils in the humid tropics.

	Total land area (%)			
General soil grouping	**Humid tropical America**	**Humid tropical Africa**	**Humid tropical Asia and Pacific**	**World's humid tropics**
Acid, low native-fertility soils (Oxisols, Ultisols, Dystropepts)	81	56	38	63
Moderately fertile, well-drained soils (Alfisols, Vertisols, Mollisols, Andepts, Tropepts, Fluvents)	7	12	34	15
Poorly drained soils (Aquepts)	6	12	6	8
Very infertile sandy soils (Psamments, Spodosols)	2	16	6	7
Shallow soils (lithic Entisols)	3	3	10	5
Organic soils (Histosols)	1	1	6	2
Total	100	100	100	100

Table 4. Some representative profiles of soils of the Latin American humid tropics. (From Sanchez and Silva 1984.)

Horizon (cm)	Clay	Silt	Sand	pH (H_2O)	Org. C (%)	Exchangeable Al	Exchangeable Ca	Exchangeable Mg	Exchangeable K	ECEC	Al sat. (%)	Available mod. P	Available mod. Zn	Available mod. Mn	Available mod. Fe	Available mod. Cu
	(.....%.....)					(.....cmol kg^{-1}.....)						(.....mg kg^{-1}.....)				
1. *Florencia, Colombia. Typic Tropudult, clayey, kaolinitic, isohyperthermic (FCC = cak)*																
0-16	37	16	47	4.8	2.0	3.60	0.95	0.80	0.23	5.58	64	14.5	4.3	290	—	1.7
16-85	52	18	30	4.7	0.5	7.76	0.22	0.43	0.03	8.44	92	2.0	4.3	26	—	1.1
85-173	49	21	30	4.9	0.2	6.50	0.10	0.47	0.08	7.15	91	2.0	4.0	48	—	1.2
173-208	28	31	41	4.9	0.1	7.00	0.10	0.41	0.13	7.64	92	—	—	—	—	—
208-228	20	24	56	4.5	0.1	6.80	0.20	0.56	0.11	7.67	89	—	—	—	—	—
2. *Napo, Ecuador. Orthoxic Tropudult, clayey, kaolinitic, isohyperthermic (FCC = Ca)*																
0-13	51	38	11	4.7	1.0	0.30	2.06	0.50	2.15	5.01	6	1.6	3.1	26	111	4.6
13-25	61	30	9	4.3	0.6	1.97	0.20	0.09	0.64	2.90	68	0.7	3.9	31	82	4.0
25-40	64	27	8	4.0	0.5	2.07	0.20	0.06	0.18	2.51	82	0.0	3.8	26	44	3.1
40-60	71	23	6	4.2	0.2	2.27	0.22	0.17	0.04	2.70	84	0.0	5.4	13	21	2.5
60-120	50	41	9	4.1	0.1	1.80	0.26	0.19	0.13	2.38	76	0.0	3.4	10	17	1.9
3. *Yurimaguas, Peru. Typic Paleudult, fine-loamy, siliceous, isohyperthermic (FCC = Leak)*																
0-10	6	21	73	4.4	1.7	1.29	1.13	0.60	0.28	3.30	39	9.5	1.7	8	934	1.3
10-30	13	21	66	4.4	0.5	3.31	0.29	0.14	0.08	3.82	87	2.5	0.9	2	544	1.0
30-50	16	24	61	4.6	0.4	3.87	0.29	0.22	0.07	4.45	87	4.1	0.8	1	494	1.3
50-70	16	22	62	4.5	0.3	4.26	0.29	0.16	0.07	4.78	89	1.6	1.1	0	309	0.7
70-100	22	21	56	4.4	0.4	4.80	0.29	0.13	0.14	5.36	90	0.0	2.0	0	83	1.5
100-150	23	19	57	4.3	0.1	6.15	0.16	0.05	0.09	6.45	95	0.0	2.3	0	23	0.7

Horizon (cm)	Clay	Silt	Sand	pH (H_2O)	Org. C (%)	Exchangeable Al	Ca	Mg	K	ECEC	Al sat. (%)	Available mod. P	Zn	Mn	Fe	Cu
	(.....	%.....	)			(.....cmol kg^{-1}.....			)			(.....mg kg^{-1}.....				)
4. *Iquitos, Peru. Typic Paleudult, clayey, kaolinitic, isohyperthermic (FCC = LCak)*																
0-16	30	36	34	4.0	2.4	5.9	1.0	0.2	0.20	7.30	81	—	—	—	—	—
16-35	40	30	30	4.5	1.0	6.7	0.4	0.1	0.08	7.28	92	—	—	—	—	—
35-70	54	26	20	4.3	0.5	9.5	0.2	0.1	0.08	9.88	96	—	—	—	—	—
70-100	54	26	20	4.5	0.3	11.6	0.2	0.1	0.06	11.96	97	—	—	—	—	—
100-150	46	34	20	4.5	0.3	10.9	0.2	0.1	0.08	11.28	97	—	—	—	—	—
150-240	28	20	52	4.7	0.2	5.4	0.2	0.1	0.08	5.78	93	—	—	—	—	—
5. *Pucallpa, Peru. Aquic Paleudult, clayey, mixed, isohyperthermic (FCC = LCga)*																
0-3	27	38	35	5.2	3.7	0.2	4.2	2.1	0.52	7.02	3	2	—	—	—	—
3-21	45	38	17	4.3	1.1	4.0	2.2	1.2	0.40	7.80	5	1	—	—	—	—
21-62	59	26	15	4.2	0.6	8.7	0.8	0.9	0.32	10.72	81	1	—	—	—	—
62+	57	22	21	4.1	0.3	11.6	0.4	0.7	0.24	12.94	90	1	—	—	—	—
6. *Tingo María, Peru. Fluventic Eutropept, fine loamy, mixed, isohyperthermic (FCC = Lk)*																
0-17	29	40	31	5.7	1.8	0.44	16.61	1.86	0.14	19.05	2	24	2.1	87	511	3.6
17-40	23	43	34	5.7	0.3	0.06	13.81	1.86	0.14	15.87	0	18	0.6	16	121	1.5
40-60	16	48	36	5.5	0.3	0.33	14.58	1.93	0.12	16.96	2	33	1.0	9	125	1.8
60-78	15	50	35	5.5	0.1	0.45	13.81	1.78	0.14	16.18	3	28	0.7	11	150	1.3
78-100	31	50	19	5.5	0.3	0.75	19.15	2.61	0.12	22.63	3	29	1.5	14	196	2.6
7. *Manaus-AM, Brazil. Typic Acrorthox, clayey, kaolinitic, isohyperthermic (FCC = Ceaik)*																
0-8	76	9	15	4.6	3.0	1.1	1.7	0.3	0.19	3.29	33	2	—	—	—	—
8-22	80	8	12	4.4	0.9	1.1	0.2		0.09	1.39	79	1	—	—	—	—
22-50	84	8	8	4.3	0.7	1.2	0.2		0.07	1.47	82	1	—	—	—	—
50-125	88	5	7	4.6	0.3	1.0	0.1		0.04	1.14	88	1	—	—	—	—
125-265	89	6	5	4.9	0.2	0.2	0.1		0.11	0.31	65	—	—	—	—	—

—Continued

Table 4. Continued.

Horizon (cm)	Clay	Silt	Sand	pH (H_2O)	Org. C (%)	Exchangeable Al	Exchangeable Ca	Exchangeable Mg	Exchangeable K	ECEC	Al sat. (%)	Available mod. P	Available mod. Zn	Available mod. Mn	Available mod. Fe	Available mod. Cu
	(.....%.....)					(.....cmol kg^{-1}.....)						(.....mg kg^{-1}.....)				
3. *Barrolandia-BA, Brazil. Typic Paleudult, fine-loamy, siliceous, isohyperthermic (FCC = Leak)*																
0-10	10	13	77	4.7	1.3	0.7	0.8	1.3	0.07	2.87	24	—	—	—	—	—
10-23	16	14	70	4.7	1.0	0.9	0.0	0.6	0.06	1.56	58	—	—	—	—	—
23-49	23	14	63	4.8	0.5	1.0	0.0	0.6	0.04	1.64	61	—	—	—	—	—
49-79	34	14	52	4.6	0.3	1.1	0.0	0.3	0.03	1.43	77	—	—	—	—	—
79-150	49	8	43	4.8	0.3	1.0	0.0	0.6	0.02	1.62	62	—	—	—	—	—
150-175	49	11	40	4.8	0.3	1.0	0.0	0.5	0.02	1.52	66	—	—	—	—	—
9. *Paragominas-PA, Brazil. Typic Acrorthox, clayey, kaolinitic, isohyperthermic (FCC = Cdhik)*																
0-6	88	10	1	4.2	2.8	1.45	2.08	0.88	0.14	4.55	32	1	—	—	—	—
6-23	88	10	1	4.1	0.9	1.86	0.64	0.56	0.07	3.13	59	1	—	—	—	—
23-60	96	4	0	4.7	0.7	1.03	0.48	0.48	0.04	2.03	51	2	—	—	—	—
60-107	89	11	0	5.1	0.5	0.41	0.32	0.32	0.03	1.08	38	—	—	—	—	—
107-155	84	16	0	5.4	0.3	0.41	0.32	0.32	0.03	1.08	38	—	—	—	—	—
10. *Porto Velho-RO, Brazil. Orthoxic Palehumult, clayey, kaolinitic, isohyperthermic (FCC = Ceak)*																
0-5	54	17	29	4.5	3.1	2.2	0.6		0.20	3.00	73	2	—	—	—	—
5-20	63	12	25	4.2	1.3	1.4	0.1		0.08	1.58	93	1	—	—	—	—
20-40	68	11	21	4.4	1.0	1.1	0.1		0.05	1.25	88	1	—	—	—	—
40-60	70	11	19	4.7	0.7	1.0	0.1		0.04	1.14	88	tr.	—	—	—	—
60-80	79	11	20	4.3	0.8	0.3	0.2		0.07	0.57	53	1	—	—	—	—

Horizon (cm)	Clay	Silt	Sand	pH (H_2O)	Org. C (%)	Exchangeable Al	Exchangeable Ca	Exchangeable Mg	Exchangeable K	ECEC	Al sat. (%)	Available mod. P	Available mod. Zn	Available mod. Mn	Available mod. Fe	Available mod. Cu
	(.....%.....)					(.....cmol kg^{-1}.....)						(.....mg kg^{-1}.....)				
11. *Ouro Preto-RO, Brazil. Ultic Tropudalf, fine-loamy, mixed, isohyperthermic (FCC = L)*																
0-12	18	32	50	6.5	1.3	0	6.5	1.6	0.31	8.41	0	6	—	—	—	—
12-32	22	26	52	6.3	0.9	0	2.6	1.6	0.24	4.44	0	—	—	—	—	—
32-47	22	29	49	6.2	0.5	0	3.1	2.1	0.15	5.25	0	—	—	—	—	—
47-70	26	30	44	5.8	0.3	0	3.1	2.1	0.17	5.37	0	—	—	—	—	—
70-112	34	24	42	5.8	0.2	0	3.1	2.1	0.24	5.44	0	—	—	—	—	—
112-125	36	23	41	5.7	0.2	0	5.0	1.9	0.28	7.18	0	—	—	—	—	—
125-200	49	30	21	5.3	0.2	0	0.8	0.6	0.08	1.48	0	—	—	—	—	—
12. *Altamira-PA, Brazil. Oxic Rhodic Paleustalf, very fine, kaolinitic, isohyperthermic (FCC = Cdik)*																
0-20	48	18	34	5.9	1.5	0	5.59	1.20	0.16	6.95	0	--	—	—	—	—
20-40	57	19	24	5.8	1.1	0	4.40	0.62	0.06	5.00	0	—	—	—	—	—
40-60	69	12	19	6.0	0.6	0	2.62	0.58	0.04	3.24	0	—	—	—	—	—
60-80	62	22	16	5.9	0.5	0	2.30	0.82	0.04	3.16	0	—	—	—	—	—
80-100	71	14	15	6.1	0.4	0	2.18	1.06	0.04	3.28	0	—	—	—	—	—

soil. (Plinthite is soil material capable of hardening into laterite if exposed by erosion.) These soils are mainly classified as Plinthaquults or Plinthaqualfs. Since most of these plinthic soils occur in flat, poorly drained topographical positions, the danger of laterite formation is minimal, as it would require massive soil erosion for exposure.

Hardened laterite of geologic origin occurs in scattered areas in the humid tropics. In some of these areas, the laterite is used as a road-building material. In areas like the Peruvian Amazon, which is essentially devoid of laterite materials, low-cost roads are definitely inferior to those of the State of Pará in Brazil where laterite outcrops are frequent. The laterite hazard, still frequently mentioned in the literature, is therefore of little importance in the humid tropics as a land-use constraint. On the contrary, where laterite outcrops occur they are often an asset to development.

Organic-Matter Content

A second common misconception is the widely held belief that tropical soils are low in organic matter. Soil organic-matter content in the humid tropics, however, compares favorably to that found in soils of temperate forests. Soils in the humid tropics have somewhat higher organic carbon and total nitrogen levels in the topsoil as well as the entire solum than their temperate counterparts (Table 5). In addition, no significant differences have been found in organic-matter contents between soils of tropical and temperate regions; between Oxisols of the tropics and Mollisols of the temperate regions; or between tropical and temperate Ultisols (Sanchez, Gichuru, and Katz 1982). Calculations of fresh organic-matter additions and decomposition rates explain the lack of differences (Sanchez and Buol 1975). As in all forested ecosystems, soil organic matter is more concentrated in the topsoil than in the subsoil. This holds true for tropical forests as well as temperate ones.

Plant Nutrient Storage

Another commonly held view is that tropical rainforest ecosystems hold most of their nutrients in the plant biomass component (Goodland and Irwin 1975). Nutrient cycling studies that include the entire soil, however, show that most of the ecosystem's nitrogen and phosphorus are located in the soil component (Table 6). This is not the case with potassium, calcium, and magnesium, the bulk of which remain in the aboveground biomass. An exception to the latter statement occurs on high base status Alfisols, which also contain the bulk of their bases in the soil. For more details, the reader is referred to the review by Salati and Vose (1984).

Soil Contraints in the Amazon Basin

Soil classification data provide a broad geographical picture of the kinds of soils that exist in the humid tropics, but application of these data to agricultural use, in practical terms, is only implied. This is because soils are mapped and classi-

fied as natural bodies and usually not according to what problems they present for one specific use. Soil survey information can be interpreted in terms of constraints to agricultural development drawing from Soil Taxonomy plus additional properties of the topsoil, the layer where most plant-soil interactions occur. Detailed soil surveys, which provide information at the phase level of soil series, if properly designed can allow for the recognition of some of the topsoil properties such as texture, thickness, general base status, and organic carbon content, which are pertinent to agronomic interpretations. Soil classification systems, such as Soil Taxonomy, do not include many of the transient properties of topsoils because they can be changed by management. In order to have a proper interpretation of the major constraints of these soils for a particular use, it is necessary to consider the measurable parameters that characterize the kinds of problems to be indicated. The Fertility Capability Classification System (FCC) is one way to quantify soil con-

Table 5. Mean organic-matter contents of soils from tropical and temperate forests. (After Sanchez, Gichuru, and Katz 1982.)

Depth (cm)	Parameter	Organic-matter content (%) Tropical forests	Temperate forests	Significance
0-15	C (%)	1.89	1.35	**
0-50		1.14	0.56	***
0-100		0.70	0.33	***
0-15	N (%)	0.18	0.08	*
0-50		0.12	0.05	**
0-100		0.09	0.03	***
0-15	C/N	11.3	17.6	*
0-50		10.3	13.2	ns
0-100		9.0	11.3	ns

*P = 5-10%; **P = 1-5%; ***P < 1%.

Table 6. Proportion of ecosystem nutrient storage in biomass and soil under native humid tropical forests.

Location	Soil	Total in the soil (%) N	P	K^+	Ca^{++}	Mg^{+++}
Manaus, Brazil[1]	Oxisol	73	69	11	0	8
Carare, Colombia[2]	Oxisol	71	85	28	5	21
Kade, Ghana[3]	Alfisol	81	—	56	61	61
Merida, Venezuela[4]	Inceptisol	81	91	14	31	31

1. Fittkau and Klinge (1973).
2. de las Salas (1978).
3. Greenland and Kowal (1960).
4. Fassbender (1977).

straints (Buol et al. 1975) and to provide a guide for the proper design of soil map units in soil surveys. A rough estimate of fertility parameters for the humid tropics as a whole is shown in Table 7.

When using a fairly detailed data base, meaningful interpretations can be made for planning and assessment purposes. This has been done for the Amazon by Cochrane and Sanchez (1982) at a scale of 1:1 million. The highlights of that study appear below, as an example of the kinds of information that may be useful to obtain for other humid tropical regions. A summary of the main soil constraints in the Amazon region (Table 8) shows that the most widespread constraints are chemical rather than physical.

Phosphorus deficiency is found in 90% of the Amazon Basin, but the severity of this deficiency will depend on which crops are to be grown. Aluminum toxicity, the main cause of soil acidity, covers the second largest territorial extent, about 73% of the region; it is important to note, however, that about 27% of the Amazon does not have significant aluminum toxicity problems, primarily including the alluvial areas and the well-drained high base status soils. Drought stress is found in 53% of the area, mainly in the near-ustic regions. Low potassium reserves are widespread in 50% of the region, suggesting the need for potassium fertilization in about half the Amazon Basin. Poor drainage and flooding occur in 24% of the region, including alluvial areas (*várzeas*) and inland swamps (*aguajales*). Many of these *várzea* regions are not severely threatened by floods and have a high production potential. This particular figure also indicates that about 76% of the Amazon region has well-drained soils.

About 16% of the Amazon soils, mainly the Oxisols and Ultisols of clayey topsoil texture, have the capacity to fix large quantities of phosphorus into relatively insoluble forms. Comparing this number with 90% of the Amazon that suffers from phosphorus deficiency, we can see that most soils of the Amazon that are inherently deficient in phosphorus are not likely to require large quantities of phosphorus fertilizers. This situation is certainly a less difficult one than in the acid savannas where high phosphorus fixation is widespread. Research conducted on phosphorus fertilization in the Amazon Basin confirms this supposition (Serrão et al. 1979, Benites 1983b). Nevertheless, there are 77 million ha of soils that are both deficient in phosphorus and have a high P-fixation capacity.

About 13% (64 million ha) of the Amazon Basin has soils with effective cation-exchange capacity (ECEC) values less than 4 cmol kg^{-1}. Many nutrient cations can be rapidly lost by leaching, particularly in well-drained soils. Also, low ECEC soils generally have a low nutrient reserve, indicating potential nutrient imbalance problems. In Yurimaguas, Peru, for example, potassium applications can cause magnesium deficiency by decreasing magnaesium uptake (Villachica 1978).

Table 8 also indicates only about 8% of the Amazon Basin has a severe erosion hazard. This is partly due to the overall level to gentle (0–8%) slopes found in 73% of the Amazon (Cochrane and Sanchez 1982) and partly to the favorable structure of many Oxisols and Ultisols. The 39 million ha of more highly erodible soils are located mainly on steep slopes and deep soils with an abrupt increase in clay sub-

soil content. These soils, mostly classified as Ultisols or Alfisols, are often quite susceptible to erosion unless protected by a plant canopy during periods of heavy rains.

The above statements do not mean that erosion is not a problem in the Amazon Basin. All soils can be eroded by mismanagement, and sheet erosion can occur in nearly level,well-drained Oxisols and Ultisols. It implies that, compared to other major regions of the world, the erodibility of the main soils of the Amazon Basin is not high. Most of the obvious gully erosion in the Amazon Basin is caused

Table 7. Area distribution of soil constraints in humid tropical regions. (Calculated according to Sanchez, Couto, and Buol 1982.)

	Percentage of region in:			
Soil constraint	Tropical America	Tropical Africa	Tropical Asia	Humid tropics
Low nutrient reserves	66	67	45	64
Aluminum toxicity	61	53	41	56
High P fixation	47	20	33	37
Slopes steeper than 30%	18	5	33	17
Acid, not Al toxic	11	22	33	18
Poor drainage	11	14	19	13
Low ECEC	8	20	5	11
Shallow depth	7	4	12	7
No major limitations	3	2	2	3
Shrink-swell capacity	1	1	2	1
Allophane	1	—	2	1
Acid sulfate soils	—	1	3	1
Gravel	—	1	1	1
Salinity	—	—	2	—
Sodic soils	1	1	—	—

Table 8. Summary of main soil constraints[1] in the Amazon Basin under native vegetation. (After Cochrane and Sanchez 1982.)

Soil constraint	Million ha	% of Amazon
Phosphorus deficiency	436	90
Aluminum toxicity	353	73
Drought stress	254	53
Low potassium reserves	242	50
Poor drainage and flood hazard	116	24
High phosphorus fixation	77	16
Low cation-exchange capacity	64	13
High erodibility	39	8
No major limitations	32	7
Steep slopes (>30%)	30	6
Laterite hazard if subsoil exposed	21	4

1. Nitrogen, sulfur, magnesium, and zinc deficiencies are also very widespread.

Table 9. Nutrient levels in the ash from burning three types of vegetation at two locations in the Amazon.[1]

Location and soil	Vegetation	Ash dry weight (t ha^{-1})	Nutrient level (kg ha^{-1})										
			N	Ca	Mg	K	P	Zn	Cu	Fe	Mn	S	B
Manaus, Brazil (Typic Acrorthox)	Primary forest	9.2	80	82	22	19	6	0.2	0.20	58	2.3	—	—
	Secondary forest (12 years old)	4.8	41	76	26	83	8	0.3	0.10	22	1.3	—	—
	Kudzu fallow (4 years old)	1.5	24	16	6	15	3	0.1	0.03	7	0.4	—	—
Yurimaguas, Peru (Typic Paleudult)	Secondary forest (25 years old)	12.1	127	174	42	131	17	0.5	0.24	4	11.1	24.2	0.3
	Secondary forest (17 years old)	4.0	67	75	16	38	6	0.5	0.30	8	7.3	—	—
	Kudzu fallow (4 years old)	1.2	6	18	15	77	17	0.7	0.07	3	2.3	2.5	0.1

1. Seubert et al. (1977), Smyth and Bastos (1984), Bandy and Sanchez (1981).

by civil engineering, rather than agriculture—along roads, building sites, and improperly designed city sewage and drainage systems. This situation, however, could change drastically if the plant cover is removed and not replaced sufficiently rapidly by another plant canopy. This seldom happens in the forested regions of the Amazon Basin because when crops or pastures fail, weeds and secondary forest grow rapidly, producing a new plant canopy. Gullying along cattle trails in overgrazed pastures, however, is an increasingly serious concern. Also, sheet erosion has been reported in poorly managed pastures at the beginning of the rainy season in the seasonal forest region. Actual erosion estimates have been determined in the Colombian Amazon (Navas, Munévar, and Perea 1977a, 1977b; McGregor 1980) and the Brazilian Amazon (Ranzani 1980).

Only about 7% of the Amazon has soils with no major limitations other than nitrogen deficiency. These are the well-drained soils, high in native fertility, classified mainly as Alfisols, Mollisols, Vertisols, and well-drained Inceptisols and Entisols. Nevertheless, they represent a total of 32 million ha and where they occur permanent agriculture has a better chance of success. This is the case in the Terra Roxa soils (Rhodustalfs) that combine high native fertility with excellent physical properties. Many of the successful cacao plantations are located in such soils. High base status soils are found near Altamira, Ouro Preto (Rondônia), in Brazil, in the Oriente of Ecuador associated with relatively recent volcanic deposits, and in the Huallaga Valley of Peru.

Land-Clearing Methods

The choice of land-clearing method is the first and probably most crucial step affecting the future productivity of farming systems. Several comparative studies conducted in the Amazon Basin confirm that land-clearing methods involving burning are superior to different types of mechanical clearing because of: (a) the fertilizer value of the ash, (b) soil compaction caused by bulldozing, and (c) topsoil displacement in mechanized land clearing.

Nutrient Additions by the Ash

The direct measurement of the nutrient content of the ash in the Amazon has been determined after burning several types of vegetation in an Oxisol from Manaus, Brazil, and an Ultisol from Yurimaguas, Peru (Table 9). Constituents in the ash contributed significant inputs of bases and other elements, which resulted in beneficial effects in soil chemical properties (Seubert et al. 1977, Smyth and Bastos 1984).

Variability in the quantity and nutrient content of ash occurs because of differences in soils, clearing techniques, and the proportion of the forest biomass actually burned. Only 20% of the forest biomass was actually converted to ash when a virgin forest on an Ultisol of southern Bahía, Brazil, was burned (Silva 1979). Moreover, when the composition of ash adjacent to individual tree species was analyzed, very wide ranges of nutrients were observed: 0.8–3.4% N, 0–14 ppm avail-

able P, 0.06–4.4 cmol kg^{-1} of Ca, 0.11–21.03 cmol kg^{-1} of Mg, and 34–345 cmol kg^{-1} of K (Silva 1979). This suggests the presence of fallow species that can accumulate different quantities of nutrients.

The fertilizer value of the ash is likely to be of less importance in fertile soils. For instance, it was observed that the increases in P and K availability caused by burning a forest on an Entisol of pH 7.0 in Santa Cruz, Bolivia, did not increase crop yields (Cordero 1964); the soil was already adequately supplied with these elements. In fact, ash additions to Alfisols with pH 6.0 have triggered iron or zinc deficiencies in Africa (Lal et al. 1975). Similar effects have been observed under large ash depositions in Oxisols of Manaus.

In addition to the nutritional value of the ash, the extent to which the ash is incorporated into the topsoil is important. Around Manaus, shifting cultivators prefer to clear loamy or sandy Ultisols on steep slopes rather than clear nearly level areas of clayey Oxisols. One reason is that the ash is not incorporated well in the Oxisols, while apparently this is not a problem in the sandier-textured surface horizon of the Ultisols.

Soil Compaction

Conventional bulldozing has the clearly detrimental effect of compacting the soil, particularly the sandy and loamy surface horizons of Ultisols. Significant decreases in infiltration rates, increases in bulk density, and decreases in porosity have been recorded in such soils in Surinam (Van der Weert 1974), Peru (Seubert et al. 1977, Alegre et al. 1986), and Brazil (Schubart 1977, Silva 1979).

Topsoil Displacement

Another consideration is the degree of topsoil displacement by the bulldozer blade and by dragging uprooted trees and logs. Although no quantitative data are available, topsoil scraping in high spots and accumulation in low spots is commonly observed. The better jungle regrowth near windrows of felled vegetation suggests that topsoil displacement can result in major yield reductions. For example, in Nigeria maize yields decreased by 50% when the top 2.5 cm of an Alfisol was removed (Lal et al. 1975). Similar data on Oxisols and Ultisols of the Amazon are not available.

Improved Mechanized Methods

The negative effects of bulldozer land clearing are becoming better known to farmers and development organizations. Government credits for large-scale mechanized land-clearing operations have been sharply reduced in the Brazilian Amazon since 1978. Other alternatives consist of mechanized clearing followed by burning, using two bulldozers dragging a heavy chain, or large tree crusher machines that literally walk over the felled forest (Toledo and Morales 1979, Toledo and Navas 1986).

The most effective method however, is the use of a shear blade, followed by burning and heavy disking to reverse the effects of compaction. Unlike the straight bulldozer blades, the floating-type or shear blades cut the trees at ground level, avoiding much topsoil carryover since no tree roots are dragged and the blade seldom touches the soil. A comparison between clearing by slash and burn, straight-blade bulldozing, and shear-blade bulldozing in Yurimaguas (Alegre 1985, Alegre et al. 1986) showed that the traditional manual method caused the least disruption in terms of water infiltration and topsoil bulk density, mean weight diameter of aggregates, and amount of organic carbon (Table 10). The shear blade treatment significantly decreased the values of many of these properties 3 months after clearing, but these differences largely disappeared after 2 years of continuous cultivation. Although straight-blade bulldozing decreased crop yields by about half, the differences between slash-and-burn and shear blade + burning + heavy disking were minor (Table 11). The use of a shear blade, therefore, is recommended if mechanical clearing is to be practiced.

Table 10. Effect of land-clearing method on topsoil physical properties and organic carbon on a continuously cropped Ultisol in Yurimaguas, Peru. (Adapted from Alegre 1985.)

Clearing method	Months after clearing	Infiltration rate (mm h^{-1})	Bulk density (Mg m^{-3})	Mean weight diameter (mm)	Organic C (%)
Before clearing	0	324	1.16	0.48	1.04
Slash and burn	3	204	1.27	0.42	1.05
Straight blade	3	14	1.42	0.29	0.82
Shear blade	3	22	1.28	0.36	0.87
Slash and burn	23	107	1.32	0.38	1.03
Straight blade	23	15	1.42	0.36	1.02
Shear blade and disk	23	110	1.32	0.36	0.89

Table 11. Effects of land clearing and post-clearing management on the relative yield of five consecutive crops after clearing a 20-year-old secondary fallow on an Ultisol of Yurimaguas, Peru. (After Alegre 1985.)

	Percentage of cumulative maximum yields[1]	
Clearing method	No tillage, no fertilizer	Tilled, fertilizer
Slash and burn	27	93
Straight blade	7	47
Shear blade	14	65
Shear blade + burning + heavy disk	28	89

1. Maximum yields of five consecutive crops in t ha^{-1}: upland rice, 4.0; soybean, 2.3; maize, 5.2; upland rice, 2.5; maize, 3.3.

Soil Management Options

Long-term research in Yurimaguas, Peru, and other areas in the Amazon Basin has led to the development of sustainable soil management options for different soils, landscape positions, and levels of infrastructure development in acid tropical America. Sanchez and Benites (1983) suggested several alternatives for the Peruvian Amazon that can be made applicable to other countries with minimum modifications (Fig. 1). Not all the soil-landscape combinations illustrated in this figure are likely to occur in any given area, but they indicate the range observed in the humid tropics.

Three types of alluvial positions are indicated in Figure 1: the beaches, low flood plains, and high flood plains. The beaches are exposed during the dry season along the deposition shores of large Amazonian rivers. These soils are among the youngest in the world, being formed and eroded away every year. The low and high flood plains roughly correspond to the low and high *várzeas* of Brazil. The low flood plains are likely to be flooded every year, while the high flood plains may be flooded once every 10 years or so. Low flood plain soils are mainly Aquents, while high flood plain soils are Aquepts, Aqualfs, Udalfs, or, in some cases, Udolls—all with high native fertility. An exception to this rule occurs when the source of sediments is other than the Andean mountains. Rivers originating in watersheds on the Guyanan or Brazilian shields, or around Spodosol areas within the Basin, are not likely to produce alluvial soils of high native fertility (Hoag et al. 1985).

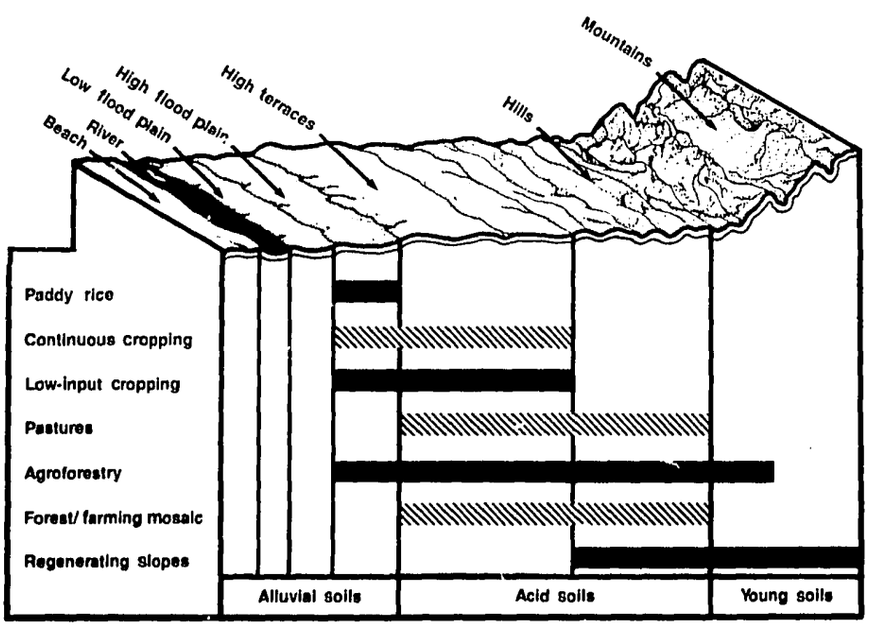

Fig. 1. Soil management options for the Peruvian Amazon.

Table 12. Performance of flooded IR4-2 rice in different land-preparation systems in a Eutric Haplaquept at a *restinga* in Yurimaguas, Peru, during the first 26 months after clearing. (From Arévalo et al. 1983.)

	Grain yields (t ha^{-1})			
	Puddled		Dry	
Crop	Transplanted	Broadcast	Transplanted	Broadcast
First crop	7.9	3.2	8.3	6.3
Second crop	5.2	4.9	6.7	5.6
Third crop	7.1	6.4	6.2	4.9
Fourth crop	6.0	4.8	5.6	4.6
Fifth crop	6.8	6.7	6.3	6.0
Mean/crop	6.6	5.2	6.6	5.5
Mean annual production	15.2	12.0	15.3	12.6

The upland areas, called *terrenos de altura* in Peru and *terra firme* in Brazil, can be divided into high terraces with flat to gently undulating slopes less than 8% suitable for mechanized agriculture, and hills with slopes of 8 to 30% that are not mechanizable. About 50% of the Amazon Basin has well-drained soils with flat topographies, while 21% of the Basin corresponds to the hill area (Cochrane and Sanchez 1982). The steeplands constitute about 6% of the area, but are quite important around the western end. The following management options for these soils are suggested.

Irrigated Rice in Alluvial Soils

The Amazon Basin has vast areas of poorly drained, high base status soils located in topographic positions that preclude annual flooding. Given the high native fertility of most of these Entisols, Inceptisols, Mollisols, and Alfisols and their proximity to rivers, efforts have been made to develop intensive utilization of beaches for irrigated rice production. Irrigated rice is usually the best management option because of the assured market and the yield stability under a paddy system.

An example from Yurimaguas illustrates the point. Beaches with soils classified as clayey Eutric Haplaquepts produced an average of 6 t ha^{-1} of supplementary irrigated rice per crop, with 2.5 crops per year (Table 12). No fertilizer response was observed during the first two crops, but nitrogen response to 50 kg N ha^{-1} was evident in the third crop (Arévalo et al. 1983). Water management trials indicated the need for irrigation to obtain high rice yields. Rainfed rice production averaged 4.6 t ha^{-1}, while irrigated rice averaged 6.3 t ha^{-1} (Arévalo et al. 1983). Transplanting, however, posed major constraints to the limited labor supply of the Basin. Puddling is convenient in order to level the paddy, and transplanting is necessary to achieve an adequate stand in poorly levelled fields. After two crops, broadcasting

pregerminated seed is as effective as transplanting, because the fields are then well levelled (see Table 12).

This technology has been adapted rapidly by new settlers migrating into the Amazon Basin from rice-producing areas in the coast of Peru. Approximately 75 000 ha of new irrigated rice land was put into production within the last 5 years in the Peruvian Amazon (INIPA 1984, and unpublished data).

Completely mechanized rice production was established at the other end of the Amazon in *várzeas* off the Jari river where 4000 ha of paddy rice were produced (Briscoe 1983). In these areas, sulfur deficiency is as important as nitrogen deficiency (Wang et al. 1976).

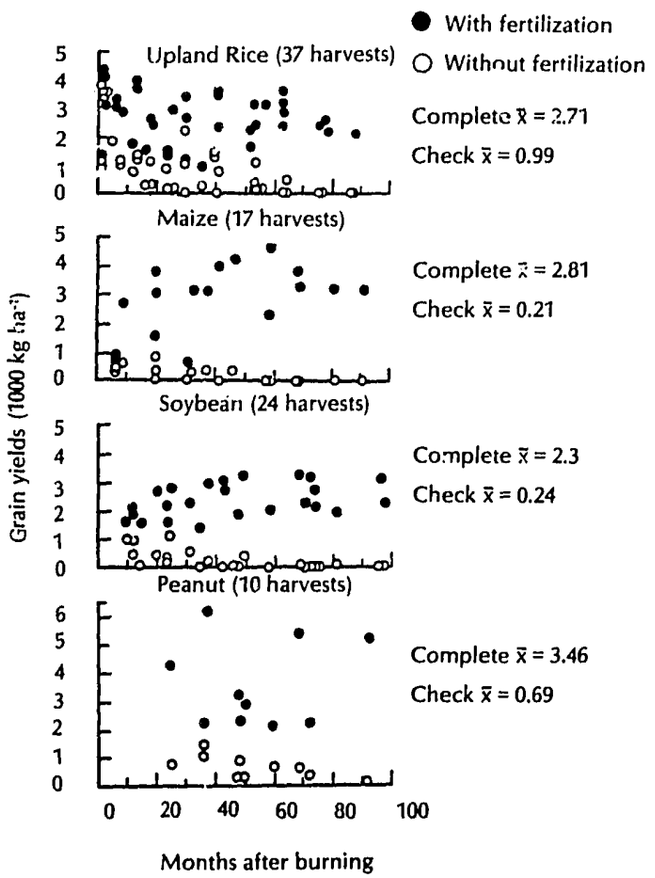

Fig. 2. Crop yields as a function of time after clearing with and without complete fertilization. Each point is mean of four replications. (Sanchez, Villachica, Bandy, and Nicholaides 1982.)

Intensive Crop Rotations

A second management option is to fully capitalize on the potential of nearly level areas of well-drained acid soils which, as mentioned earlier, cover about half the Amazon. For areas with sufficient road, market, and credit infrastructure, the correction of nutrient deficiencies by fertilizers and liming and the use of mechanization is an attractive and usually highly profitable option.

Promising results were obtained at Yurimaguas by growing three crops a year in a rotation of upland rice-maize-soybean or upland rice-peanut-soybean. These rotations are adapted to the rainfall pattern and keep the ground covered most of the year. Continuous monoculture of the same crops, however, has not produced sustained yields because of pathogen buildups (Valverde and Bandy 1982).

Thirty-two consecutive crops have been harvested from the same field in Yurimaguas since it was cleared by slash-and-burn operations in October 1972 and cultivated to the rice-maize-soybean rotation. Without fertilization, yields dropped to zero after the third consecutive crop. With complete NPK fertilization and liming, the long-term average of this rotation, which was replicated in three fields, is 7.8 t of grain ha^{-1} y^{-1} (Sanchez, Bandy, Villachica, and Nicholaides 1982).

Long-term yields of 88 harvests of these four crops with and without complete fertilization during 8 years are shown in Figure 2. Upland rice, soybean, and peanut yields were excellent, but maize yields were moderate. There is also a reasonable yield stability for the four crops. Continuous production, therefore, can be achieved in the Amazon Basin with adequate fertilization. A similar experiment is ongoing in Oxisols of Manaus and is now in its tenth consecutive crop, showing similar sustained yields.

The term "adequate fertilization" was not arrived at lightly. It took about 4 years to gather conclusive data on the changes in soil properties that occurred after clearing and burning a 17-year-old secondary forest and growing annual crops continuously. The nutrient dynamics have been monitored after each harvest since October 1972 and provide the key to continuous cultivation (Fig. 3).

The lime and fertilizer recommendations developed at Yurimaguas are presented in Table 13. Like all sound fertilizer recommendations, these data are site-specific; nevertheless, they represent the general level of fertilizer input required for continuous crop production in Ultisols. For example, these fertilizer levels do not differ substantially from those used to grow maize, soybean, and peanut in Ultisols of the southeastern United States. On-farm trials around Yurimaguas show that the system is economically viable under a wide range of crop and fertilizer prices, levels of capital, and labor force composition (Hernández and Coutu 1981). The practical limitation in many areas, however, is a sufficient infrastructure to assure the flow of inputs and products.

Although it is commonly believed that cultivation degrades soils in the humid tropics, our results indicate that soil properties improve with continuous cultivation systems that combine intensive management with appropriate fertilization. After 20 consecutive crop harvests at Yurimaguas, the topsoil pH increased from

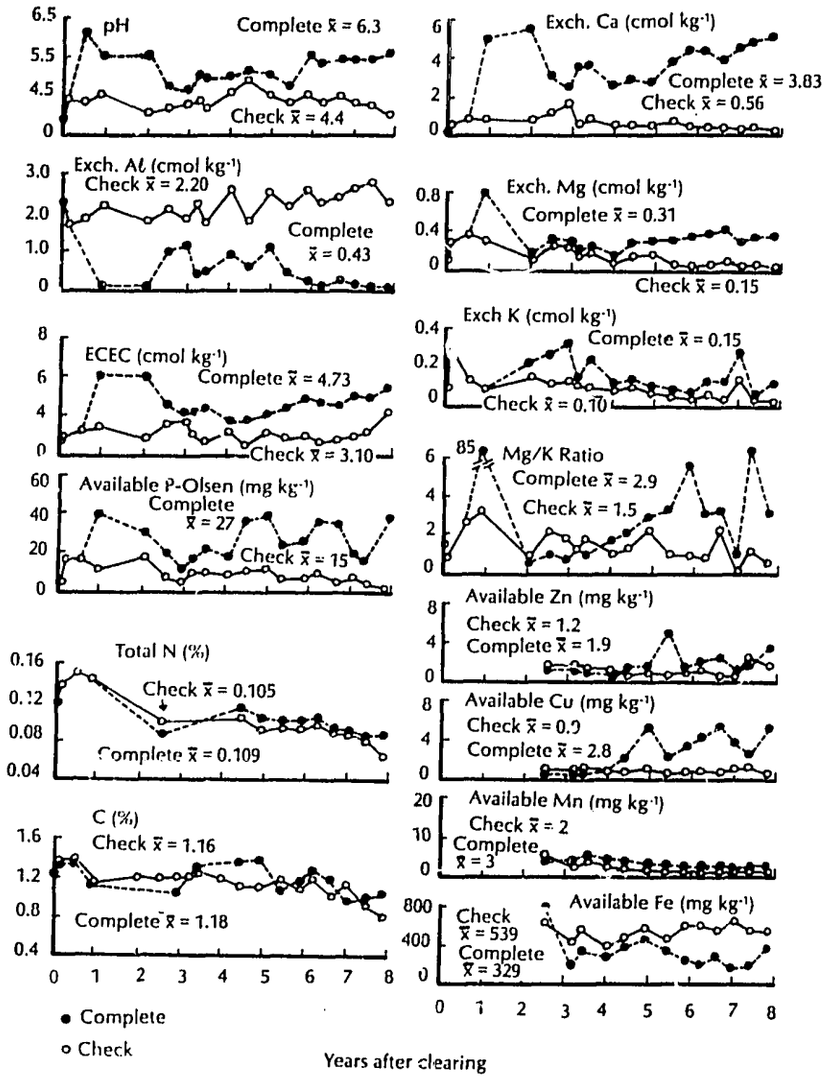

Fig. 3. Topsoil fertility dynamics within 8 years after clearing an Ultisol in Yurimaguas, Peru, and grown to a three-crop-per-year rotation without fertilization or liming (check) or with complete fertilization. (Sanchez, Villachica, and Bandy 1983.)

a very acid 4.0 before clearing to a favorable level of 5.7 (Sanchez, Villachica, and Bandy 1983). Organic-matter content decreased by 27%, but most of this loss occurred during the first year after which a new equilibrium level was reached. Exchangeable aluminum decreased from very high levels to minimal amounts; exchangeable calcium increased 20-fold (a consequence of lime applications), and exchangeable magnesium doubled. Exchangeable potassium did not increase despite the application of large quantities of potassium fertilizer, suggesting rapid utilization by crops and perhaps losses due to leaching. Effective CEC doubled as a consequence of the pH-dependent charge of kaolinite and iron oxides. Fertilization also increased available phosphorus content from below the critical level of 15 ppm (Olsen method) to substantially above it. The same trend occurred with zinc and copper. Available manganese, however, decreased to levels approaching deficiency. Available iron remained considerably above the critical range of 20 to

Table 13. Fertilizer requirements for continuous cultivation of annual rotations of rice-maize-soybean or rice-peanut-soybean on an acid Ultisol in Yurimaguas, Peru. (From Sanchez, Villachica, Bandy, and Nicholaides 1982.)

Input[1]	Rate	Frequency and crop requirements
Lime	3 t lime ha^{-1}	Once every 3 years
Nitrogen	80 to 100 kg N ha^{-1}	Rice and maize only
Phosphorus	25 kg P ha^{-1}	Every crop
Potassium	80 to 100 kg K ha^{-1}	Every crop, split application
Magnesium	18 kg Mg ha^{-1}	Every crop (unless dolomitic lime is used)
Copper	1 kg Cu ha^{-1}	Once a year or once every 2 years
Zinc	1 kg Zn ha^{-1}	Once a year or once every 2 years
Boron	1 kg B ha^{-1}	Once a year
Molybdenum	20 g Mo ha^{-1}	Mixed with legume seeds only

1. Calcium and sulfur requirements are satisfied by lime, simple superphosphate, and magnesium, copper, and zinc carriers.

Table 14. Effects of completely fertilized continuous cropping on selected soil physical properties (three crops per year). (Adapted from Seubert et al. 1977, NCSU 1980.)

Years after cropping	Infiltration rate (cm h^{-1})	Bulk density (Mg m^{-3})
0 (1 month after clearing)	10.6	—
1	9.6	1.51
4	12.7	1.44
6	10.0	1.55

40 ppm. On the whole, these changes indicate improvement in the topsoil's chemical properties.

There have been no unfavorable changes in soil bulk density or infiltration rate thus far (Table 14) because of the protection three well-fertilized crops per year provide against raindrop impact. Although crop residues are left in the field until the experimental plots are tilled for the next planting, the soil is exposed for up to 30 days before a full crop canopy is reestablished. Occasional runoff losses have been observed, but they have not been of sufficient magnitude to affect yields.

Yurimaguas is not the only location in the Amazon where continuous cultivation has improved topsoil and chemical and physical properties. Similar positive results were obtained from continuously cultivated farms in the Braganca region of northeastern Pará in Brazil (Falesi et al. 1982).

Acid, infertile subsoils of Oxisols and Ultisols frequently act as chemical barriers to root development. Crop roots are unable to enter subsoil that is highly saturated with aluminum ions but is very low in exchangeable calcium (North Carolina State University 1980/81, Ritchey et al. 1980). This produces shallow root systems. Even though the subsoil may still have plant-available water, the roots cannot reach it. With time, however, this problem is alleviated. We observed significant increases in contents of calcium, magnesium, and effective CEC and a decrease in aluminum saturation at depths of 15 to 45 cm (Fig. 4). Fertilization promotes the downward movement of these basic cations, which often results in a more favorable environment for root development than before clearing.

Attempting continuous cultivation without adequate fertilization, however, did result in soil degradation. The lack of a full crop canopy left the soil exposed for most of the year. Fertility was so limiting that even weed growth was suppressed. Although not measured, runoff losses from these plots must be considerable as the soil surface appears more sandy and is highly compacted.

Intensive continuous cropping has also been practiced with success by farmers on fertile alluvial soils not subject to flooding. The higher native fertility and higher ECEC of these soils preclude the need to lime and result in lower rates of fertilizers required. Weed control, however, becomes more critical in these better soils.

Low-Input Cropping

Intensive, fertilizer-based continuous cropping is likely to be limited to areas with relatively good access to inputs and markets. Research on another option was initiated to develop alternatives that would minimize chemical inputs according to low-input technology concepts (Sanchez and Salinas 1981). This management option is based on three main strategies: the use of crop varieties tolerant to acid soils, the return of crop residues to the soil, and the use of managed fallows as an intermediate alternative between continuous and shifting cultivation.

Germplasm believed to have high yield potential under humid tropical conditions was tested in limed and nonlimed plots in Yurimaguas at aluminum saturation levels of about 20 and 80%, respectively. Germplasm was considered highly

tolerant if its yields in acid soils were 85% or more of those obtained in the limed plots, and moderately tolerant if the relative yields were between 65 and 85% (Nicholaides and Piha 1985). The overall results (Table 15) indicate a high degree of acid tolerance in upland rice and cowpea. No acid tolerance was detected in the soybean, maize, and winged bean germplasm tested, but moderate tolerance was found in sweet potatoes and peanuts. Some local peanut cultivars appear highly aluminum-tolerant in growth vigor, but not in yields.

The upland rice-cowpea rotation was selected as the basis for a low-input cropping system. It is designed to mesh with the traditional shifting cultivation practices. After slash and burn, the traditional upland rice variety is sown with a planting stick (*tacarpo*) at conventional spacing, using broadleaved post-emergence herbicides as conventionally done. Improvements are then introduced at the time farmers normally abandon the field, after the rice harvest. All the rice straw is cut low and spread evenly. The acid-tolerant improved rice variety Africano desconocido is planted with a *tacarpo* at 30- by 50-cm spacing. It is then followed by

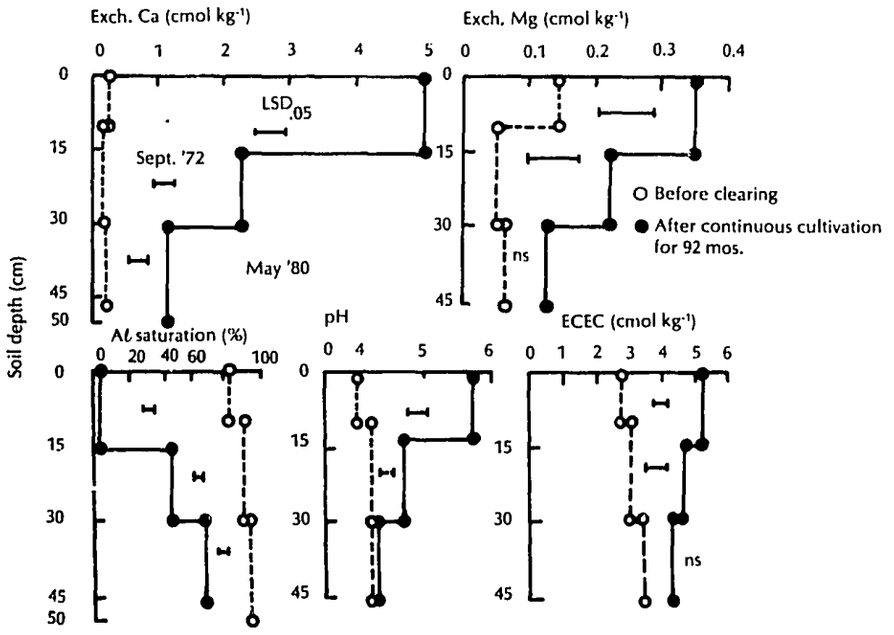

Fig. 4. Improvement in subsoil chemical properties after 7½ years of continuous cultivation of a rice-maize-soybean rotation in an Ultisol of Yurimaguas, Peru. (Sanchez, Villachica, Bandy, and Nicholaides 1982.)

Table 15. Summary of varietal testing for acid tolerance[1] at Yurimaguas, Peru. (After Nicholaides and Piha 1985.)

		Number of accessions		
Crop	Accessions tested	Very tolerant (RY >85%)	Tolerant (RY = 65-85%)	Sensitive (RY <65%)
Rice	32	8	16	8
Cowpea	30	22	7	11
Soybean	22	0	0	22
Maize	20	0	0	20
Winged bean	16	0	0	16
Sweet potato	10	0	2	8
Peanut	10	0	1	9

1. Tolerance based on relative yield (RY) $= \frac{\text{Yields at 80\% Al satn.}}{\text{Yields at 20\% Al satn.}} \times 100.$

Table 16. Productivity of a low-input system after slash burning a 10-year-old secondary forest in an Ultisol of Yurimaguas, Peru, during the first 29 months (September 1982-January 1985). (After Benites and Nureña 1985 and unpublished data.)

		Grain yield (t ha^{-1})	
Crop sequence	Planting date	No fertilizer or lime	Fertilized crops 2, 4, 6
1. Rice cv. Carolina	Sept. 1982	2.44	2.44
2. Rice cv. Africano	Feb. 1983	2.99	3.11
3. Cowpea cv. Vita 7	Sept. 1983	1.09	1.24
4. Rice cv. Africano	Dec. 1983	2.77	3.22
5. Cowpea cv. Vita 7	May 1984	1.19	0.94
6. Rice cv. Africano	Sept. 1984	1.84	2.02
Total grain in 29 months		12.32	12.97

Table 17. Performance of minimum-input system with kudzu fallow rotation[1] with no lime or fertilizer addition. (From Bandy, unpublished.)

Year	Management	Maize yields (1st crop after burn) (t ha^{-1})	Rice yields (2nd crop after burn) (t ha^{-1})
1977	Burn 20-yr-old secondary treatment, plant	4.0	3.3
1978	First kudzu fallow	—	—
1979	Burn kudzu, plant	1.1	1.7
1980	Second kudzu fallow	—	—
1981	Burn Kudzu, plant	0.7	1.5

1. Dashes indicate no cropping.

acid-tolerant cowpea (Vita 6 or Vita 7 from IITA) also planted with the *tacarpo*. After threshing, all rice straw and cowpea tops are spread evenly over the field, in spite of the extra labor involved. The results of a 1-ha field cleared of a 10-year-old secondary forest on an Ultisol with pH 4.6 after burning are shown in Table 16. The field included a fertilizer differential, either zero or 30 kg N ha^{-1}, 50 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1} applied to each rice crop except the first one. The results show high yields of six consecutive crops harvested, without a significant fertilizer response (Benites and Nureña 1985). Such results are quite different from the check plots of the intensive rotations, where yields dropped to practically zero after the second consecutive crop without fertilization (see Fig. 2). The combination of acid-tolerant cultivars, no tillage, and complete residue return may be responsible for the difference.

There is no assurance that these yields will be sustainable and, in fact, a yield decline in the sixth crop was apparent. After about 2 years, however, the stumps rotted, thus clearing the way for a shift to intensive, mechanized continuous cropping. Other alternatives include establishment of pastures, agroforestry, or managed fallows. The low-input cropping system, therefore, may be considered a transition technology between slash-and-burn and intensive agriculture.

Managed fallows provide another alternative, giving farmers a safe way to rest the soil without major weed encroachment. Research with tropical kudzu (*Pueraria phaseoloides*) fallows at Yurimaguas showed some advantages as well as limitations. Tropical kudzu grows luxuriously in the Amazon Basin, and, contrary to temperate-region experience with the species *Pueraria lobata*, it is relatively easy to eliminate tropical kudzu by cutting and burning during the drier part of the year. Alternating 1 year of cropping with 1 year of kudzu fallow has produced respectable yields, while providing total soil protection during the fallow period. Crop yields, however, are declining with time (Table 17), and the decline seems to be related to potassium deficiency.

The effect of kudzu fallows in recycling nutrients from Ultisol subsoils, however, has been of little relevance (Bandy and Sanchez 1981). In these very acid and infertile subsoils, no significant nutrient recycling occurs because, in contrast to areas with high base status subsoils, there is little to recycle. Nevertheless, cutting and burning 2 to 3 years' growth of kudzu fallow produced similar crop yields as cutting and burning a 25-year-old secondary forest fallow. Additional advantages of kudzu fallow include the maintenance of the residual effects of previous liming and fertilization, and its grazing potential as a "protein-bank" combined with adjacent grass pastures. Also, kudzu fallows provide excellent protection against erosion.

Pastures

Pasture-based beef and dairy production is the largest single activity on cleared land in the Amazon Basin and is a major source of controversy, particularly in Brazil. There are about 3.7 million ha of cultivated pastures in the Amazon Basin,

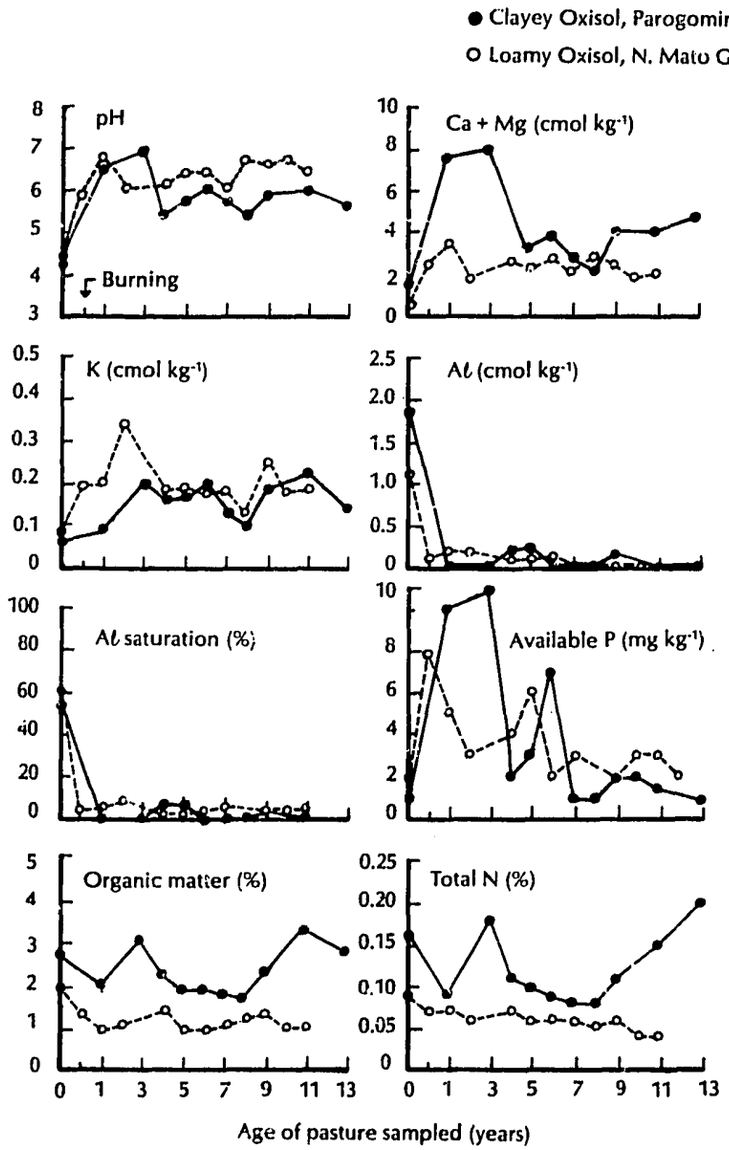

Fig. 5. Changes in topsoil properties of *Panicum maximum* pastures of known age in eastern Amazonía (sampled at the same time). (Adapted from Serrão et al. 1979.)

according to estimates by Serrão et al. (1979). Most of them consist of *Panicum maximum*, without legumes or fertilization, and have a carrying capacity of one animal unit per ha, producing about 100 kg ha^{-1} of annual liveweight gain. After the first 3 to 4 years, pasture productivity begins to decline, secondary growth invades, and the pasture slowly changes into secondary forest fallow. It is estimated that 20% of the area planted to pastures in the Brazilian Amazon is in some state of degradation (Serrão et al. 1979). This has raised serious questions as to the value of pasture production in the Amazon (Goodland and Irwin 1975, Schubart 1977). The Brazilian government has reduced credits for new land clearing for pasture and is concentrating its research efforts to reclaim degraded pastures.

A series of studies conducted primarily in the ustic portions of eastern Amazonia has shed light on the soil dynamics through time in pasture production (Falesi 1976, Baena 1977, Fearnside 1978, Serrão et al. 1979, Hecht 1983). Soil samples were taken in pastures of known age in several farms. Although the sample size is small, time and space are confounded, and variability is high, a clear trend has emerged from these studies: pastures retard the rate of fertility decline, maintaining for several years some of the benefits of burning, particularly a high soil pH, elimination of aluminum toxicity, high calcium and magnesium contents, and, for the first 4 to 5 years, sufficient levels of available phosphorus. This decline has been attributed to nitrogen and phosphorus deficiency and the poor adaptation of *Panicum maximum* to this environment (Serrão et al. 1979).

Data for a clayey Oxisol from Paragominas and a loamy Oxisol from northern Mato Grosso are summarized in Figure 5 and suggest a remarkable degree of nutrient recycling and maintenance of soil fertility under pastures in the eastern Amazon Basin. Observations on animal productivity indicate that its decline is associated with available phosphorus levels decreasing below 4 ppm P. The speed of this decline is faster in soils with clayey surface horizons than in soils with loamy surface horizons (Serrão et al. 1979). Since phosphorus fixation in Oxisols and Ultisols usually increases as a function of topsoil clay and iron oxide contents (Sanchez and Uehara 1980), it is not surprising that the clayey-textured Oxisols show pasture degradation symptoms earlier than the loamy ones. Since *Panicum maximum* responds very strongly to phosphorus fertilization, it is also not surprising that it tends to disappear and is overtaken by jungle regrowth. Excessively high grazing pressures were also found to accelerate pasture degradation (Serrão et al. 1979). A look at Figure 5 suggests that these pastures are periodically burned as the sharp increases in bases and available phosphorus are evident.

The solution to this apparently hopeless situation is remarkably simple: clear the jungle regrowth (*juquira*) by hand, burn the pastures, broadcast 25 kg P ha^{-1}—half as single superphosphate and half as rock phosphate, and plant aluminum-tolerant species such as *Brachiaria humidicola* and *Pueraria phaseoloides*. When such practices were applied to a 13-year-old degraded pasture at Paragominas (Serrão et al. 1979), the pasture recuperated with increases in carrying capacity (Serrão 1981, Serrão and Homma 1982). Because of the labor requirements, pasture regeneration in this fashion should be done in relatively small areas at one time.

In the udic portions of the Amazon Basin of Peru, considerable advances have been made in developing legume-based pastures to replace the degraded *torourco* complex (*Pallum conjugatum* and *Axonopus compressus*), which rapidly becomes dominant once planted *Panicum maximum* disappears (Toledo and Morales 1979, Ara et al. 1982). A wide range of grass and legume accessions from CIAT's Tropical Pastures Program has been tested at Yurimaguas, Pucallpa, Tarapoto, Tingo María, Puerto Maldonado and other locations of the Peruvian Amazon (Reátegui et al. 1984). The various accessions were planted at Yurimaguas on Ultisols with a pH value of 4.0 and 90% aluminum saturation and received only 50 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1}. Four grass species and five legume species have been identified as promising for the Peruvian Amazon (Table 18). They all combine growth and persistence under acid soil stress with reasonable tolerance to insects and diseases.

Some of these species were combined in 0.45-ha grazing plots, on previously cropped Paleudults at the Yurimaguas station. Unlike temperate-region experience, the legumes established themselves quickly but the grasses suffered from poor establishment, partly because of excessive tillage and partly because of vigorous weed competition. During the first year, continuous grazing was used at an average stocking rate of 4 animals ha^{-1}. This resulted in modest liveweight gains and in the virtual disappereance of the grass component in some mixtures. Grazing management was changed to rotational grazing at 42-day intervals during the second year. The first 3 years of grazing produced relatively modest individual animal weight gains but very high annual total liveweight gains per ha due to the high stocking rate (Table 19). More time is needed to ascertain the persistence and productivity of these grass-legume mixtures, as well as to learn how to manage them in a rainforest environment. Nevertheless, the productivity of 200 to 700 kg ha^{-1} y^{-1} of liveweight gains underscores a significant potential for legume-based pastures in the region, considering that annual liveweight gains on degrading pastures is on the order of 50 to 100 kg ha^{-1} y^{-1}.

Knowledge about how to maintain grass-legume pastures in the humid tropics is very limited. Annual maintenance fertilizer applications of about 25 kg ha^{-1} of phosphorus and potassium and possibly some quantities of magnesium and sulfur are probably needed. Grazing management is of utmost importance to maintain an acceptable grass-legume balance. Most of our understanding of grass-legume mixtures in the tropics comes from ustic soil moisture regimes where the main objective is to maintain a supply of green forage during the dry season. This is mainly accomplished by the legume component, which remains green while the grasses mature and dry out. In the humid tropics, grasses remain green throughout the year, posing a question of what is the role of legumes under this environment. Many of these grasses have lower nutritional quality than was expected from savanna experience. Research is underway to provide a better understanding of pasture quality, the role of legumes, nitrogen transfer, and nutrient recycling.

Perennial Crops and Agroforestry

Many scientists believe that the "natural vocation" of the Amazon Basin is trees and that ultimately a tree canopy should replace crop or pasture canopies. Experience in the Amazon on relationships between soil and perennial crops lags far behind that of humid tropical Asia. Most of the research knowledge is based on cacao plantations in Alfisols of the State of Bahía, Brazil (Alvim 1979, 1982; Alvim and Cabala-Rosand 1984), although successful coffee and oil palm plantations exist in the humid tropics of Colombia, Ecuador, Peru, Brazil, and Costa Rica. Knowledge and appreciation of the myriad of agroforestry systems practiced by native tribes and settlers in the humid tropics is becoming increasingly available (Hecht 1982, Peck 1982, Valencia 1982, Denevan et al. 1983). Information on forestry species is also emerging (Russell 1983, Romero and Romero 1984). Some advances have been made on how tree plantations affect soil properties in the humid tropics (Sanchez et al. 1985). A major difference in soil acidity and base status was observed between mature *Gmelina arborea* and *Pinus caribaea* plantations on Ultisols in the Brazilian state of Jari without any fertilization (Fig. 6). The topsoil under *Gmelina* had a pH of 5.2 while that under *Pinus* was about the same as under native rainforest, pH 3.9. The rise in pH under *Gmelina* is accompanied by an actual increase in exchangeable calcium reserves of 860 kg Ca per ha as compared with 40 kg in the forest and 100 kg in the *Pinus* plot. *Gmelina* seemed to act as a calcium accumulator under acid soil conditions, while *Pinus* more nearly

Table 18. Promising pasture accessions for the Peruvian Amazon based on tolerance to acid stresses and pathogens and adaptability to environments.

Grasses	Legumes
Andropogon gayanus 621	*Centrosema* hybrid 438
Brachiaria decumbens	*Centrosema macrocarpum*
Brachiaria dyctioneura	*Desmodium ovalifolium* 350
Brachiaria humidicola	*Pueraria phaseoloides*
	Stylosanthes guianensis 136, 184

Table 19. Productivity of mixed pastures in Yurimaguas, Peru. (From Reátegui et al. 1984.)

	Productivity					
	Year			Year		
	1	2	3	1	2	3
Grass/legume associations	(g/animal d^{-1})			(kg ha^{-1} y^{-1})		
A. gayanus / Centrosema hybrid	—	435	553	—	884	449
A. gayanus / S. guianensis	219	402	570	390	703	689
B. decumbens / D. ovalifolium	398	419	316	639	046	513
B. humidicola / D. ovalifolium	—	—	453	—	—	735

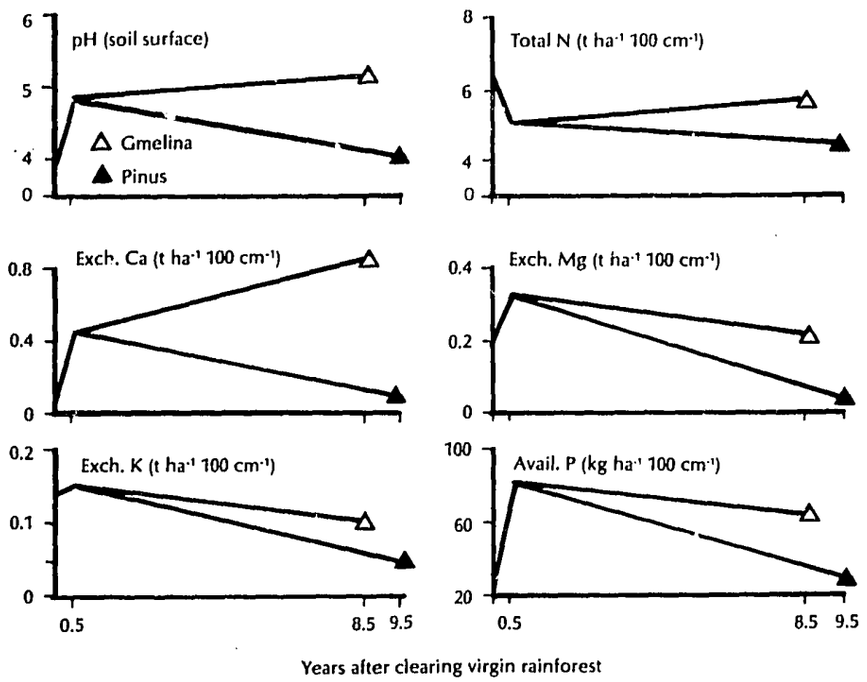

Fig. 6. Effects of *Pinus caribaea* and *Gmelina arborea* plantings on surface soil pH and nutrient content of the top 1 m of a sandy Ultisol in Jari, Brazil. (Adapted from Russell 1983.)

simulated the rainforest level. *Gmelina* maintained exchangeable magnesium, exchangeable potassium, and total nitrogen contents at pre-clearing levels, whereas contents of these nutrients suffered considerable decreases under *Pinus*. *Gmelina* also tripled the available soil phosphorus contents over the original forest or *Pinus*.

Other fast-growing tree species have also produced increases in exchangeable bases. Results on an Oxisol in Brazil indicated a doubling or tripling of topsoil exchangeable bases after 10 years under *Cordia trichotonia* and *Caesalpinia echinata* relative to the native forest, but the precious wood species *Dalbergia nigra* did not produce significant increases over the native forest (Table 20).

Leaching losses under tree plantations are also being quantified. Recently, negligible losses of phosphorus but measurable losses of potassium, calcium, and magnesium were found at all sites in a sandy Ultisol in Brazil, including the virgin rainforest (Table 21). Large leaching losses of bases occurred after the forest was cleared and burned, and prior to the establishment of tree cover. This explains in part the decreases in nutrient availability observed in some cases during the establishment phase. Leaching losses during the mature growth stage and even 1.5 years into the second rotation were actually lower than those under the rainforest. Consequently, the nutrient cycling mechanism seems to work effectively under *Pinus caribaea*.

Nutrient inputs from atmospheric deposition were also determined (Russell 1983), and the balance between atmospheric deposition and leaching is presented (Table 22). This calculation shows a virtual absence of net nutrient losses from the rainforest, from the mature *Pinus caribaea* plantation, and even from the 18-month-old second rotation of pine preceded by *Gmelina arborea*.

The question of leaching in perennial crops has also been examined. For instance, a balance was developed between nutrient inputs and outputs in a high-yielding, mature 17-year-old cacao plantation with a leguminous tree shade on a fertile Alfisol in Itabuna, Bahía, Brazil (Table 23). The balance between inputs (rainfall and litter) and outputs (harvest and leaching) was positive for nitrogen, phosphorus, potassium, and calcium and neutral for magnesium. The efficiency of this system is outstanding considering it is operating at very high yield levels. When such plantations are fertilized with N, P, and K, nitrogen leaching losses decrease; this is attributed to a stimulating effect of NPK fertilization on the development of ca-

Table 20. Effects of 10-year growth of various timber species on topsoil (0-30 cm) properties of an Oxisol from Porto Seguro, Bahía, Brazil. (Adapted from Silva 1983.)

Plantation	C (%)	Nutrient level in topsoil (cmol kg^{-1}) Ca	Mg	K
Native rainforest	1.65	0.70	0.50	0.05
Cordia trichotonia	2.18	1.70	0.95	0.12
Caesalpinia echinata	1.40	1.75	1.00	0.13
Dalbergia nigra	1.92	0.95	0.60	0.07
L.S.D. ($P < .05$)	0.23	0.90	0.35	0.03
C.V. (%)	12	35	25	23

Table 21. Annual leaching losses from different stages of tree plantations in a sandy Ultisol of Jari, Pará, Brazil. (From Russell 1983.)

Site	Nutrient leached from soil (kg ha^{-1}) P	K	Ca	Mg
Rainforest, virgin	0.04	12.7	16.7	8.1
Rainforest, logged	0.08	37.1	39.1	16.1
Rainforest, logged and burned	0.21	199.5	103.7	146.6
Pine I, 6 mos. old	0.16	89.9	89.4	74.7
Pine I, 10.5 years old	0.05	9.6	12.1	6.1
Pine II, 1.5 years after 8.5 years of Gmelina I	0.08	9.9	17.5	6.3

cao rootlets, which presumably absorb more nutrients and prevent them from leaching (Santana and Cabala-Rosand 1982). The perspective of such efficient use of nutrients under ideal conditions in perennial crop production predicts the efficiency of well-managed, well-fertilized tree plantations.

Other Options

The information on agroforestry systems per se is not inprogress on alley cropping on acid soils, managed fallows, soil dynamics under natural fallows, and the management of promising indigenous Amazonian palms such as *Guilielma gasipaes.*

Table 22. Annual gain or losses of nutrients, balancing atmospheric input with leaching losses in a sandy Ultisol of Jari, Pará, Brazil. (From Russell 1983.)

Site	Nutrient level changes in soil after 1 year (kg ha^{-1})			
	P	K	Ca	Mg
Rainforest, virgin	+0.10	−2	−0.3	−5
Rainforest, logged	+0.06	−25	−22	−12
Rainforest, logged and burned	−0.06	−181	−84	−137
Pine I, 6 mos. old	−0.02	−80	−73	−71
Pine I, 10.5 years old	+0.06	+1	−1	−3
Pine II, 1.5 years after 8.5 years of Gmelina I	−0.09	+1	+1	−3
Mean atmospheric input:	0.14	10	16	3

Table 23. Nutrient inputs and outputs of a high-yielding 17-year-old cacao plantation shaded by *Erythrina fusca* on a fertile Typic Tropudalf of Itabuna, Brazil (mean of 2 years). (Calculated from Santana and Cabala-Rosand 1984.)

	Nutrient (kg ha^{-1} y^{-1})				
	N	P	K	Ca	Mg
Inputs					
Rainfall	23	3	21	18	12
Litter	112	13	25	162	53
Total	135	16	46	180	65
Outputs					
Harvest 1 t ha^{-1} of wet beans + 1 t ha^{-1} of pods	44	10	20	1	3
Leaching	68	0.5	2	38	63
Total	112	10	22	39	66
Balance	+23	+6	+24	+141	−1

Additional options include the use of forest-agriculture mosaics, *barrial* farming (Sanchez and Benites 1983), water buffalo production in *várzeas* (Nascimento et al. 1979), recuperation of degraded lands (Benites et al. 1984), and others.

Conclusion

Much needs to be learned about these and other soil management options for the Amazon Basin and the humid tropics as a whole. Local validations are essential, particularly in view of different socioeconomic conditions. In spite of present knowledge limitations, it is obvious that *without* appropriate soil management, agricultural development in the humid tropics will result in widespread failures of worldwide dimensions. With appropriate soil management technology *and* infrastructure, agricultural development is feasible and can support sustained farming. For every hectare of humid tropics that is cleared and farmed continuously, many hectares will be spared from the shifting cultivator's ax. This will lessen the pressure for clearing more and more tropical rainforest and therefore promote a balance between cleared areas and rainforest.

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Management of Acid Tropical Soils in the Savannas of South America

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Summary

The environmental features of the acid savannas of South America make them suitable for agriculture. The soil constraints are mostly chemical, with generalized nutrient deficiency and excess of active Al. Subsistence cropping without inputs of fertilizer and lime seems unlikely in the long run. Therefore, any soil-management strategy must concentrate efforts on: (a) decreasing the detrimental effects of soil acidity; (b) building the fertility status, especially that of phosphorus; (c) managing the soil surface properly to avoid compaction and erosion; and (d) improving root growth conditions below the plow layer. The knowledge already available is sufficient to support a cooperative program among research institutions, focusing on soil-management validation. A network should concentrate its efforts on (a) testing the level of extrapolation of actual research results obtained in a few sites, (b) validating the technology already available to solve the main soil constraints, namely liming and phosphate fertilization and, (c) determining the most efficient input level for typical farming systems.

Introduction

The acid savannas cover a significant proportion of the tropical region of South America, especially in Brazil, Colombia, and Venezuela. In Brazil they are locally known as *Cerrado* and in Colombia and Venzuela as *Llanos*. These savannas cover about 300 million ha, much of which could be developed for arable cropping.

Large urban areas are already located in the boundary of the *Llanos* and within the *Cerrado* in Brazil; as a consequence, the demand for agricultural products is increasing. The high potential of the *Cerrado* region for agricultural production

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has been demonstrated, and realization of this potential on a substantial part of the area would meet the regional demands and even produce a surplus.

Agricultural research has occurred only recently in these areas, with most of the results obtained within the last decade and at only a few sites in Brazil and Colombia. This paper is a review of published information, and most of the data used for illustration were obtained either at the Cerrado Agricultural Research Center (CPAC/EMBRAPA), near Brasília, Brazil, or at the Carimagua Experimental Station, of ICA (Instituto Colombiano de Agricultura) and CIAT (Centro Internacional de Agricultura Tropical), near Villavicencio in the *Llanos* of Colombia. The purposes of this review are to (a) describe the environmental conditions of the acid savanna region for food and energy production; (b) summarize actual knowledge related to acid soil management; and (c) suggest areas of cooperation among institutions, especially for technology validation purposes. This paper is largely based on a recent review about management of *Cerrado* soils, presented by Goedert (1983).

Environmental Features of the Acid Savannas

Socioeconomic development differs significantly from site to site within the savanna region. The infrastructure of the southern portion of the *Cerrado* (below 15°S, Fig. 1) is well developed in terms of availability of transportation, market, supplies, and services. This is not true for the rest of the savannas, where infrastructure development is less advanced. In general, however, the infrastructure is already suitable for intensive agricultural activities. Furthermore, heavy investments are actually being made to develop the northern *Cerrado*.

The dominant vegetation can be defined as subhumid wooded savanna, although there is a large variation from pure grassland to closed-tree canopy (Ferri 1977). In general, biomass is less in the *Llanos* than in the *Cerrado*. The most common use of the native vegetation is for extensive grazing, even though wood and charcoal are produced in the more wooded areas. The topography and the soil physical conditions are suitable for intensive mechanized agriculture over half of the South American savanna.

Elevation varies from around 1000 m, near Brasília to less than 200 m in Carimagua (Figs. 1, 2). Variations in elevation and latitude are responsible for the range of temperatures within the savanna areas. The average yearly temperature varies from 20 to 27°C, being higher near the equator and at lower elevations. As shown in Figure 2, the average temperatures of Brasília and Carimagua are 21.3 and 26.5°C, respectively. Because these areas are in the tropics, the average monthly temperature is almost constant throughout the year. Daily solar radiation input is high over the whole area, varying from 350 to 450 Langleys. The temperature and the energy characteristics, therefore, are very favorable for the growth of almost any commercial crop during the whole year.

Total annual rainfall in the region varies from about 900 to 2500 mm; its distribution is characterized by distinct wet and dry seasons, with 80% of the total

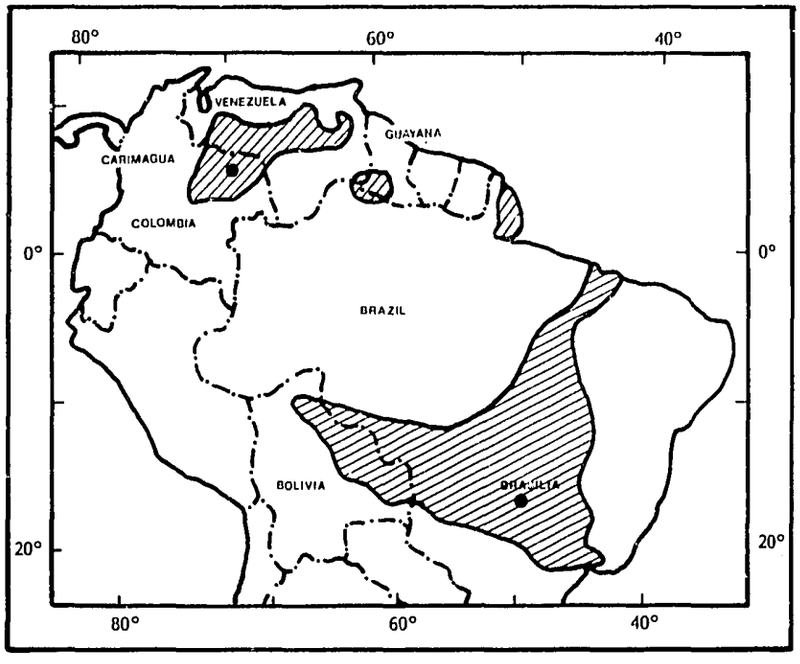

Fig. 1. Approximate distribution of acid savanna areas in South America.

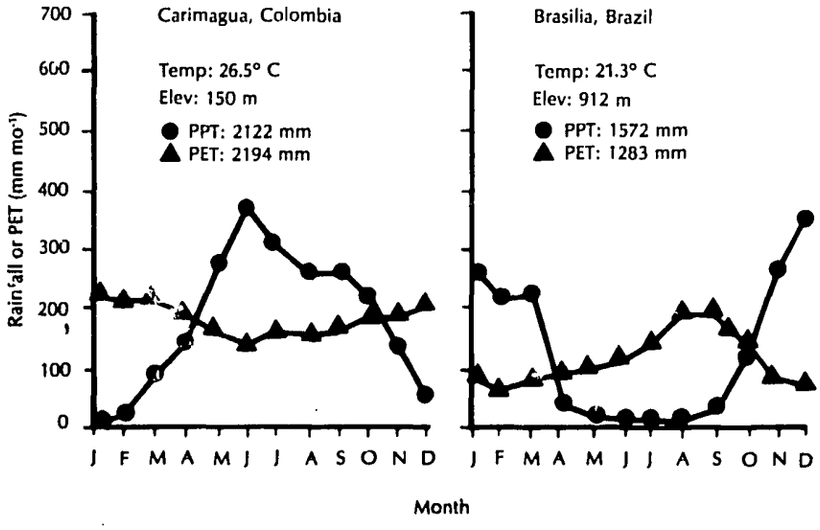

Fig. 2. Climatic summary of two locations of the acid savannas of South America. (From Sanchez and Isbell 1979, EMBRAPA/CPAC 1976.)

Table 1. Some chemical and physical properties of representative soils of the acid savanna areas of South America.

Horizon	Depth (cm)	Clay (%)	OM (%)	pH (%)	Exchange cations (cmol kg^{-1}) Al	Ca	Mg	K	ECEC	Al sat. (%)	Available P (mg kg^{-1})
Haplustox from Carimagua, Colombia[1]											
A_1	0-20	37	3.1	4.9	2.80	0.20	0.20	0.10	3.40	82	0.9
A_3	20-51	39	1.5	5.0	2.00	0.10	0.10	0.10	2.30	85	0.4
B_1	51-82	40	0.8	4.8	1.90	0.10	0.10	0.10	2.20	84	0.9
Dark Red Latosol from Brasília-DF, Brazil[2]											
A_1	0-10	45	3.1	4.9	1.90	0.25	0.15	1.10	2.40	79	1.0
B_1	10-35	48	2.0	4.8	2.00	0.12	0.08	0.05	2.20	89	—
B_2	35-70	47	1.5	4.9	1.60	0.12	0.08	0.03	1.80	88	—
Red-Yellow Latosol from Brasília-DF, Brazil[3]											
A_1	0-15	46	3.4	4.7	1.50	0.60	0.40	0.08	2.58	58	1.0
A_3	15-37	48	2.2	5.0	1.10	0.40	0.20	0.03	1.63	65	1.0
B_1	37-70	49	1.0	5.0	0.90	0.60	0.30	0.02	1.82	47	1.0

1. Spain (1979).
2. Lobato and Goedert (1977).
3. Rodrigues (1977).

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precipitation falling during the rainy season, which is between November and April south of the equator and between April and November north of the equator. The length of the dry season varies within the region from about 3 to 6 months. Short-term droughts (locally named *veranicos*) occur commonly during the rainy season and may be deterimental to crop growth because of the high evapotranspiration rate, low soil available-water capacity, and adverse soil chemical conditions for root growth.

Detailed soil surveys have been made only of parts of the region. Based on this information and on LANDSAT images, extrapolation for the whole region indicates that Oxisols cover more than 50% of the region; the remainder consists mostly of Ultisols, Entisols, and Inceptisols (Freitas and Silveira 1977, Sanchez and Cochrane 1980). Sandy soils may cover as much as 15% of the area.

Most of the soils are loamy or clayey, very deep and well-drained, which, together with very good aggregate stability, makes them easy to cultivate at almost any moisture status. A combination of these factors with the gentle slopes (commonly less than 3%) favors intensive agricultural mechanization. When steeper slopes are cultivated, erosion may become a problem due to high rainfall intensities, and preventive measures must be taken.

Red Yellow Latosols and Dark Red Latosols, most classified in the suborder Ustox, are preferred for intensive agriculture. Their texture is variable, but most are clayey (Table 1). The clay fraction is dominated by kaolinite, gibbsite, and iron oxides (Hughes 1980). The predominance of these low-activity clays is responsible for most of the soil behavior, especially in terms of ion exchange, water-holding capacity, and phosphate-sorption characteristics. Their organic-matter content is greater than in most other soils in a tropical ustic environment and is important, particularly as a source of nutrients.

The cation-exchange capacity of many soils is commonly calculated as the sum of exchangeable cations (Al + Ca + Mg + K) extracted by unbuffered solutions. This index, also known as the effective cation-exchange capacity (ECEC), is very low in most profiles (see Table 1), and most of the capacity is saturated by Al. In some profiles, Al saturation decreases with depth.

Surveys of the status of topsoil fertility show a wide range of clay content, organic carbon, and iron oxides (Lopes and Cox 1977). Uniformly the ECEC is very low, and Al saturation is above 50%, which is considered toxic for most crops (Foy 1974). Exchangeable Ca and Mg are often below the critical level for plant nutrition and, together with high Al saturation, represent major constraints for root growth. Phosphorus is the most deficient plant nutrient: one report stated that 92% of topsoil samples from the *Cerrado* area contained less than 2 ppm P as extracted by the Mehlich I procedure (Lopes and Cox 1977). In addition to low total and available P contents, clay soils have high phosphate-sorption capacities. The amount of P required to obtain 0.1 ppm P in equilibrium solution has been reported to vary from 110 to 405 ppm P (Le Mare 1982, Smyth and Sanchez 1982, Le Mare and Goedert 1984). Deficiencies of Zn, Ca, Mg, N, and S have also been reported (Lopes and Cox 1977, Sanchez and Cochrane 1980).

In addition to acidity and low nutrient status, these soils present a further important soil-related constraint to intensive agricultural development. As reported by Goedert (1983), only 6–8% of the water is retained at tensions less than 1 bar, and almost no available water is retained at higher tensions. This means that these clay soils behave similarly to sandy soils in water retention and that the water stored in the plow layer is sufficient to maintain a crop in full growth for only 8–10 days. This, combined with chemical barriers to root development (high Al saturation and low Ca status), may result in severe yield losses due to water stress during dry periods that occur with varying frequency and length during the rainy season.

In summary, the conditions of the acid savannas are suitable for intensive agriculture, and the soil constraints are mostly chemical.

Major Soil-Management Components

The soils are deficient in (or have very small amounts of) P, Ca, Mg, K, and Zn and contain excessive amounts of active Al. Initially, the mineralization of N is sufficent for moderate yields of nonlegumes (2000 to 3000 kg ha^{-1} of maize [*Zea mays* L.]), providing the deficiencies listed above are corrected.

There are two consequences of these limitations:

1. Even if crops tolerant of the native conditions were found, removal of a very limited number of crops would deplete many of the available nutrients in the soil, and, since all the primary minerals are weathered away, the soil quickly becomes nonproductive.
2. Probably any crop tolerant of the native fertility levels would have a low yield potential and/or rate of growth. Therefore, sustained cropping without inputs of fertilizer and lime seems unlikely in the long run. Recycling of the nutrients is likely to be ineffective because seldom is the recycling quantitative; losses of nutrients by harvest are inevitable. The fact that there is essentially no shifting cultivation practiced in acid soils of the *Llanos* and the *Cerrado* supports the above assertion.

These considerations suggest that crop production requires inputs of fertilizer and lime. In the following section some of the known input-output relationships are discussed. Any soil-management strategy for the acid savannas of South America must concentrate efforts on: (a) decreasing the detrimental effects of soil acidity; (b) building the fertility status, especially that of phosphorus; (c) managing the soil surface properly to avoid compaction and erosion; and (d) improving root growth conditions below the plow layer.

Liming

The constraint of soil acidity can be solved by the joint effort of plant breeding and soil management. There has been a substantial amount of work to breed and select varieties of crops and pasture species tolerant to Al, and some good results

have been obtained (Sanchez and Salinas 1981). In spite of this fact, the soil-management component is very important, due to the low CEC, low Ca status, and low biological activity of soils in their undisturbed state.

In terms of soil management, the first step is the addition of limestone when acid-sensitive crops are to be grown. The positive effects of liming in savanna soils have been reported by several reviewers (Lathwell 1979a, Miranda et al. 1980). A marked yield response to lime is illustrated in Figure 3. The total yield of seven crops was approximately doubled by an application of 2 t ha^{-1} of limestone, and positive responses were observed up to 8 t ha^{-1}. The long-term residual effect of liming was also evident, even at the lowest rate of limestone application (Goedert 1983).

In addition to the changes in pH, Ca, Mg, and Al status, liming resulted in a significant increase of the ECEC, due to the predominance of variable-charge components of the clay fraction. This effect may be significant in terms of nutrient and water retention.

The efficiency of fertilizers is also improved by liming. An example is shown with the response of soybean to phosphate applications (Fig. 4). The change in the shape of the curve suggests that liming decreases the P-sorption capacity. It has been found that the addition of lime to increase the pH to about 6.0 decreases by about 30% the amount of P sorbed nonexchangeably in a Haplustox (Le Mare and Goedert 1984). Recent data indicate that similar effects may be obtained by the incorporation of green manure, perhaps temporarily (Le Mare and Goedert, unpublished).

In conclusion, the experience accumulated in the savanna region shows that the acid soils exhibit high response to liming, which is a consequence of the following effects (Goedert 1983).

a. Supply of the nutrients Ca and Mg;
b. Decrease in Al toxicity;
c. Increase in ECEC;
d. Decrease in P-fixation capacity;
e. Increase in fertilizer's efficiency; and
f. Increase in soil biological activities, such as nitrogen fixation.

Lime recommendations are usually based on exchangeable Al and, sometimes, also of exchangeable Ca + Mg levels. Lime-requirement rates have been calculated according to formulae such as (a) $CaCO_3$ (t ha^{-1}) = 2 × meq exchangeable Al per 100 g; (b) $CaCO_3$ (t ha^{-1}) = (2 × meq exchangeable Al per 100 g) + 2 meq exchangeable (Ca + Mg) per 100 g. Recently, base saturation is being used as a parameter to define lime requirements. The use of rates calculated according to the second equation will result in an increase of the soil pH to values between 5.5 and 6.0, which neutralizes most of the exchangeable Al, but is not high enough to induce deficiency of some micronutrients, especially Zn and Mn. However, if these problems are solved, there may be benefits in increasing the soil pH above

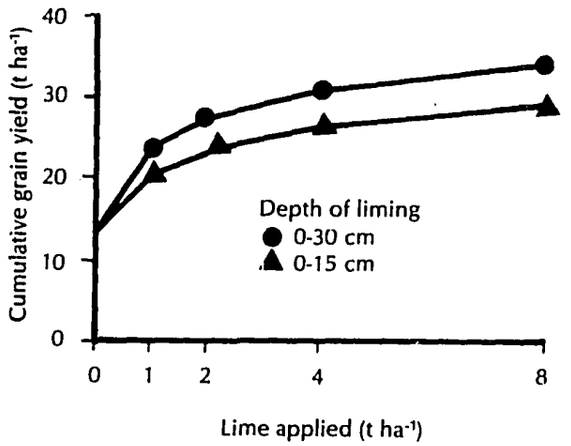

Fig. 3. Cumulative crop performance as a function of rates of lime applied before the first crop, at two depths, on a Typic Haplustox, Brasília, Brazil. A total of seven crops were grown in the experiment: the first three, the fifth, and the sixth were maize; the fourth was sorghum, and the seventh was soybean. (After Goedert 1983.)

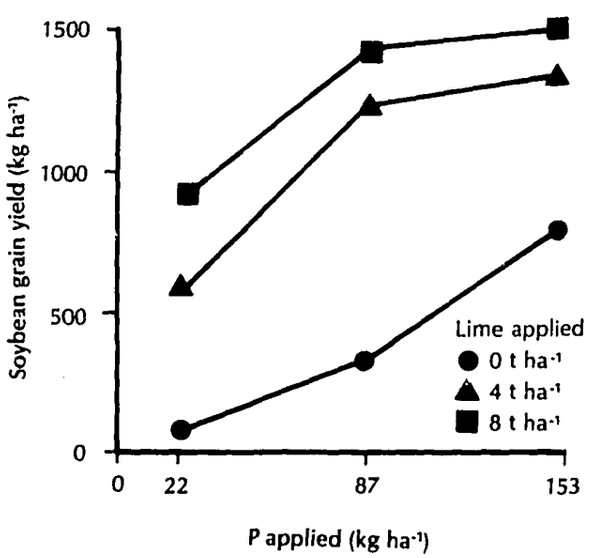

Fig. 4. Yields of soybean grain grown in a Typic Haplustox at CPAC, Planaltina, at three levels of lime and P applications (P as triple superphosphate). (After Le Mare and Goedert 1984.)

6.0. Such recommendations are feasible because there is abundant dolomitic limestone in most of the *Cerrado*, in spite of the high cost of transportation.

The rates of lime required are also closely related to the kind of farming system. A cropping sequence such as upland rice followed by pasture requires smaller amounts of lime than any sequence that includes Al-sensitive crops such as soybean and maize.

Phosphate Fertilization

Total P content of the soils is low, usually between 250 and 350 ppm P per kg of soil (Le Mare 1982), and the P extracted by routine soil analysis procedures is much lower than the level required for most pastures (3–5 ppm P) or grain crops (8–10 ppm P). These figures refer to the Mehlich I method.

The performance of all crops without the addition of P is poor, and large responses are observed with the addition of this nutrient. Typical crop responses to P fertilization in virgin *Cerrado* soils are depicted in Figure 5 with soybean. Similar results were reported for soils of the *Llanos* of Colombia (CIAT 1978).

Figure 5 also illustrates the high potential of these soils for agricultural production, once P deficiency is corrected. However, high initial applications of P are needed to achieve good yields in the initial years of cropping. The cost can be as high as the price of the land in some parts of the region, especially in areas more distant from the fertilizer industries. Hence, improved methods must be found to make the most efficient use of the applied phosphate.

Several approaches can be used to increase P fertilizer efficiency; however, local research indicates four main avenues: (a) minimize phosphorus fixation; (b) determine the best fertilizer rates and placement methods; (c) efficiently use the available sources of P; and (d) enhance P uptake by plants.

Phosphorus fixation can be decreased by the addition of lime and green manures, as mentioned earlier. This can also be accomplished by the application of soluble fertilizer in the form of granules. Much work has been done in the savanna region to study P fertilization rates and placement methods, and several reviews were published (Lathwell 1979b, Sanchez and Salinas 1981, Goedert 1983). On a long-term basis, cumulative crop yields were found to be a function of the rate of P application, independent of the placement methods. Usually, broadcast applications outyielded band application during the first crops, due to enhanced root growth. With subsequent crops, this effect disappeared, as the band-placed fertilizers were mixed with the rest of the topsoil by tillage. In practice, however, the farmer tends to apply fertilizers in furrows at planting time, an intermediate form between banding and broadcasting.

The amount of P needed to obtain commercial yield is often high, as shown in Figure 5. To obtain about 80% of the maximum yield of soybean, several combinations of phosphate rates and placement methods may be used. However, the most effective was the combination of 88 kg P ha^{-1} broadcast initially with 44 kg P ha^{-1} band applied at sowing time for every crop. The final decision for P application, however, will depend on the magnitude of the residual effects.

Another important aspect revealed by the research is the high recovery of the fertilizer phosphate in these high P-sorbing soils. The high residual value makes P fertilization economical (Goedert and Lobato 1984).

Fertilizer recommendation schemes are being arranged as a function of extractable-P levels, soil texture, the level of expected yield, and the kind of farming system. Even though the results so far have indicated that a high initial rate is required for high yields, including the first crop, more work is needed to find the most efficient long-term rates and placement methods with different soils, crops, and farming systems.

One alternative to decrease the cost of P fertilization would be the direct application of local rock phosphates. Studies have shown that Brazilian rock phosphate is of low agronomic effectiveness (Smyth and Sanchez 1982, Goedert and Lobato 1984). Compared with triple superphosphate, the relative efficiencies of four Brazilan rock phosphates (Patos, Araxá, Catalão, and Abaeté) measured over 8 years of cropping varied between 15 and 45%. The results obtained with Colombian rock phosphates (Pesca and Huila) indicate that their agrononic effectiveness is slightly higher (Chien 1981, Hammond et al. 1981). Therefore, the alternative of using local sources of rock phosphate for direct application is limited for grain crops. When used, these sources should be broadcast in conjunction with band applications of soluble superphosphates. Furthermore, they seem to be more useful for crops that do not require large quantities of P for short periods of time, such as tropical pastures.

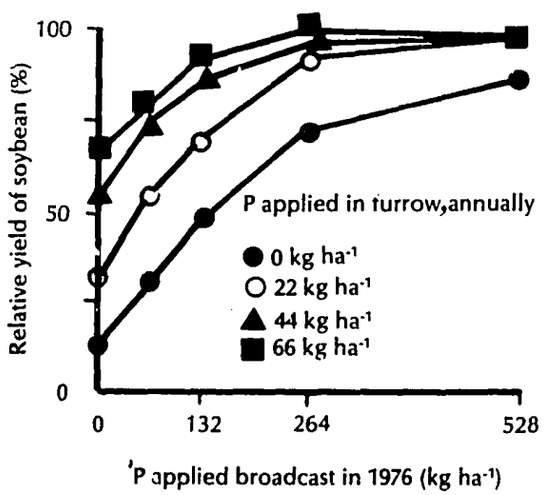

Fig. 5. Cumulative yield of three soybean crops as a function of phosphate broadcast in 1976, superimposed by annual furrow applications on a Typic Haplustox (100% = 7230 kg ha^{-1} of grain). (After EMBRAPA/CPAC 1981.)

Another line of action is to increase P uptake by plants. Most of the crops under cultivation in the savanna region are associated with native species of mycorrhiza; but several exotic species are more efficient in increasing P uptake than native species under controlled laboratory conditions (Mosse and Hayman 1980, EMBRAPA/CPAC 1981). Research is needed to take full advantage of this phenomenon, particularly the technology to produce massive quantities of inoculum and to inoculate this organism on a practical basis in large areas.

The response of crops to phosphate additions is usually measured in experiments where the other nutrients are maintained at adequate levels. However, as shown by Figure 6, this response is strongly affected by the level of N and K. This clearly illustrates that P is not the only deficient nutrient and that attention must be paid to other nutrients, the degree of which vary from one site to another.

Very recently, a network of soil-fertility experiments was initiated to test the extrapolation of results already obtained in several sites, such as at the Cerrado Center. Preliminary data have confirmed a general response to the additions of P, but the degree of it has shown great variation.

Management of the Soil Surface

The savanna soils of South America have good physical properties for intensive cropping. However, poor management can change this situation.

A marked decline in yield of grain crops was observed in some *Cerrado* farms that have been cultivated intensively for 8 to 10 years. Field measurements indicated that soil compaction is a major cause of yield declines. The data presented in Figure 7 show that a compacted layer has developed just below the soil surface. This may be attributed to (a) decrease in organic-matter content, with subsequent aggregate destruction and downward movement of fine soil particles; (b) mechanical compaction by frequent use of heavy machinery, and (c) use of inadequate tillage equipment, year after year, epecially concerning the depth of tillage.

The formation of a compacted layer near the soil surface has drastic negative effects on root growth and consequently on water and nutrient absorption by plants. However, the worst consequence is the decrease in water infiltration with increasing risks of runoff and soil erosion. For example, cultivation for 10 consecutive years decreased the water permeablity from 153 to 48 mm h^{-1} at the site where mechanical impedance data presented in Figure 7 was collected.

This problem can be avoided through proper soil-management planning. When a compacted layer is formed, it can be removed by loosening the soil with proper tillage equipment. As shown in Figure 7, chiseling improves the mechanical impedance in the top 30 cm of the soil layer. This indicates that one alternative for avoiding the formation of a compacted layer is to change the depth and the kind of tillage equipment. In the Brazilian *Cerrado* it is common for farmers to use only a disk plow, thus loosening the same soil layer year after year. Combining the mechanical approach with other agronomic practices, such as the incorporation of crop residues, however, will help prevent compaction and erosion. Research in-

dicates that keeping a crop cover on is very important to avoid the direct impact of raindrops, which disrupts aggregates, compacts the soil surface, and causes soil erosion. An early good soil surface cover can be obtained with the proper combination of several agronomic practices, such as time of seeding, seed quality, and level of fertilization. Reduced tillage practices have also been shown to be useful in decreasing soil compaction and erosion (Mondardo and Dedecek 1980).

Improvement of the Soil below the Plow Layer

Restricted crop root growth in acid savanna subsoils often reduces yields because the volume of soil explored by the roots is not sufficient to supply nutrients and water during rainless periods in the rainy season (Ritchey et al. 1980). Deep growth of roots in subsoils is often inhibited by an excess of exchangeable Al, by low levels of available Ca, or both (Bouldin 1979).

The alternative solution through plant breeding has been important but of limited value, since the chemical constraints of the soil below the plow layer are usually very severe. Aluminum saturation is often above 80%, and exchangeable Ca is below 0.2 meq per 100 g. Root growth of crops is restricted when the exchangeable Ca is less than about 0.15 meq per 100 g (Ritchey et al. 1984).

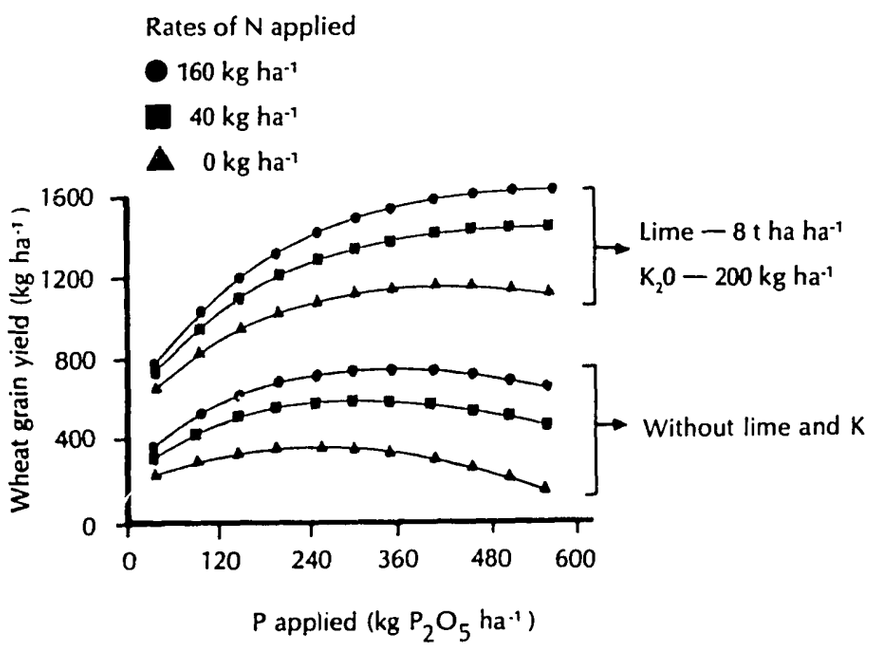

Fig. 6. Response of wheat to phosphate addition to a Typic Haplustox at different levels of N, K, and lime, Brasília, Brazil, 1983. (Courtesy of Dr. P.I.M. Souza.)

The solution to this constraint is closely related to the soil-management scheme. Potentially, there are two alternatives: (a) deep incorporation of lime (and possibly phosphate); and (b) promotion of the downward movement of Ca and Mg in the soil profile.

As illustrated in Figure 3, those treatments in which lime was incorporated deeper gave higher yields than those with shallow application. This was found to be closely associated with enhanced root growth in the 15- to 30-cm layer and consequent nutrient and water extraction from a greater volume of soil (Gonzalez et al. 1979, Lathwell 1979a, Miranda et al. 1980, Sanchez and Salinas 1981). Therefore, deep incorporation of lime is recommended for soils with subsoil acidity and related problems. However, this alternative is limited mainly by the costs of incorporation below the plow layer.

The promotion of "controlled" leaching of Ca and Mg produces positive results. The simple addition of high rates of lime may enhance the downward movement of Ca and Mg with a consequent decrease in Al saturation (Sanchez and Salinas 1981), but this process requires more than 3 years to produce the desired effects.

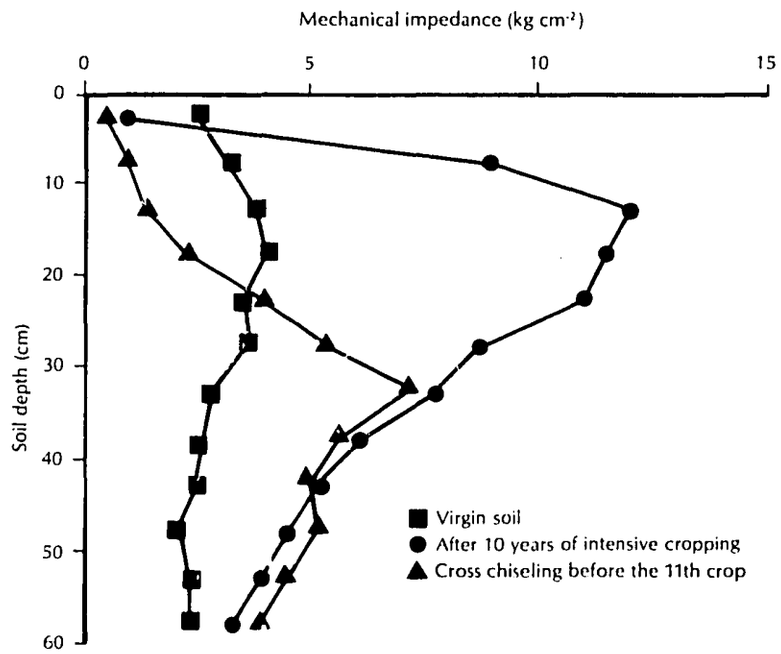

Fig. 7. Mechanical soil impedance of a Typic Acrustox, in virgin conditions, after 10 years of intensive cropping, and with cross chiseling made before the 11th crop, São Gotardo-MG, Brazil, 1984. (Courtesy of Dr. E. Freitas, Jr.)

The speed of the downward movement of cations is closely related to the species of the anion available to move with it. The supply of sulfate anions seems to be adequate for savanna Oxisols (Ritchey et al. 1980). Ca and Mg movement accompanied by sulfate is not as fast as it would be with nitrate or chloride anions, but also not as slow as when accompanied by phosphate, carbonate, and silicate anions.

These findings have been useful to understand why soils to which ordinary superphosphate (OSP) was applied had deeper growth of plant roots than those receiving triple superphosphate (TSP). A practical example is depicted in Figure 8, reflecting the situation of two adjacent *Cerrado* farms after a long period without rain. In one farm soybean was seeded for the first year in a virgin soil, and TSP was the only source of P. All the Ca added through liming was in the plow layer; roots were not able to grow in the subsoil to absorb water (Fig. 8) and, as a consequence, yield was very low. A very different picture could be seen in the second farm where OSP was used and the land was cropped during a 4-year period. With time, Ca moved downward, giving good conditions for root growth and, consequently, good yield, in spite of the same long dry period.

The potential beneficial effects of enhanced root growth below the plow layer, such as recycling of nutrients and increase of the biological activity are also worthy of consideration.

Input Efficiency

So far, the discussion has focused on the potential of acid savannas of South America and the feasibility of solving their soil constraints. There is no doubt that much

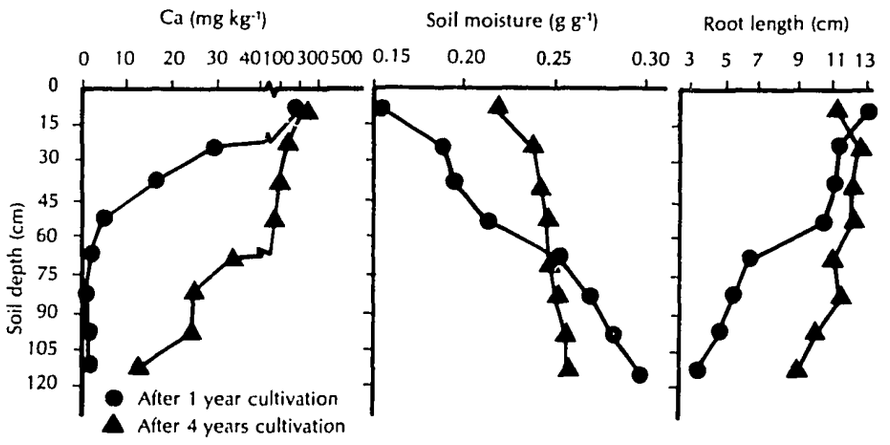

Fig. 8. Exchangeable Ca and soil-moisture distribution in profiles of two neighboring soybean farms after 1 and 4 years of cultivation, and wheat root growth evaluated through greenhouse experiments with soil samples extracted from the same profiles. (After Ritchey et al. 1984.)

of the knowledge and technology available is sufficient to transform this potential into a reality. High yields can be obtained with adequate plant and soil management, even though relatively high inputs are required, especially in terms of liming and phosphate fertilization. Another important question, therefore, is the efficiency of these inputs in an overall analysis of all production factors.

The success of agricultural activities is a function of a harmonic combination of capital, land, and labor. In this way, the most efficient input level is that which best uses the resources and results in the higher economic returns, on a sustained basis.

The adequate level of inputs is strongly dependent upon the kind of farming system and management level of the enterprise. The same level of input can be considered high for one farm and low for another. For example, in rainfed agriculture, the rates of liming and P fertilization mentioned earlier represent a high proportion of the total investment and therefore can be classified as high-input technology. However, for irrigated agriculture, that proportion is low and it may be considered low-input technology.

Futhermore, the efficiency of an input such as P fertilization varies depending on the management of the other inputs and resources. The projections shown in Table 2 illustrate the case of a farmer who has the capital to acquire a limited amount of P fertilizer (12 tons of P_2O_5), but has no limitation in terms of land, equipment, and labor. Therefore he could apply this total amount of P fertilizer

Table 2. Potential production of four soybean farms, located in a Haplustox with high response to P and using the same amounts of P fertilizers, Brasília, Brazil.

	Farm size (ha)			
	300	200	150	100
P rate ($kg\ P_2O_5\ ha^{-1}$)	40	60	80	120
Potential yield[1] ($t\ ha^{-1}$)	0.9	1.3	1.6	2.2
Total grain production ($t\ ha^{-1}$)	270	260	240	220
Costs (t grain)[2]				
Fixed[2]	210	140	105	70
P[3]	48	48	48	48
Total	258	188	153	118
Net income (t grain)	12	72	87	102
Net return per unit of P_2O_5 (kg soybean per kg P_2O_5)	1.0	6.0	7.3	8.5

1. Based on field experiment, for a virgin *Cerado* soil.
2. Expressed in equivalent tons of grain. Fixed costs for 700 kg soybean.
3. 1 kg P_2O_5 = 4 kg soybean.

in any area to all or part of the farm. Four areas were chosen for the illustration in Table 2, with different P rates.

As observed in Table 2, total production is slightly higher when lower rates of P are applied to larger areas, but the net income (total production less total costs) is considerably lower than when a higher P rate is applied to a smaller area. Furthermore, the net return per unit of phosphate applied increases with rate of P application. The first option in Table 2 certainly represents a waste of the phosphate resource as well as a waste of labor, energy, and land, and, therefore, cannot be recommended. The most efficient input level use is to apply 120 kg P_2O_5 ha^{-1} to only one third of the farm fields (see Table 2).

Another way to illustrate P fertilization efficiency is depicted in Figure 9. The actual average yield of soybean in the *Cerrado* is roughly 1.7 t ha^{-1} (point "A," Fig. 9). This average could be improved simply by increasing the rate of P (point "B"). However, if the whole management system were improved simultaneously (better varieties, adequate level of other nutrients, liming, etc.), higher efficiency of P fertilization could be achieved. All yields represented by "C," "D," and "E" are possible to obtain with actual knowledge and, certainly, are more economic than the actual average yield. Such yields could represent a goal to be reached by an IBSRAM soil management network.

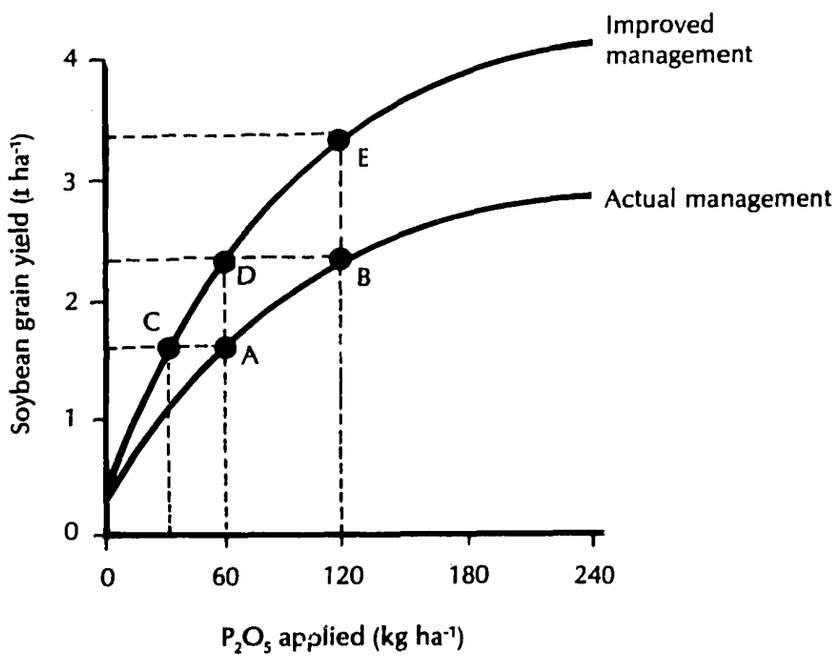

Fig. 9. Schematic representation of soybean response to levels of phosphate fertilization with traditional and improved management practices in acid savanna soils.

Soil Management Network

The acid savanna regions of South America, Africa, and Southeast Asia cover a large area and research is confined to a few sites. Current knowledge, however, is sufficient to support a cooperative program among research institutions.

Even though the potential growing season is longer and the soils in South America have a better structure than do the savannas of Africa and Australia (Jones and Wild 1975, Sanchez and Isbell 1979), the following suggestions for a network may be valid for the savannas of the world.

A network should concentrate its efforts on three main objectives:

a. To test the level of extrapolation of actual research obtained in a few sites,
b. To validate the technology already available to solve the main soil constraints, namely on liming, phosphate fertilization, management of the soil surface, and improvement of soil below the plow layer, and
c. To determine the most efficient input level for typical farming systems.

The first objective can be achieved by exchange of information among cooperating institutions and by the formation of a network of experiments on representive, well-characterized sites. In addition to yield data, detailed information must be collected related to plant, soil, and environmental factors that may affect yield. As a starting point, the variables of these experiments can focus on the major tropical acid soil constraints: acidity and low levels of available phosphate.

To meet the second objective, the validation should also be made at the farm level, thus involving the cooperation of selected farmers. The experiments may use larger areas than traditional research plots, approaching farm conditions. Consequently, the statistical design must be simple. Depending upon the diagnosis of the farm problems, the experiments could combine, for example, two levels of liming with three strategies of P fertilization and with two tillage systems.

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Part 2. Review of Critical Issues

Pedological Research in Relation to Soil Fertility

R.F. Isbell*

Summary

Soil fertility depends not only on soil chemical properties but also on soil physical conditions, which influence root development and activity. Thus, any assessment of soil fertility and transfer of management results has to deal with problems of soil variability and scale. Only limited data on soil characteristics are available for the acid soils of the tropics, however, and transfer usually involves extrapolation or prediction from a field and/or laboratory assessment, which is essentially a point-source evaluation. For transfer, it is usually assumed that if a soil at one site is fully characterized and classified at an appropriate level in a suitable classification scheme, then a soil similarly classified at another site will have essentially similar properties and will behave in a like manner.

Unfortunately, this premise is imperfect to varying degrees: it depends on a high degree of covariance among soil properties; it assumes that the laboratory methods employed adequately identify relevant conditions existing in the field; and it assumes that a satisfactory soil classification system is available. None of these assumptions is universally true. Selected chemical properties of importance to the acid soils of the tropics—P sorption, Al toxicity and low base status, measurement of soil acidity, and cation retention—all highlight the lack of and need for greater and often more appropriate soil characterization. This is necessary to enable functional relationships relevant to soil fertility to be established, and then it will be appropriate and profitable to devise models that can predict plant behavior. Unless these steps are taken, it will not be possible to provide reliable estimates of likely nutrient deficiencies in the widespread acid soils of the tropics, nor to provide realistic means of overcoming them.

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Introduction

Soil fertility is essentially concerned with the growing of plants, but in view of the known differences in plant tolerance to adverse soil conditions, and the diversity of rooting depths of various species, it is obvious that there are many difficulties involved in trying to define soil fertility.

E.W. Russell once remarked that he thought a fertile soil must have the following properties: (a) it must be in an environment favorable for plant growth, (b) it must be a good reservoir of soil water, (c) it must contain a reasonable amount of humus, and (d) it must usually contain a reservoir of inorganic nutrients. Thus, it follows that pedological research in relation to soil fertility will need to be very broad in scope, but, as in the case of soil fertility, there are a number of interpretations of the concept of pedology.

In this paper, pedology is considered to be that area of science concerned with the description, classification, distribution, and genesis of soils. It is obviously not possible in a review of this length to consider the pedological implications of all the factors relevant to soil fertility; accordingly, a selection has been made of several topics of importance to acid soils of the tropics. In particular, this paper highlights our lack of knowledge and understanding of a number of soil physical and chemical properties, indicating that not only is greater characterization of the acid tropical soils needed, but also that further research is required into how the soils in question may be more appropriately characterized. Both these activities are a concern of pedological research.

Problems of Scale in the Assessment of Soil Fertility

Any assessment of soil fertility has to come to terms with problems of heterogeneity and scale of observation. This adds to the difficulty of extrapolation or prediction from a field and/or laboratory assessment, which is essentially a point-source evaluation. For extrapolation purposes, we should consider both individual sites and larger land areas.

At this level, I assume we can relate various chemical and physical measurements of the soil to plant growth and yield—i.e., the amount of a nutrient in the soil measured by some method can be correlated with a response or lack of response by a particular plant being grown in the pot trial, field trial, or farmer's field.

The soil in an individual experimental site up to about 1 ha or a farmer's field of similar size may or may not be uniform, but because of the relatively small size, it is possible, by using a statistically sound sampling technique, to characterize the soil adequately and/or to conduct pot and field experiments, the results of which should apply to the whole area.

Areas of land for extrapolation purposes, on the other hand, may range from tens of hectares to vast tracts such as the *Cerrado* of Brazil. These areas are too large to examine and sample intensively or to conduct the impossibly large numbers of pot trials or field experiments that would be needed.

In such cases the traditional approach has been to conduct some kind of soil survey of the area, group what are thought to be like soils into classes, and sample for laboratory analysis "representative" members of each important class. Additional pot and field experiments might be done on a smaller number of class representatives. In this approach, it is assumed that the soil scientist either creates a suitable soil classification for the purpose or is satisfied with existing national or international soil classification systems. In many cases, either assumption is open to serious question.

Over the past decade or so, soil scientists have become more conscious of the need to assess and quantify soil variability—in particular, to become aware of the substantial short-range variation present in most soils for many properties. Beckett and Webster (1971) summarized most of the earlier literature on soil variability, while Mausbach et al. (1980) gave some more recent references in their study of variability of a large number of paired pedons in the United States. As Webster (1981) noted, one of the tasks of survey is to judge the best compromise between creating many classes to diminish within-class variance and increasing the sampling effort needed to describe those classes adequately.

Recently, geostatistical techniques, which provide procedures to measure the spatial dependence of soil properties, have been used to assess soil fertility and have been applied to soil chemical properties on large land areas, for example on the Island of Hawaii (Yost et al. 1982a, 1982b) and in the country of Rwanda (Vander Zaag et al. 1984).

It is evident that, apart from the small individual site situation, where a plant may be grown under experimental conditions, there are several key assumptions made in attempts to assess the soil fertility status of areas of land.

First, although many soil chemical attributes cannot be observed in the field and must be measured in a laboratory, it is assumed that there is some degree of covariance between these and some other properties, either recognizable or easily measured in the field. For example, perhaps some idea of the P-sorption characteristics of a soil might be gained from other readily determined soil properties. Unfortunately, this premise is not always valid, or at least has not always been demonstrated.

Second, it is assumed that the laboratory methods employed adequately identify relevant conditions existing in the field. Appropriate soil-solution ratios should be used, of course; morevoer, some properties are best measured at the pH of the soil rather than at an arbitrary pH such as 7.0.

Third, it is assumed that traditional soil survey methods can subdivide an area of land into classes about which more definitive statements can be made than about the area as a whole. The first assumption is also involved here, but there may well be conflict in that the soil surveyor's classes could essentially be differentiated on the basis of some characteristic important for his particular purpose (e.g., subsoil permeability), but which may not be related to properties of interest to others. The history of soil survey abounds with such examples.

Fourth, it is often assumed that if a soil at one site is fully characterized (mor-

phologically and in the laboratory) and classified according to some particular national or international classification system at an appropriate hierarchical level, then a soil similarly classified at another site on the basis of the relevant keying characteristics will have essentially similar properties and will behave in a like manner. This is the basis of much agrotechnology transfer by the analogy concept, and a sophisticated testing of this hypothesis was recently attempted under the general title of the Benchmark Soils Project (Beinroth et al. 1980). Unfortunately this assumption is also imperfect to varying degrees, because it also depends on a high degree of covariance among soil properties.

Some Soil Physical Properties Relevant to Soil Fertility

Soil fertility is often viewed entirely in a chemical context. However, the quantity of nutrients extracted by plants also depends on the influence of soil physical conditions, especially the spatial distribution of roots, water, and nutrients relative to one another (Greenwood 1981).

Usually soil profile morphology is emphasized in characterizing and classifying soils; thus, it might be expected that many of these and associated soil physical properties have been adequately quantified. Such is not usually the case, however, particularly in the tropics, and there is a dearth of measured physical properties that are thought to be important to soil fertility, such as bulk density, aeration, hydrological properties such as water-holding capacity, infiltration, and transmission characteristics.

There is also a lack of knowledge about what many of the measured values mean to plant growth in different kinds of soils, largely because of the implicit interrelationships among and between such properties as bulk density, strength, aeration, and soil hydrology. In fact, few areas of scientific investigation are as unintelligible as the relationships among soil physical properties, aeration, and plant growth (Grable 1966). Several examples may be used to illustrate the general problem.

Bulk Density

Data on root restriction in relation to limiting bulk density, all of which are from temperate areas, were compiled, and it was concluded that there is no evidence in the literature of satisfactory root growth at bulk density greater than 1.75 gcm^{-3} in sandy soils and greater than 1.65 in others (O'Connell 1975). It was also claimed that the bulk densities that stop *most* roots of *most* crops in the southern United States are about 1.55 g cm^{-3} for clay loams, 1.65 for loams, 1.80 for sandy loams, and 1.85 for loamy sands (Taylor 1980). If these conclusions hold generally, there are probably many acid subsoils that present problems for root growth. For example, the Ultisols referred to later in this paper commonly have subsoil bulk densities ranging up to 1.7 g cm^{-3} (Adams and Moore 1983, Adams and Hathcock

1984). In the tropics subsoil values up to 1.8 g cm^{-3} in Ultisols and Alfisols have been recorded in Venezuela (Schargel 1977).

Attention has been drawn to the lack of information on the influence of interaction between bulk density and gravel concentration on root development of tropical crops (Maurya and Lal 1979). High concentrations of ironstone nodules occur in some acid tropical soils, and measured bulk density can be high. In such soils there is obviously also an important reduction in available water capacity.

Paralithic Contacts

A good example of a taxonomic criterion that is little understood is the paralithic contact of Soil Taxonomy (Soil Survey Staff 1975). The material below the paralithic contact is non-soil and, although it is not hard in an engineering sense, roots cannot enter. Thus any chemical fertility the layers might contain would have to be regarded as beyond the reach of plants.

Studies of paralithic contacts showed that high bulk density, low water retention, and low hydraulic conductivity were not consistently responsible for the root restriction (Schafer et al. 1979, Paetzold and Mausbach 1984), however. Thus, it was speculated that soil strength properties were responsible, and that at the moment the only way to determine if the material prevented root entry was to actually inspect the profile (Paetzold and Mausbach 1984). While this may be considered adequate in a practical sense, it says little for our understanding of rooting restrictions in soil-like materials, and additional studies of soil strength are obviously needed.

Rate of Clay Increase with Depth

An even simpler example of our lack of knowledge of the importance of some physical properties in soil profile behavior is the rate of clay increase with depth. Clay increase is widely used as a criterion in soil classification (Soil Survey Staff 1975, Northcote 1979). In Soil Taxonomy, clay increase is a diagnostic feature of the important concept of the argillic horizon, but the limits are very wide: in brief, there must be a 3% absolute increase when clay contents in the eluvial horizon are less than 15%; the increase must be 1.2 times or more between 15 and 40% clay; and there must be an 8% increase when contents are more than 40%. The increase must occur within a vertical distance of 30 cm or less.

It follows that the presence of an argillic horizon is thus unlikely to tell us much about the rate of clay increase in any particular profile. Even when particle-size data are available, we are often still unsure of the significance of a clay increase in relation to soil fertility and plant growth through its effect on soil hydrological properties.

The few simple examples given above highlight the need for further study of certain physical properties, particularly in relation to soil hydrology and root growth. As an example more relevent to the theme of this workshop, we need only look

at the general lack of hydrological data for the tropical Ultisols and Oxisols, as shown by the reviews by Lal (1980) and El-Swaify (1980). As so often happens, good data are available for certain limited situations—for example, the Oxisols of Hawaii and the Oxic Alfisols of West Africa—but this leads to over-generalization without sufficient evidence to know if such data are representative of the wider scene.

Selected Chemical Aspects of Soil Fertility

One aim of pedological research is to try to predict chemical parameters relevant to soil fertility without having to measure them every time an answer is required. This usually means that we must keep trying to understand what governs the availability and distribution of nutrient elements in soils, as well as being sure we are measuring the right things in the first place. Additionally, we try to relate chemical conditions to easily observed or readily measured morphological features of soils. This approach, of course, has been used with varying degrees of success for a long time. Probably the earliest correlation made was in equating organic-rich A horizons with good chemical fertility—a generalization we now know is not always true. For instance, some highly organic A horizons may be so strongly acid that they pose severe restrictions on plant growth.

Problems associated with the acid soils that are the subject of this workshop (i.e., excluding peats, podzols, and acid sulfate soils) have been described many times in recent years (for example, IRRI 1980). One study provided a list of a daunting array of major soil constraints and their geographical extent in tropical Latin America (Sanchez and Cochrane 1980), and another presented some data for other continents (Sanchez 1987). The sheer magnitude of these constraints is almost overwhelming, even though the subjectivity of the estimates is stressed (Sanchez and Cochrane 1980). A look at some of these constraints follows.

Problems in Relation to P Sorption

Although there is a voluminous literature on the subject of P sorption, there is little conclusive agreement. This is at least partly due to the complexity of laboratory procedures, which are considerably influenced by experimental variables (Probert 1983). However, high P sorption has usually but not exclusively been related to acid soils with a large surface area and an abundance of "reactive" Fe or Al. For example, a "high P-fixation by iron" modifier was created in the Fertility Capability Classification system (Sanchez et al. 1982), and large areas of tropical Latin America were depicted with this and other soil constraints.

The success or otherwise of the Fertility Capability Classification and related approaches relies on the adequacy of the relationship proposed between P sorption and the free Fe_2O_3 and clay values suggested, and, of course, no quantitative relationship is implied. It is well documented, however, that factors other than iron can be involved. For example, the P-sorption data given for Brazilian *Cerrado* soils (Lopes 1977, Lopes and Cox 1979) show that P-sorption and P-buffering capac-

ity are more strongly correlated with Al than with Fe compounds. In Puerto Rico, P-sorption was found to be more dependent on the goethite and gibbsite contents than on other constituents in highly weathered soils (Jones 1981, Jones et al. 1982).

The response of plants to applied phosphate is complex in acid soils (Haynes 1984). For instance, high concentrations of Al inhibit phosphate uptake and translocation by plants. Hence, liming may be needed, and this, in turn, leads to complex interactions with phosphorus. Many researchers consider the P-sorption approach of Fox and coworkers (Fox and Kamprath 1970) to be the most appropriate, so perhaps attention should be paid to the determination of P-sorption curves by a simple automated procedure. In the meantime, it seems that we must continue searching for appropriate surrogate properties that will enable better extrapolation from limited numbers of P-sorption determinations. Here there is a need for close collaboration between soil chemists and pedologists, so that relationships may be looked for between laboratory results and certain morphological characteristics of particular classes of soils.

Problems in Relation to Exchange Properties

Al toxicity and low base status. It is necessary to consider together the problems of Al toxicity and low base status because in most acid, oxic soils they are closely associated and difficult to separate. There are several aspects to the problem, quite apart from the question of critical values, which are known to vary according to plant species.

In the case of acid surface soils, liming will alleviate both problems. However, effects of liming on modifying subsoil properties may be minimal in the short term. For example, 3 years after liming, there was little effect on ameliorating subsoil acidity in a Nigerian Paleudult even though the equivalent of 0.17 t ha^{-1} of lime was leached from the surface soil in this period (Friesen et al. 1982). Thus we may need to know whether the well-known acid soil syndrome of poor subsoil root development is due to Al toxicity, Ca deficiency, or both. In many publications, the effects of Al and Ca have not been separated, and a large number of experiments in which a response to lime was obtained have tended to relate this to the alleviation of Al toxicity. It might therefore be questioned if various levels of Al saturation quoted as being deleterious are in fact realistic, particularly when doubt can be cast on the usefulness of the widely used KCl-extractable Al in relation to Al toxicity.

From a pedological point of view, two important papers (Adams and Moore 1983, Adams and Hathcock 1984) can be used as examples of some of the difficulties involved. After studying exchangeable Ca, KCl-extractable Al, and soil-solution Al in relation to root growth of cotton, the authors concluded it did not appear that soil classification was going to be very helpful in predicting Ca deficiency and Al toxicity in subsoil horizons of soils in the Coastal Plain of the southern United States. This conclusion was based on the following evidence: in the 1983 study, six Paleudults had similar Al saturation values (up to 77%) in the Bt, E, and EB

horizons and were equally acid (pH 4.6 to 5.5); the E and EB horizons, however, were found to be nontoxic, irrespective of Al solution concentration. Ca deficiency occurred in both eluvial and illuvial horizons, although only in those with Ca saturations of 17% or less. In the 1984 study, generally similar results were obtained on selected horizons of two different Paleudult series.

These authors concluded from the above and other comparisons between woodlands and cultivated fields, in which any given amount of measured Al in the latter was much more toxic than an equal amount measured under woodlands, that the major problem was the inability of the chemical methods—including soil-solution concentrations—to discriminate between inorganic Al and Ca (plant-available forms) and organically combined forms of these ions (plant-unavailable forms).

There has been a diversity of results obtained from using "critical" Al saturation values as an index for Al toxicity (Adams 1984). For example, on Ultisols in the United States, levels ranging from 6 to 25% for soybeans and from 1 to 50% for maize have been obtained. For instance, only maize responded to liming when the mineral soils were more than 70% Al saturated, whereas for soybean to respond the Al saturation had to be less than 30% if growth was not to be limited (Evans and Kamprath 1970).

In view of these diverse results, it is no wonder that the Al saturation criterion based on KCl-extractable Al is being questioned. It has been argued that the concentration of Al in the soil solution is a more appropriate parameter than either KCl-extractable Al or Al saturation. There are still several problems with this approach. Solution concentration studies are ill-adapted to routine determination, and, in spite of a number of successful experiments (e.g., Evans and Kamprath 1970, Carvalho et al. 1980, Pavan et al. 1982), evidence shows that all is yet far from being completely understood (Adams and Moore 1983, Adams and Hathcock 1984). One can only endorse the conclusion that: "It seems clear that more definitive data are needed for either Al saturation of cation exchange sites or soil solution Al activity to be reliable predictors of Al toxicity under a range of soil conditions. The chemistry of solution, exchangeable and solid-phase Al in soils still needs further elucidation (Adams 1984)." Suggestions for the use of Al saturation as a class differentiate in soil classification, then, are probably premature in light of our present knowledge.

Measurements of exchangeable acidity. It is commonly stated that exchangeable acidity in soils is due almost entirely to monomeric Al^{3+} ions (Kamprath 1984, Thomas and Hargrove 1984). Yet many published analyses of soils that are not highly organic or extremely acid continue to show appreciable contents of KCl-"exchangeable" H^+—e.g., the data reported in Adams and Moore (1983) and Adams and Hathcock (1984) where H^+ saturation values of up to 40% at about pH 5.0 have been recorded for Ultisol subsoils with low organic-carbon contents. If combined with Al, these H^+ values considerably increase the "acidity" saturation. Attention has also been drawn to marked differences between exchange acidity

and exchangeable Al, and it was suggested that the two be distinguished (Bruce and Lyons 1984).

Perhaps studies like those of Yuan (1959, 1963), who worked on sandy Florida soils, could profitably be extended to a range of acid oxic soils, and, in addition, the possible interference with Al by Fe in the titration procedure could be investigated.

Cation retention. It is now well known that in many acid soils cation-exchange capacity (CEC), as measured by adsorption of an index cation, depends on the pH at which the determination is carried out. Measurements made at pH values higher than soil pH overestimate actual CEC, and this has led to increasing use of methods aimed at estimating CEC at or near soil pH—e.g., the determination of "effective" CEC by summation of basic cations and acidic cations extracted with unbuffered salts such as 1*M* KCl, or the compulsive exchange method of Gillman (1979).

Investigations using such methods have indicated that most acid soils of the tropics have a low CEC and, hence, little capacity to retain added nutrient cations under prevailing high leaching conditions. Nevertheless, fertilizers will be required to correct deficiencies, and amendments will be needed, especially to alleviate Al toxicity. Our considerations cannot be confined to surface soils, because problems usually become more acute with depth. Recent studies on Brazilian soils (Ritchey et al. 1980, 1982; Pavan et al. 1984) indicate that certain compounds such as gypsum might be very successful in allowing controlled leaching of Ca to the subsoils.

It is important that we better understand the competition between the various cations for the limited number of exchange sites, and the effects of addition of relatively large quantities of one cation on the balance and profile distribution of other cations. Recent research on the charge characteristics of acid tropical soils has led to the development of methods that enable us to better understand the mechanisms by which cations are retained in such soils (Gillman 1984). These kinds of studies now need to be extended to a wider range of acid tropical soils.

Sulfur Deficiency

Several recent reviews suggest a widespread deficiency of S in the acid soil regions of the world tropics (for Latin America, Sanchez and Cochrane 1980; for Southeast Asia and the South Pacific, Blair and Till 1983). Widespread responses to S in these countries and in Africa were listed (Blair 1979). While it is obvious from these reports that S deficiency is very common, it seems impossible on present evidence to realistically estimate the size of areas that may be deficient in S or the likely magnitude of S response. It is clear that most knowledge relates to sites where actual experiments have been conducted, with little extrapolation based on soil analyses.

The first question to be resolved is what kind of soil data is required? There is agreement that plant responses to S are not closely related to total or organic S in soil, whereas the inorganic S in soil, particularly the phosphate-extractable S, has

been successfully related to growth responses by a number of workers (e.g., Probert and Samosir 1983). However, in spite of the fact that sulfate has been known to be sorbed in Ultisols and Oxisols at depth (e.g., Ensminger 1954, Kamprath et al. 1956), there are surprisingly few reports for the tropics which provide sorbed-S data for soil profiles.

A number of workers have reported on the soil chemical conditions required for S sorption (some of these have recently been reviewed by Fox et al. 1983 and Probert and Samosir 1983). It is obvious that conditions favorable for S sorption will not occur in all acid soils of the tropics, nor will S-sorbing soils all do so to the same extent. At present, the lack of data severely limits our understanding of why some soils sorb S more strongly than others and the depths at which sorption occurs. No simple relationships with pH, for example, are likely to be found, in light of the results of Fox (1982).

Because most sorbed S occurs at depth, much of the available literature on responses based on pot experiments with surface soil is not likely to be helpful in predicting areas of S deficiency. More use will perhaps need to be made of indices such as the weighted profile mean proposed by Probert and Jones (1977). In addition, there are some soils that contain large quantities of adsorbed sulfate but are unable to provide a sufficiently high intensity to ensure plants obtain enough S (Fox 1980).

Fox et al. (1983) make the point that although the capacity for sulfate sorption increases with soil weathering, well-drained soils usually will not contain sorbed sulfate, even if such soils have developed considerable sorption capacity, unless sulfate accrues to the soil from outside sources. These authors have discussed some of these sources, but it is obvious there is a lack of data on S inputs for much of the tropics—many areas of which are remote from the sources of man-induced S fallout so common in many temperate areas of the world.

Discussion

Need for Additional Soil Characterization

A constant theme of this paper so far has been the plea for more and better characterization of acid tropical soils. While this may not be strictly considered as research, the fact is that we cannot hope to improve our understanding of many of the properties and interrelationships of soils if we do not have sufficient facts on which to build and test hypotheses. In many instances, we have not yet passed the initial period of discovery, so that the search for functional relationships often cannot proceed simply because of a lack of adequate data.

One approach to assist characterization of soils of the tropics is a statistical one, involving correlation and multiple linear regression. An example of such a study involving 15-bar moisture content, CEC, organic carbon, extractable iron, and base saturation is given for Puerto Rico (Philipson and Drosdoff 1972). Two findings of interest are as follows:

1. Field property equations alone did not explain as large a proportion of the variation of the dependent variable as equations including both laboratory and field properties, yet in most cases R^2 values did exceed 50%.
2. Being able to predict a property in most soils provides no guarantee that it can be reliably predicted in all soils. As examples, clay content provided a poor estimate of 15-bar moisture content in Oxisols, and soil reaction provided a poor estimate of base saturation in Ultisols.

Another approach to the use of soil characterization data as an aid to predict other soil properties involves the use of pattern analyses. Recently, an examination was made of the relative importance of texture, structure, organic matter, and clay mineralogy to the nature of the soil moisture characteristic for an extensive group of Australian soils (Williams et al. 1983). This enabled the soil moisture characteristic to be successfully modelled as a power function, and the error of the model's predictions for 44 horizons based on this simple approach appeared to be only marginally larger than that encountered in conventional laboratory methods. The authors note that given the nature of soil heterogeneity, it can be argued that, following further development, such predictions may be adequate in many hydrological and agricultural applications.

When quantitative relationships relevant to soil fertility have been established, it is appropriate and profitable to devise models that can predict plant behavior. As a simple example, the model of Probert (1985) and Williams and Probert (1984) describing P response is based on principles that describe P behavior in soils, and the effect of climate on plant production. More comprehensive models in which soil, plant, and climate data are being brought together are under development. The IBSNAT proposal, discussed at a recent symposium on minimum data sets for agrotechnology transfer (ICRISAT 1984), intends to use such models in its program. The summaries of discussions at this meeting, however, highlighted the present lack of agreement as to what soil fertility parameters need to be considered as essential for any minimum data set. A related proposal by the International Fertilizer Development Centre (unpublished) calls for the establishment of a Fertilizer Evaluation Data System and Advisory Unit (FEDSAU).

Question of Soil Variability

The question of soil variability has partly been discussed earlier, but unfortunately there have been few studies on soil variability in the tropics. Several aspects were considered in Stelly (1978), and in particular Wilding and Drees (1978, 1983) drew attention to systematic vs. random variation. The former has long been a focus of pedological research, but the latter has had less attention. Of course when the soil system is investigated in greater detail, some of the variation originally considered random may be recognized as systematic. Another aspect is that some variation may be man-made, as suggested for cleared rainforest sites (Sanchez et al. 1983).

Before soil variability can be effectively studied, it is necessary to have a measure of sampling and analytical errors before judgment can be made about differences that may exist among soil samples (Wilding and Drees 1978). One example of such a study of within-pedon variability is given by Patterson and Wall (1982). Similar investigations are surely needed for some of our tropical soil areas. The survey of the vast area of *Cerrado* surface soils in Brazil (Lopes and Cox 1977) gives medians and ranges of a number of properties, but we have no idea of how much short-range variation is present in such a survey. An attempt to give some estimate of the variability of soil chemical properties of relevance to soil fertility has been made (Isbell et al. 1976).

Improved Soil Classification

The topic of improved soil classification was discussed in a previous publication (Isbell 1984), and most of the points made then are relevant to the present discussion. It is heartening that a number of classification problems related to acid tropical soils are being thoroughly discussed by several international committees under the auspices of the Soil Management Support Services to improve Soil Taxonomy in areas where weaknesses have become apparent. Also of importance is the current attempt by Brazil, with its vast areas of acid tropical soils, to revise its national soil classification system. With increasing availability of appropriate data, attempts such as these can only lead to much needed improvements, although we must critically question whether some of the pedological criteria we currently use in soil classifications are relevant to soil fertility.

Concluding Remarks

This paper has looked briefly at the pedological implications of several topics in soil physics and chemistry of relevance to soil fertility problems of the acid soils of the tropics. Many other topics of importance have not been considered, a notable omission being clay mineralogy, which is fundamental to many soil properties. But the message is clear: in spite of greatly increased knowledge obtained over the past decade, many of our tropical soils are still relatively little known and need additional basic characterization by standardized methods now known to be relevant to the particular nature of these soils. Additionally, soils need to be treated as dynamic, three-dimensional bodies. It has been stated that much of the failure in applying science to soil problems has been due to the elementary mistake of confusing soil material (the laboratory specimen) with soil as an individual—i.e., soil in the field. It is in this regard that there must be closer collaboration between physicists, chemists, and pedologists.

The soil fertility problems of the acid soils of the tropics are serious, and although they can be overcome (Sanchez et al. 1983), high inputs will often be required. In view of the generally low level of affluence of much of the world tropics, it is even more necessary that greater attention be paid to more reliable estimates of the likely nutrient requirements of these soils. This will require the establishment

of sound principles, for as pointed out (Nye 1963), unless a more fundamental approach to soil fertility is adopted, the future of soil testing will consist of an endless series of fertilizer trials designed for correlation with an ever-increasing number of hit-or-miss extractions, a prospect most tropical countries do not have the financial and technical resources to contemplate, and one which we would consider to be a denial of the discipline we refer to as soil science.

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The Need for a Soil Fertility Reference Base and Nutrient Dynamics Studies

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Summary

Acid infertile tropical soils, which occupy almost half the potentially arable land in the world, are considered marginal for agricultural production. Examples of previous success in sustained agriculture in these soils, however, demonstrate that, with adequate technology and rational use of lime and fertilizers, it is feasible to use them on a continuous basis. To achieve a real impact in agricultural production on these soils, there are needs for: (1) a concerted research effort in management of their identified constraints; (2) a scientific basis for extrapolation of the results within a country and among countries; and (3) extension of the new technology to farmers. This paper stresses the need for a better linkage of soil classification to soil fertility, suggests some fertility parameters to compose a reference base, and focuses on the need for adequate follow-up of soil dynamics under different management systems.

Introduction

Acid infertile tropical soils, which occupy about 498 million ha of the potentially arable land in the world, are considered marginal for agricultural production. However, the degradation of more fertile soils and the need to intensify the use of new arable land due to population pressures are forcing agricultural development on these soils.

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Despite the enormous area covered by acid tropical soils (700 million ha of humid tropics and 300 million ha of savannas) and despite the differences in these two environments, these soils as a group have common constraints. The magnitude and significance of these constraints, however, vary with the ecosystem and the use and management of these soils (IBSRAM 1984).

A few examples of success in sustained agriculture in these soils (mainly in savannas) demonstrate that, with adequate technology and rational use of lime and fertilizers, it is feasible to use these soils on a continuous basis. If this were done, it would reduce food shortages in the third world. To achieve a real impact in terms of agricultural production on these soils, however, there are needs for:

1. A concerted research effort in management of their constraints;
2. A scientific basis for extrapolation of the results within a country and among countries;
3. Extension of new technology to the farmers.

The preproposal for the Acid Tropical Soils Management Network (IBSRAM 1984) suggested a network that would assist in meeting these needs and proposed six activity areas: (1) pedology-fertility interactions; (2) soil acidity; (3) efficiency of phosphorus fertilization; (4) management of the soil surface; (5) rehabilitation of degraded lands; and (6) soil dynamics in different farming systems. This paper stresses the need for a better linkage of soil classification to soil fertility; suggests some fertility parameters to compose a reference base; and focuses on the need for adequate follow-up of soil dynamics under different management systems in two of these activity areas (pedology-fertility interactions and soil dynamics in different farming systems).

Pedology-Fertility Interactions

Two components of this proposed activity area are discussed in more detail: the linkage between soil classification and soil fertility, and the need for a reference base of major fertility constraints of acid tropical soils.

Linkage of Soil Classification to Soil Fertility

Ideally the two important subdisciplines, soil classification and soil fertility, should work closely together, but experience has shown that such an interaction seems to be much more an exception than a rule. What is more amazing is that most researchers from both subdisciplines appear to accept this situation.

According to Buol et al. (1975), the major difference is one of emphasis. While soil survey people illustrate the existing natural conditions by producing maps, fertility groups evaluate the soil's potential for crop production through soil tests and field experiments. Soil classifiers place more diagnostic value on subsoil characteristics, whereas fertility evaluation specialists are primarily interested in epipedon features.

Although many soil fertility parameters are temporary, it should be possible to cluster classes of such properties. There is some concern that the parameters now employed to define soil classes should be supplemented with some management-related parameters in the new soil classification systems. Inclusion of such parameters should improve the system for technology transfer.

Fertility evaluation specialists once limited their sampling to the plow layer. Currently, due to the imperative need to ameliorate subsoil acidity in areas subject to *veranicos* (periods of drought during the rainy season), sampling depths are changing to include layers as deep as 80 cm (Lopes 1983).

Moreover, it is clear that there is a need for (a) good characterization of all experimental conditions, including monitoring of weather, management variables, and soil properties, and (b) implementation of a technical classification system for soil fertility.

Considerable effort has been expended to define levels of soil characterization, adequately diagnose soil fertility problems, and permit extrapolation of experimental results. The agronomic results of the Benchmark Soils Project suggest that soil families, as defined in Soil Taxonomy (Soil Survey Staff 1975), provide groupings of soils that have (1) relative homogeneity in properties important to plant growth, (2) common and predictable responses to management practices, and (3) similar crop production potential and thus stratify the agroenvironment into distinct niches of agroproduction (Beinroth 1982). The validity of these findings and the need to increase the degree of detail must be tested for acid tropical soils. To do this, some other parameters already in use in the Brazilian Soil Classification System could probably be added to the family level to enhance the degree of extrapolation of knowledge gained from field experiments.

A technical classification system for soil fertility in acid tropical soils is definitely an urgent need. The Fertility Capability Soil Classification System (Buol 1972, Buol et al. 1975), presented in a most recent version in 1982 (Sanchez et al. 1982), seems to be a good starting point. This version should be tested, improved, and consequently adopted in acid tropical soils, probably excluding some parameters not commonly observed in these soils and including others for improved definition of site specificity.

If we really aim to increase food productivity, something must be done to achieve real teamwork involving soil classification and soil fertility. It seems that a good initial approach would be a combination of soil classification of experimental sites at the family level (or preferably at the series level), along with a technical soil fertility classification. IBSRAM can assist in integrating these systems.

Need for a Reference Base of Major Soil Fertility Constraints in Acid Tropical Soils

In many countries in the tropics, yield declines have been observed to result from a decline in soil fertility and inadequate soil management (Lopes 1984). This problem cannot be solved simply by improved crop varieties. The considerable num-

Table 1. Approximate extent of soil-related constraints in the acid infertile soil region of tropical America.[1] (From Sanchez and Cochrane 1980.)

Constraints	Extent of constraint (million ha)[1]						Percentage of total
	Oxisols (512)	Ultisols (320)	Inceptisols (119)	Entisols (88)	Histosols (4)	Total area (1043)	
Physical							
Low water-holding capacity	504	0	0	79	0	583	56
Water stress >3 months	170	35	15	79	0	299	29
Erosion hazard	17	160	47	80	0	304	29
Compaction	0	160	0	9	0	169	16
Waterlogging	0	72	47	0	4	123	12
Laterite	48	71	0	6	0	119	11
Shallow depth	17	11	47	6	0	81	8
Vertic properties	0	0	0	0	0	0	0
Low temperatures	0	0	0	0	0	0	0
Chemical							
P deficiency	512	320	83	83	4	1002	96
K deficiency	512	160	0	40	4	799	77
N deficiency	504	306	71	88	0	969	93
Al toxicity	409	256	18	73	0	756	73
S deficiency	512	160	0	73	0	745	72
Ca deficiency	504	224	0	0	4	732	70
Mg deficiency	496	224	0	7	4	731	70
P fixation	512	160	0	0	0	672	65
Zn deficiency	468	100	0	77	0	645	62
Low CEC	504	0	0	73	0	577	55
Cu deficiency	256	50	0	?	4	310	30
Salinity	0	0	0	0	0	0	0
Alkalinity	0	0	0	0	0	0	0
Fe deficiency	0	0	0	0	0	0	0
Acid sulfate soil	0	0	2	0	0	2	0
Mn toxicity	?	?	?	?	?	0	?
B deficiency	?	?	?	?	?	?	?
Mo deficiency	?	?	?	?	?	?	?

1. Total extent of each order is in parentheses. Question marks indicate insufficient information. Figures are rough estimates subject to change as more information becomes available.

ber of chemical methods used to assess nutrient availability and the divergence in interpretation indicate a need for improved coordination throughout the region. In the past, the International Soil Fertility Evaluation and Improvement Program gave a substantial coordination focus in Latin America in terms of soil testing and plant analysis (ISFEIP 1974). Since its termination a major gap has emerged: there is an urgent need to develop a common language, i.e., a reference base, and common units for expression of results to facilitate communication between researchers in different countries.

In pedology, this situation has been satisfactorily resolved with input from Soil Taxonomy (Soil Survey Staff 1975). Such is not the case in soil fertility, where there remains a strong need for a reference base at the international level to ease information exchange and subsequent agrotechnology transfer. This task must be accomplished without interfering with standard methods presently in use in each country; rather, national methods should be supplemented for international exchange. Additionally, there is a need to create and reinforce national laboratories to execute the reference base methods, as well as to improve precision and accuracy of local methodologies.

Efforts must be made to better use results of long-term field experiments and to increase the probability of success of extrapolation and use of the gathered information. To be avoided, however, is the use of soil classification as a reference base only at the order, suborder, or great group level, as well as routine soil test information from only the plow layer. When one tries to put these data together, the lack of common language and of other important fertility parameters make it difficult to establish a sufficient degree of data uniformity, thus rendering the picture incomplete.

In order to give a first approximation in terms of parameters to be evaluated and propose a reference base for soil fertility purposes, one should examine the main soil constraints in acid tropical soils. A summary of the extent of soil-related constraints, both physical and chemical, in the acid infertile soils of tropical America (Sanchez and Cochrane 1980, Sanchez and Salinas 1981) is given in Table 1. Deficiencies of N and P are, by far, the most limiting soil chemical constraints in terms of percentage of total area. Deficiencies of K, S, Ca, Mg, Zn, and Cu; Al toxicity; P fixation; and low CEC complete the list of major constraints. However, one should also keep in mind the soil physical constraints to food productivity in these soils. Similarly, in humid tropical Africa, Ultisols and Oxisols present low nutrient retention; low reserves of N, P, Ca, Mg, Zn, and possibly Cu; and problems associated with soil acidity (Moormann and Greenland 1980). Similar soil fertility problems occur in acid tropical soils in southeast Asia (Dent 1980).

The similarity of fertility problems across continents suggests similarity of parameters to be evaluated as a reference base for soil fertility. However, it is necessary to stress that some other problems that are less extensive in these soils (Mn toxicity, B deficiency, and Mo deficiency) are critical in specific situations of soil, climate, and crop species.

To give some insight into the potential for a reference base for fertility charac-

terization of acid tropical soils, several points will be discussed. These points should be considered initial guidelines rather than final conclusions.

Nitrogen Deficiency

Available N is defined as N in the root zone in a chemical form readily absorbed by plant roots (Scarsbrook 1965). This N is derived from various sources. In production agriculture, it is primarily from fertilizers, biological N_2 fixation, and mineralization of organic N from wastes, crop residues, and soil organic matter (Keeney 1982). In most Oxisols and Ultisols in the tropics, a significant amount of soil organic N is mineralized during a growing season, mostly due to favorable temperature and moisture environments.

Proposed laboratory indices of soil N availability can be split into biological and chemical tests (Bremner 1965). Beyond furnishing a valid index of soil N availability, a laboratory index method should be simple, rapid, and reproducible and should not be affected by sample pretreatment. The latter requirement in essence rules out biological methods (Keeney 1982).

Total nitrogen and organic carbon are usually poorly correlated with nitrogen response in the field. Because of the lack of a better method, however, many laboratories use these measures to provide some information to farmers (Sanchez 1976). Extractions using $0.01M$ $CaCl_2$ or $1N$ KCl solutions for directly evaluating inorganic nitrogen have been successful under greenhouse conditions (Lathwell et al. 1972); however, few correlation studies between inorganic N and field response have been conducted in humid tropical areas. Recently it was found that the ultraviolet (UV) absorption by $0.01M$ $NaHCO_3$ soil extract at 260 nm was well correlated with the N-supplying capability of eight soils, five of which were Ultisols (Fox and Piekielek 1978). This method is as rapid, simple, and inexpensive as the methods currently used to measure availability of other essential nutrients. If further field studies show this test to be well correlated to the N-supplying capability of Oxisols and Ultisols in tropical areas, it could serve as a reference base for this nutrient problem in routine soil testing. Top priority should be given to finding a reliable reference base for N availability in acid tropical soils.

Phosphorus Deficiency

Acid tropical soils normally possess a limited phosphorus reserve and often have a high sorption capacity (Dabin 1980). Economic application of phosphorus fertilizers should allow P reserves to be increased gradually to improve the fertility level. Adequate interpretation of the results of P analysis is definitely an important step in solving the P problem.

Because there are various methods of measuring available P (the term labile P is preferred, Dabin 1980), published research results must be accompanied by the name of the method used, and, in addition, the data must be calibrated with crop production in the field. The methods that furnish the highest correlations with plant growth and yield are the most suitable for extrapolation purposes.

Methods employing acid extractants have been commonly used for routine analysis in the tropics. These methods appear to be less effective for tropical soils high in sesquioxides, where labile phosphorus consists mainly of Al-P and Fe-P compounds (Dabin 1980). The Mehlich III (Mehlich 1984) method (CH_3COOH, NH_4NO_3, NH_4F, HNO_3 and EDTA at 1:10 soil-solution ratio) seems to extract more P than Mehlich I (Mehlich 1953) (0.05*N* HCl + 0.025*N* H_2SO_4 at 1:5 soil-solution ratio) and has a broader range of applicability (Cox, F.R., personal communication). Mehlich I has serious limitations for soils derived from mafic rocks, areas previously fertilized with rock phosphates, and lowland soils (personal observation). The Mehlich III method should be one of the options for evaluating P status on Oxisols and Ultisols across the tropics in a network fashion. Although more difficult to use for routine purposes, anion resin methods have given excellent results for these soils and should be further tested (van Raij and Quaggio 1983). According to Dabin (1980), anion resin methods are slightly superior to those using isotopic techniques, which are also more expensive and complicated.

Phosphorus Sorption

It is well established that Fe and Al-oxyhydroxides adsorb and desorb P in the soil. Consequently, phosphorus sorption tends to be high and solution concentration tends to be low in most acid tropical soils where these oxidic components are abundant. The quantity factor (sorbed P) plays a major role in plant nutrition. For adequate P nutrition and evaluation of the levels of available P, estimates of the P-sorption capacity of soils are very important.

Likewise, knowledge of the degree of reversibility of P sorption by soil constituents is of agronomic significance because the rate of desorption often is a limiting step in the uptake of phosphorus by crops (Cabrera et al. 1981). Under acid tropical conditions, such knowledge is even more important due to the commonly found extremely low values for available P (Curi 1983).

Measurements of P-sorption capacity are standardized. They depend upon the soil:solution ratio, time of contact, temperature, shaking velocity, and the method of evaluating sorption data. For acid tropical soils, the most satisfactory methods include (1) a soil-solution ratio of 1:20 rather than 1:10; (2) a period of 12 hours of contact; and (3) the sorption data being evaluated assuming two types of adsorption sites by applying the Langmuir two-surface equation (Barber, S.A., Purdue University, personal communication; Curi and Franzmeier 1984). Langmuir equations, however, are probably of limited direct value for agronomic recommendations. Information about how much P fertilizer has to be added to give the critical soil test level is of greater value.

If one wishes to determine P desorption, the samples previously used for P adsorption can be shaken for 12 hours with 0.01*M* $CaCl_2$ (1:20), centrifuged, and the amount of P desorbed taken as that present in the solution after shaking. It appears that four desorption extractions give reasonable insight into the P release rates with time.

Potassium Deficiency

Oxisols are often deficient in K; Ultisols, particularly those under continuous cropping systems, may also reveal K deficiency (Kemmler 1980).

Soil testing and fertilizer trials are used in many countries to obtain knowledge for overcoming potassium deficiency. Careful examination of crop response and soil test data is needed and has been done in some long-term fertilizer experiments (Kemmler 1980). In such cases, K is no longer adequately supplied by soil reserves.

Under tropical conditions, the K status of soils is often evaluated with 1*N* ammonium acetate. In some Latin American countries, "available" K is routinely extracted with the Mehlich I solution (0.5*N* HCl + 0.025*N* H_2SO_4). One important advantage of the 1*N* ammonium acetate and the Mehlich I methods is that they extract other exchangeable cations. Both methods extract about the same amounts of Ca, Mg, N, and K. To improve soil test interpretation for potassium, the soil analysis report should at least contain details on soil texture, effective CEC (as an indicator of clay composition), and pH, as well as qualitative estimates of soil permeability and water regime.

The electro-ultrafiltration method (Németh 1972, 1978, 1979), which measures the desorption rate and its change with time for K and many other nutrients, could be tested further within the IBSRAM network for acid tropical soils. With this method, one can infer the potassium concentration in the soil solution, the quantity of exchangeable potassium, potassium fixation, buffering, and potassium reserves. According to Kemmler (1980), electro-ultrafiltration is the only method that provides a thorough insight into the potassium dynamics (and that of other nutrients) of soils.

Aluminum Toxicity and Subsoil Acidity

The epipedon of Oxisols and Ultisols is generally dominated by exchangeable Al (Curi 1983, IBSRAM 1984). The subsoil in typically kaolinitic soils has an exchange complex that is dominated by exchangeable Al. Also, the typically oxidic soils have an exchange complex that is normally low in exchangeable Al. The high amounts of Al, and at times Mn, and the low contents of Ca, Mg, and other nutrients frequently account for the low productivity of crops grown on these acid soils. Liming and the use of acid-tolerant crops alleviates this constraint.

According to Kamprath (1980), crop production is drastically reduced when Al saturation of the active cation exchange sites is greater than 60%, and it tends to be optimum when this value is nil. In Soil Taxonomy (Soil Survey Staff 1975), base saturation (BS) of the surface soil is used only with the great group Eutrorthox; in all other instances, the BS of a subsurface horizon is used. Thus, one cannot draw any specific conclusions about the base saturation of the surface horizon in Oxisols and Ultisols except in one great group. The Brazilian Soil Classification System, which is being revised, recognizes and names the soils or layers with Al saturation equal to or greater than 50% (allic character) and uses terms such as "epiallic" or "endoallic" for specifying surface or subsurface problems related to

this constraint (Camargo, M.N., personal communication). When the whole profile presents this situation, the term "allic" is used alone. Standard use of this terminology would assist in filling the gap previously mentioned.

Soils with Al toxicity problems can be identified by extracting Al with 1*N* KCl and the exchangeable Ca, Mg, and K with ammonium acetate (Kamprath 1980). Aluminum saturation is normally determined by the expression:

$$\%\text{Al saturation} = 100 \times \text{Al}/\text{Ca} + \text{Mg} + \text{K} + \text{Al}$$

with all cations expressed as meq 100 g^{-1} or meq 100 cm^{-3}, cmol kg^{-1} or cmol L^{-1}. By analogy one can calculate the base saturation of the effective CEC:

$$\text{BS}\ (\%) = 100 - \%\ \text{Al(saturation)}.$$

The importance of this fertility parameter can only be adequately evaluated if there is sufficient information on crop sensitivity and soil properties (Resende and Rezenda 1983).

Calcium and Magnesium Deficiency and Low Effective Cation-Exchange Capacity

In most Ultisols and particularly in Oxisols, the low amounts of Ca and Mg, as well as other nutrients, and a low effective CEC are well known to be major fertility constraints that often account for poor crop productivity. Evaluation of these parameters in subsurface layers should receive special attention. In Oxisols of Brazil, poor root development through the profile is associated not only with Al toxicity but also with low levels of exchangeable and soil solution Ca (Ritchey et al. 1982, 1983). Consequently, it is important to quantify these parameters, especially in areas subject to periods of water stress because of the root development limitations imposed. Technology to increase rooting depth should receive priority in order to achieve efficient agricultural development of these soils.

Although the ammonium acetate extraction only provides information about the quantity factor (exchangeable forms), its advantage, as previously mentioned, is that Ca, Mg, and K can be extracted simultaneously. Its disadvantage is that Al cannot be determined by titration as well.

To complete the cation-exchange capacity evaluation in these soils, it is probably necessary to determine H + Al by using a buffered extractant solution at pH 7.0. Calcium-acetate buffered to pH 7.0 is used routinely for pedology purposes in Brazil (EMBRAPA 1979). The advantage of this determination is that one can calculate the CEC at pH 7.0 by the summation of Ca + Mg + K + (H + Al). This parameter, if we compare with effective CEC, estimates pH-dependent charges and allows further knowledge of the behavior of these soils. For example, one can estimate base saturation (BS) at pH 7.0. This parameter is necessary to calculate rates of lime according to methodologies used now in some states in Brazil (Quaggio 1983, Quaggio et al. 1983).

Sulfur Deficiency

The highly weathered soils that occupy large areas of the tropics have low total S because of low S amounts in the parent materials, extensive weathering, and anion leaching (Blair et at. 1980).

The methods used to extract available S from soil can be grouped into four categories: soluble sulfates, soluble and sorbed sulfates, total and organic S, and microbiological methods. The second category normally is better correlated with S availability to plants than the first. Accordingly, there is a need for correlation studies in tropical areas with specific crops, sulfur extractants, and methods of extraction (Blair et al. 1980). In general, sorbed sulfate is removed by neutral and slightly alkaline extracts and by extractants containing a strong replacing ion, such as a phosphate.

Two extractant solutions suggested (Blair et al. 1980) are (a) sodium bicarbonate at pH 8.5 (Bardsley and Kilmer 1963), which is commonly used as an extractant for available P, and (b) Ca phosphate, because the divalent Ca does not cause dispersion of the clay and organic matter, which may occur when potassium or sodium is used. For laboratories with limited equipment, the barium sulfate turbidimetric method is the commonly used procedure. The instability of the barium sulfate precipitate can be overcome by the use of stabilizers (Blair et al. 1980).

Micronutrients

Zinc, B, Cu, and Mo are the most common micronutrient deficiencies throughout the tropics, whereas Fe deficiency and Mn toxicity are relatively localized (Lopes 1980). A worldwide sampling of acid tropical soils of diverse physiographical, climatic, and landscape characteristics and evaluation of total and available micronutrients in the laboratory and greenhouse are desirable. The approach followed by Sillanpää (1982) is an excellent guide in this regard.

Estimation of micronutrients in relation to soil properties that affect their availability, such as pH, with detailed soil description and characterization, and climatic conditions, can be an adequate approach to extrapolation (Lopes 1980).

Because modern methods of soil analysis for micronutrients such as ICP (inductively coupled plasma-atomic emission spectrometry) are available now, total trace element determinations could be performed rapidly, using solutions generated by mixed-acid digestion (Lechler et al. 1980). Using this method, some data concerning tropical soils are already available (Curi 1983).

Available Zn, Cu, Mn, and Fe could be extracted with the Mehlich III method. Available B is usually determined by hot-water extract (Dible et al. 1954); however, some studies should be conducted using the Mehlich III method. The traditional method for determination of Mo is by extraction with ammonium oxalate at pH 3.3 (Grigg 1953). Data with this method for acid tropical soils are almost nonexistent.

Other Parameters

Organic-matter percentage, pH in H_2O and in 1*N* KCl, and texture are some other parameters that must be included in a reference base for soil fertility. One should not forget, however, some other parameters (climatic, physical, etc.) that are also important considerations in a broad characterization of experimental sites but, in general, are not evaluated. Due to the scope of this paper, these additional parameters will not be discussed; however, at some level of the Acid Tropical Soils Management Network they should be an important component.

Soil Nutrient Dynamics in Humid Tropical and Acid Savanna Ecosystems

Cultivation of acid soils in the humid tropics is preceded by the removal of forest vegetation by one of several land-clearing methods. When burning is involved, soil nutrient levels increase significantly as a result of the ash deposited (Seubert et al. 1977, Dantas and Matos 1981, Smyth and Bastos 1984a). During subsequent cultivation, soil nutrient availability has been observed to decline in proportion to the intensity of land utilization and management. Nutrient dynamics can be defined as the monitoring of soil fertility parameters with time after clearing or initial cultivation.

Differences in native vegetation provide a major distinction between acid savanna and acid humid tropical ecosystems. During land clearing of the savannas, the influence of burning on initial soil nutrient availability is less drastic than that for forests since biomass nutrient reserves for savanna vegetation are lower than those for humid tropical forests (Nye 1958). Consequently, initial productivity for acid savannas is closely related to the magnitude of fertilizer inputs.

In the humid tropics, a continual monitoring of the declining nutrient availability has been used as a guideline for establishing judicious fertilization programs for sustained productivity (Sanchez et al. 1983). In acid savannas, monitoring the nutrient status has been used to assess residual effects of fertilizers such as P (Miranda et al. 1982, Goedert and Lobato 1984), K (Souza et al. 1979), and micronutrients (Galrão 1984). Measurements of exchangeable bases and Al over time of cultivation and soil profile depth in a savanna Oxisol have demonstrated the advantages of Ca movement into the subsoil on root proliferation and soil water utilization (Ritchey et al. 1980).

Nutrient Dynamics Sampling Methodologies

Most of the currently available nutrient dynamics data in the humid tropics has been acquired by two sampling procedures: (1) sampling the same site over time and (2) sampling adjacent areas with known ages at the same time. The latter procedure requires previous knowledge of soil variability within the sampling area, since

variability in time and space are confounded (Sanchez 1984). Variations in climate and the intensity of burning during land clearing in successive years can provide long-lasting effects on nutrient dynamic patterns (Sanchez et al. 1983).

Separation of the effects of different soil management treatments on nutrient dynamic patterns for a given soil and climatic condition often requires special planning. If nutrient deficiencies occur at different times during cultivation, as was observed for an Ultisol in the Peruvian Amazon (Sanchez et al. 1983), then allowances should be made during conception of the study to evaluate the individual nutrient responses as they occur.

This approach was used in an on-going nutrient dynamics study on a Typic Acrorthox in Manaus, Brazil (Smyth and Bastos 1984b). Initial land clearing from primary forest was performed on an area of sufficient size to eventually establish three or four rates (replicated) of each nutrient when soil and plant analyses suggested a probable deficiency. Upon obtaining a yield response to a particular nutrient, all remaining field plots received (or will receive) a uniform application of the nutrient prior to planting the succeeding crop. Once plots were assigned specific nutrient treatments, they were continually monitored for the specific nutrient response, as a means of obtaining continual feedback on residual effects and future reapplications of fertilizers. This approach was used to maximize uniformity in plot management history and to ensure proper correction of previous nutrient problems when evaluating yield responses over time to a particular nutrient.

Factors Influencing Nutrient Dynamics

Land-clearing methods. Land-clearing methods often provide an immediate effect on the initial levels of nutrients in humid tropical soils and, consequently, affect nutrient dynamic patterns. The traditional system of slash-and-burn clearing results in the maximum deposition of ash and nutrients on the soil. The other extreme would be mechanized clearing and removal of vegetation, along with part of the topsoil (Seubert et al. 1977). For an Ivory Coast Ultisol with oil palm plantations ranging in age from 1 to 14 years, soil nutrient levels were higher in the windrows where materials carried by machines were deposited during initial land preparation (Ollagnier et al. 1978).

Post clearing management. Currently available data also suggest that nutrient dynamics are influenced by post-clearing management. Soil nutrient availability appears to decline faster under arable cropping (Sanchez et al. 1983, EMBRAPA 1984) than under pastures (Serrão et al. 1979) or tree crops (Pushparajah 1984; Ollagnier et al. 1978). Groundcover management of interrows in rubber plantations has been observed to positively influence the changes in soil nutrient levels with time (Pushparajah 1984).

Soil properties. The influence of inherent soil properties on soil nutrient dynamic patterns is difficult to assess since the majority of studies performed on dif-

ferent soils also include different management systems. Available soil P levels in *Panicum maximum* pastures in the Brazilian humid tropics have declined more rapidly in clayey than in loamy Oxisols or Ultisols (Serrão et al. 1979).

Soil nutrient dynamics under arable crop production were monitored for the initial 3.5 years after slashing and burning a primary forest on a clayey, kaolinitic, isohyperthermic Typic Acrorthox in Manaus, Brazil (EMBRAPA 1984, Smyth and Bastos 1984b). Changes in nutrient availability for the unfertilized treatments on this soil and on a fine loamy, siliceous, isohyperthermic Typic Paleudult at Yurimaguas, Peru (Sanchez et al. 1983) are compared in Figures 1, 2, 3, and 4. These data reflect some of the differences associated with original soil properties, namely clay and organic-matter content. Phosphorus availability for the Manaus Oxisol was not increased appreciably by the ashes deposited after burning, whereas it was increased for the Yurimaguas Paleudult (Fig. 1). Differences in P-sorption capacity in the surface or layer between the clayey Acrorthox (76% clay) and the loamy Paleudult (6% clay) help explain the observed P dynamics (Fig. 5). Topsoil organic C and total N levels were higher in the Oxisol than in the Ultisol (Fig. 2). Dynamic patterns for these parameters demonstrated a continual decline in the Oxisol as opposed to little change after clearing the Ultisol. These differences may also be associated with texture.

Trends for soil acidity and exchangeable bases over time of cultivation were similar in both soils but differed in magnitude (Figs. 3, 4). Initial increases in soil pH and exchangeable Ca and Mg were larger in the Oxisol and were sustained for longer periods of cultivation than in the Ultisol. Consequently, Al saturation in the Manaus Acrorthox remained lower than in the Yurimaguas Paleudult throughout the initial 2 years of cultivation (Fig. 3). These differences are associated more with the amount of ash than with particular soil properties.

Differences in soil nutrient dynamics between the Oxisol and Ultisol were also reflected in the sequence of fertilizer and lime applications during continuous crop production (Table 2). Aluminum toxicity and Cu deficiency were immediate soil constraints for this Ultisol, whereas P deficiency occurred first in this Oxisol. Additional constraints with N, Mg, B, and S, observed during the initial year of cultivation on the Ultisol, either occurred at later times or were not considered limiting during the 35 months of cultivation on the Oxisol. These comparisons, however, should not be interpreted as differences at the soil order levels, but as differences between two soils with different properties.

Management practices for acid soils in the humid tropics are often evaluated by whether soil properties are improved or degraded with time. Determination of the appropriate practices for the diversity of humid tropical soils will require additional knowledge of how the chemical, physical, and biological alterations occur in soils as a function of soil properties and management systems. Periodic analyses of routine chemical soil properties and selected physical and biological soil characteristics on specific sites and selected management systems would improve the precision of future interpretations.

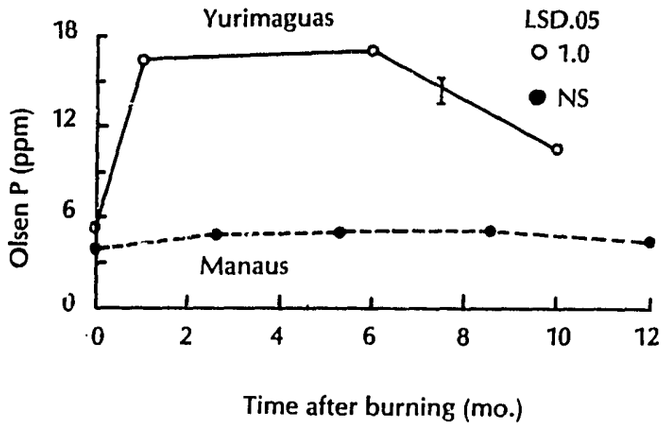

Fig. 1. Amount of phosphorus (modified Olsen procedure) for a Typic Paleudult at Yurimaguas, Peru, and a Typic Acrorthox at Manaus, Brazil. (After Sanchez et al. 1983, Smyth and Bastos 1984b.)

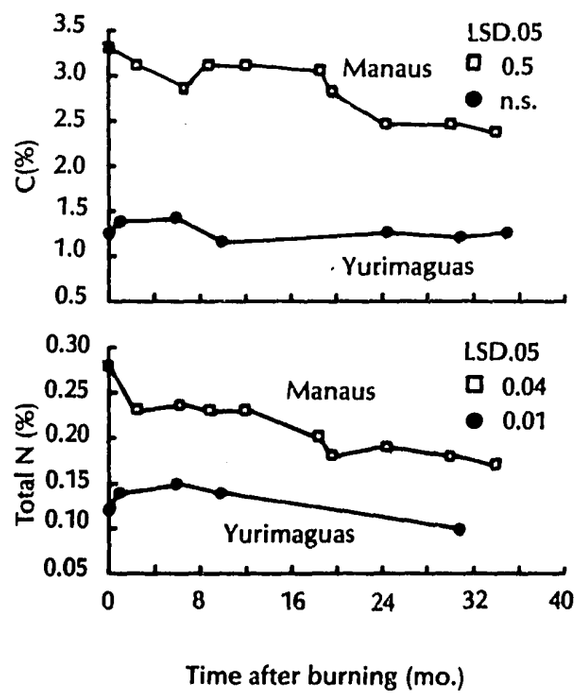

Fig. 2. Percentage of carbon and percentage of total nitrogen for a Typic Paleudult at Yurimaguas, Peru, and a Typic Acrorthox at Manaus, Brazil. (After Sanchez et al. 1983, Smyth and Bastos 1984b.)

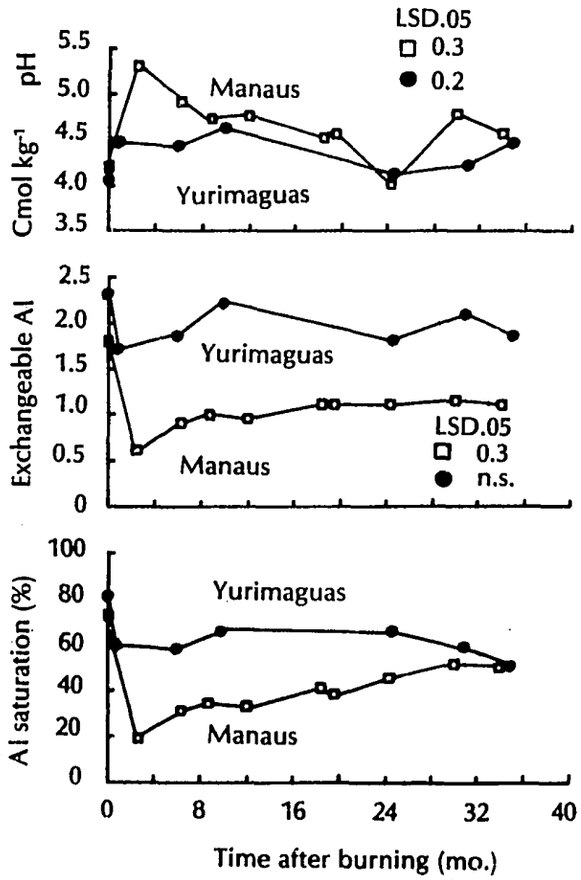

Fig. 3. Amount of soil acidity for a Typic Paleudult at Yurimaguas, Peru, and a Typic Acrorthox at Manaus, Brazil. (From Sanchez et al. 1983, Smyth and Bastos 1984b.)

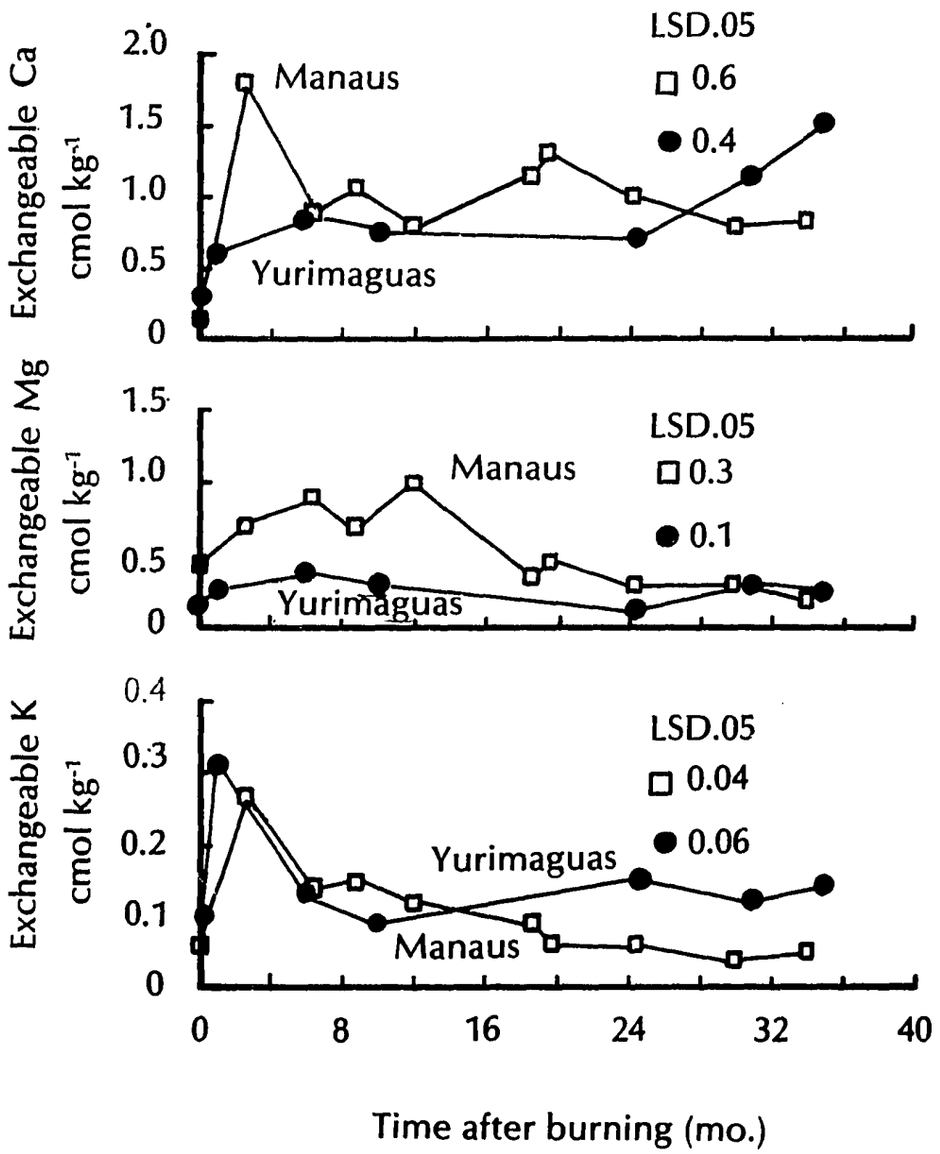

Fig. 4. Exchangeable bases for a Typic Paleudult at Yurimaguas, Peru, and a Typic Acrorthox at Manaus, Brazil. (After Sanchez et al. 1983, Smyth and Bastos 1984b.)

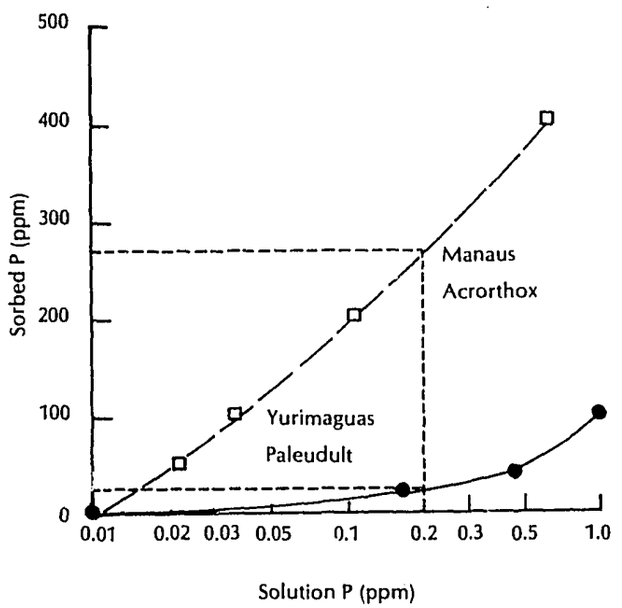

Fig. 5. Schematic representation of phosphorus sorption curves for a Manaus Acrorthox and a Yurimaguas Paleudult.

Table 2. Comparative sequence of soil fertility limitations during 35 months of continuous cropping on a Brazilian Oxisol and a Peruvian Ultisol in the humid tropics.

Constraint	Limitation first occurred (mo. after burning)	
	Oxisol[1] Manaus, Brazil	Ultisol[2] Yurimaguas, Peru
N deficiency[3]	28	6
Al toxicity	18	1
Mg deficiency	None noted	12
K deficiency	9	4
P deficiency	1	10
S deficiency	None noted	6
Cu deficiency	28	1
B deficiency	None noted	6

1. Adapted from Smyth and Bastos (1984b).
2. Data for Chacra II from Sanchez et al. (1983).
3. Differences in N deficiency related to a longer period of cultivation with legumes.

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Surface Soil Degradation and Management Strategies for Sustained Productivity in the Tropics

R. Lal*

Summary

This report reviews the processes and consequences of surface soil degradation of soils in the tropics and suggests management strategies for maintaining a sustained yield. Soil and ecological constraints to increased food production are not unique to the tropics, and drastic increases in production are achievable with ecologically compatible systems of soil management. Although similar to those in northern latitudes, processes and factors of soil degradation in the tropics differ in rates and quantitative limits, which have been only inadequately defined. Surface soil management technologies suggested are those that minimize dependence on purchased inputs and sustain economic production without causing severe damage to the soil resources and environments. In spite of the known constraints, soil resources of the tropics can maintain high production with continuous and intensive cultivation.

Introduction

Are our expectations for productivity of soils of the tropics and their ability to sustain economic yields too high? Can high soil productivity in the tropics be maintained with intensive and continuous farming without causing severe degradation of soil and environmental quality? What are the appropriate soil management and land-use strategies to achieve and sustain productivity? These questions have caused major concern among agriculturists, environmentalist, and planners around the world. Although there is a considerable misuse of the word "constraints," agricultural advances over the past 2 decades in some tropical countries of Asia are

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This paper was invited but not presented at the Workshop.

definitely positive achievements to be recognized. No doubt there are regions with severe food deficits, but the overall achievements in the tropics are impressive indeed.

And yet food production has grossly lagged behind in some regions of the tropics, particularly in tropical Africa. In addition to sociopolitical factors, the causes of this deficit are usually attributed to fragile environments, inherently infertile soils, and severe soil degradation. Some sociologists rightly add that no farmer, no matter where he is, will produce more than his immediate needs unless he is assured of appropriate reward in exchange for his hard-earned farm produce.

Environmental Fragility and Soil Resources

The tropics cover about 40% of the earth's surface, and land resources are sufficient to produce food for the present and future populations (Table 1). Of the total potentially arable land area of 3419 million ha in the world, 789 million are in Africa and 819 million are in South America. Only about 21 and 15% of the potentially cultivable land area is currently being cultivated in Africa and South America, respectively. Considering the possibilities of multiple and double cropping, the gross arable land area is considerably higher.

The predominant soils of the tropics are Oxisols (23%), Ultisols (20%), Entisols (16%), Alfisols (15%), Inceptisols (14%), Vertisols (5%), and others (7%) (Buringh 1979, Sanchez and Salinas 1981). Oxisols and Ultisols are leached acid soils of relatively low chemical fertility. Alfisols, in contrast, have better nutrient status but often poor physical properties. In general many Entisols and Inceptisols have favorable chemical fertility. With the exception of Oxisols, generalized distribution of major soils in the tropics is not drastically different from that found in northern latitudes.

It has become customary to refer to tropical ecosystems as "fragile" and to the soils as easily "degraded" without precisely defining the terms "fragility" and "degradability." The major tropical ecosystems are rainforest, semi-deciduous forests, and tropical savanna. Are these systems fragile? If so, in what respect? The fragility of an ecology refers to its ability to resist drastic changes in its biophysical processes to the state that existed before man intervened. The term "fragility" implies irreversible changes in biophysical processes of anecosystem—i.e., permanent alterations in energy balance, water balance, disruption of cycles of major ele-

Table 1. Land resources of the tropics (million ha). (After Dudal 1982.)

Region	Arable land	Irrigated land	Potentially cultivable land
Africa	163	8	789
Asia	456	134	472
Oceania	45	2	—
South America	124	7	819

ments (C, N, P, K, S), and change in the species diversity and complexity of its flora and fauna. This is a very complex process indeed, and, to be meaningful, these changes, in relation to antecedent soil and environment properties, must be quantified. Similarly, soil degradation needs to be defined in terms of rate of change in soil quality in relation to crop productivity. It is also necessary to understand the critical limits of soil properties that are affected by different land uses and soil management practices and which influence crop productivity. What are the lower limits of soil organic-matter content, porosity, water and nutrient status, and tolerable levels of toxic elements for major soils of the tropics below which crop yield is drastically reduced? Over what time periods do the soils reach these production limits under different land-use systems? How do these limits interact with different levels of soil and crop management? What are the critical limits beyond which a soil is liable to undergo irreversible degradation? It is important to define these limits in order to properly assess the decline of soil productivity in the tropics.

Soil Degradation

Degradation refers to deterioration in soil quality with reference to adverse changes in soil characteristics—i.e., porosity, water retention and transmission, acidity and aluminum toxicity, etc. The degree of soil degradation can be assessed with the knowledge of the tolerable or optimum level of these characteristics in relation to crop production. The tolerable/optimum levels of these characteristics are not only soil and crop specific but also exhibit seasonal variability due to strong interaction with climatic parameters. The generalization of soil degradation, therefore, is difficult without reference to baseline information on soil characteristics and to crop requirements. It is also important to distinguish between the degradation processes and the measurable effects.

Processes of Soil Degradation

Soil degradation processes influence edaphic factors that result in low crop yield. It is difficult to distinguish different processes because of the strong interaction that exists among them. Important degradation processes include the following.

Decline in soil organic-matter content. A decrease in the active soil organic-matter content influences a multitude of soil properties that affect crop yield both directly and indirectly. The adverse effects of a drastic decline in soil organic matter include structural degradation (not a major consideration in Oxisols), low buffering capacity, low biotic activity of soil fauna, acidification, and nutrient imbalance. The rate of mineralization of organic carbon in tropical soils may be about four times as high as in temperate-region soils (Jenkins and Ayanaba 1977), although their total organic-carbon contents are similar.

High soil temperature. Prevalence of a high soil temperature, especially at the onset of rains in areas that have an ustic soil moisture regime, has an adverse ef-

fect on rate of mineralization of soil organic matter, seed germination, crop establishment, and biotic environments (Ghuman and Lal 1981).

Structural degradation. Decline in soil structure is hard to quantify. From the edaphic point of view, soil structure should be defined in terms of porosity (i.e., total volume, pore size distribution, pore stability, and channel continuity). Structural degradation leads to crusting, compaction, decline in infiltration rate, and low water-holding capacity. Decline in structural stability increases soil detachability, which, coupled with low infiltration rate, increases the susceptibility of soil to erosion. High erosion hazard is, therefore, a direct result of structural degradation. Accelerated soil erosion, in turn, influences soil quality, which affects crop productivity.

Clay eluviation. Loss of clay and soil colloids influences water- and nutrient-retention capacity, structural stability, and buffering against acidity. Many researchers (e.g., Roose 1977) have observed the loss of clay to subsurface horizons by percolating water and by interflow. The loss of clay by surface erosion is an important process that influences many other factors of production.

Leaching. Loss of bases and the increase in acidity by leaching are direct results of decline in soil colloids and their water- and nutrient-retention capacities. Decline in soil organic-matter content and absence of deep-rooted perennials enhance this leaching process and result in soil acidification.

Consequences of Soil Degradation

The results of soil degradation are the direct consequence of the degradative processes listed above. Soil mismanagement results in a decline in soil organic-matter content and the effective cation-exchange capacity, reduction in water- and nutrient-holding capacity, overall soil compaction and decline in macroporosity and transmission pores, lack of oxygen in the root zone, and frequent occurrence of moisture deficit. This degradation process is set in motion by man's intervention in his quest for producing more food and is further accentuated by accelerated erosion. The results of soil degradation include the following.

Soil compaction. Soil compaction is a more severe problem than hitherto anticipated, particularly in Ultisols and Alfisols with sandy tropical textures. The soils with low-activity clays have slight or negligible shrink/swell capacity. Decline in soil organic-matter content, degradation of soil structure, and drying accompanied by high soil temperatures generally lead to consolidation and compression by mechanisms not well understood. Over and above these factors is the compactive effect of heavy machinery. It is estimated that some 90% of the soil surface may be traversed by tractor wheels during, for example, the primary tillage operations (Soane 1975). Smearing at the plow sole creates a pore discontinuity that inhibits water movement and root development.

Characterization of soil compaction is another problem that is particularly severe for heterogeneous gravelly soils. The usual criteria (such as bulk density, to-

tal porosity, and penetrometer resistance) are not the best indicators of the problem that plant roots experience. Perhaps the void ratio, the specific volume, air and water permeability, or pore size distribution and continuity may be better indices of plant response than the bulk density. The available research information on these aspects for soils in the tropics is rather scanty.

Soil erosion. Degradation in soil structure and the absence of the protective vegetation cover are the processes that lead to accelerated soil erosion. Because of low inherent fertility and skewed nutrient distribution in the profile, even a low level of soil loss can result in a drastic reduction in soil productivity if corrective measures are not undertaken. The soil loss tolerance of many soils may be as low as 0.5 to 1 t ha^{-1} in coarse-textured Alfisols (Lal 1983).

Excessive leaching and the resulting acidification are the direct results of decline in water- and nutrient-retention capacity due to structural degradation and decrease in the soil organic-matter content.

Processes and results of soil degradation in the tropics are similar to those in the temperate regions, although there can be noticeable differences in the rates of the various processes involved—e.g., decomposition of organic matter, high rate of erosion in some soils, soil compaction, and so on.

Basic Principles of Soil Surface Management

It is generally recognized that most plant nutrients in the ecosystem are bound in the standing biomass and in a few centimeters of the soil surface. If vegetation is cut, removed, or burned or if the soil surface is eroded or scraped off during clearing, the soil loses most of its nutrient reserves and inherent fertility. Coarse-textured Ultisols and Alfisols are easily compacted after land clearing (Seubert et al. 1977, Lal and Cummings 1979) and their structure deteriorates rapidly. This is followed by a drastic reduction in infiltration and in high rates of sediment-laden runoff (Lal 1976, 1981). High soil temperatures on cleared land is generally less than optimum (Lal 1974, McCown et al. 1980), and drought stress is often seen in the humid tropics for shallow soils with low root volume. Coupled with high incidence of pests and diseases, it is not surprising, therefore, that attempts at modernizing tropical agriculture have met with only limited successes.

The soil degradation process is set in motion by the drastic change in soil and microclimatic factors caused by cultural practices that result in soil exposure and disturbance of the soil-vegetation-climate equilibrium. This implies that the protective native vegetation cover should be removed with the least possible disturbance. Furthermore, as the soil is protected when covered by the forest canopy, it should be continuously covered after the forest cover is removed and during the cultivation phase. This can be achieved by replacing the forest canopy with a low canopy cover that will protect the soil against impacting raindrops but not shade the seasonal crops. Furthermore, the soil should not be disturbed by mechanical manipulation. Maintenance of active soil organic matter is an important factor in preserving the fertility level of the soil, stabilizing soil structure, and stimulating

Table 2. Possible techniques for decreasing runoff volume and peak runoff rate.

Soil	Principle	Technique
Structurally unstable coarse-textured soils, in subhumid regions.	Prevent surface sealing and raindrop impact.	Mulching, reduced tillage, cover crop.
Soils with low activity clays and coarse texture, in semiarid to arid regions.	Increase surface detention.	Rough cloddy surface by plowing at the end of rainy season.
Loamy to clayey-textured soils easily compacted.	Improve infiltration.	Vertical mulching, chiseling.
Good-structured soils. Soils with well-aggregated, stable structure.	Prolong draining time.	Tied ridges, contoured ridge-and-furrow system.
Vertisols; soils with expanding clay minerals in arid regions with short rainy season.	Maintain soil surface at moisture potential above the hygroscopic coefficient and reduce heat of wetting.	Mulching, soil inversion just prior to rain.
Vertisols; soils with expanding clay minerals in semiarid or subhumid regions with long rainy season.	Dispose water safely and recycle for supplementary irrigation.	Graded ridge-and-furrow system with grass waterways and storage tank, camber bed technique.

biological activity, including that of earthworms. It is more effective to leave organic matter on the soil surface than to incorporate it into the soil by plowing or other mechanical operations. Deep-rooted perennials should be grown in association with the shallow-rooted annuals so that they absorb the water and nutrients from different horizons. An orderly arrangement of annuals with perennials may help facilitate farm operations and crop management. The overall objective is to develop methods that (a) avoid soil degradation and enable economic crop yield, (b) optimize soil physical conditions to attain the potential yield, and (c) increase output per unit of purchased inputs.

Considering the socioeconomic conditions and financial resources of the small-scale farmers concerned, the emphasis is on low-input, self-sustaining, and ecologically compatible technologies. The appropriate land-use and soil management systems are those that sustain economic yields rather than those that produce only short-term high returns. The objectives of soil surface management are to preserve or restore and sustain soil productivity, maintain ecosystem stability, and optimize biophysical environments, by adapting crops to the specific soil environments.

Soil and Water Conservation

Soil erosion is caused by particle separation via raindrop impact and by overland flow. Many soil and water conservation technologies can be combined to reduce soil erosion and water runoff within acceptable limits. In addition to controlling soil splash by use of a vegetative cover, decreasing runoff volume and peak runoff rate are important factors in controlling soil erosion. Basic principles of runoff control are listed in Table 2. The emphasis is on preventive measures based on soil surface management rather than on engineering techniques of safe disposal of surplus runoff.

Alternate Management Strategies

For soil productivity to be maintained, it is necessary to prevent or control erosion, maintain adequate levels of soil organic-matter content, prevent slaking of the soil surface and improve aggregate stability, provide favorable soil temperature and moisture conditions, and adapt suitable packages of agronomic practices that sustain economic production. Regular additions of a sizeable quantity of organic residues are beneficial to improve soil structure in most soils and to preserve nutrient- andwater-retaining capacities. The basic ingredients of improving and maintaining high agricultural production are:

1. Liberal use of crop residue mulch (except where there is a high hazard of disease build-up);
2. High frequency of legume cover in the cropping sequence;
3. Use of no-till or minimum tillage systems;

Table 3. Possible strategies for soil surface management for sustained production on small-scale farms in tropical soils.

Structurally active soils	Structurally inert soils
(a) 1. Grain crop—cover crop rotation 2. No-till or minimum tillage method 3. Minimum inputs of chemical fertilizers	(a) Contour ridges
(b) 1. Grain crop—alley-cropping 2. No-till or minimum tillage method 3. Minimum inputs of chemical fertilizers	(b) Tied-ridge system
(c) 1. Integrating livestock with food crop production 2. Pasture in rotation with food crop production 3. Growing woody perennials to supplement feed during dry season	(c) Periodic subsoiling or chiseling to loosen the soil
(d) Agroforestry systems of growing food crops in association with perennial cash crops during the initial establishment phase. The food crops to be grown with system (a) above.	(d) Alley-cropping based on appropriate perennial species
(e) Strip-cropping with growing alternating strips of soil-conserving crops with grain crops. The grain crops to be grown with system (a) above.	

Table 4. Possible strategies for soil surface management for sustained production on large-scale farms.

Structurally active soils	Structurally inert soils
(a) 1. Grain crop—cover crop rotation 2. No-till or minimum tillage method with periodic loosening of subsoil by chiseling or paraplow when needed 3. Planting trees or woody perennials on 1-m contours	(a) 1. Contour ridges following plowing 2. Terraces to control erosion
	(b) 1. Tied-ridge system 2. With or without terraces
	(c) Permanent ridge-furrow system following minimum tillage
(b) 1. Integrating livestock with food crop production 2. No-till farming for grain crops following a lightly grazed pasture	(d) Plowing at the end of rainy season and minimum tillage at seeding

4. Effective nutrient recycling systems by incorporating weedy legumes with deep taproot systems in the crop rotation;
5. Decrease in the number of passages of heavy machinery on the soil surface.

These principles encompass biological means of fertility maintenance. The other strategy of soil surface management is based on mechanical means of erosion control with contour ridges or the tied-ridge system. The two management strategies are not necessarily mutually exclusive. Management strategies for small-scale and large-scale farmers are listed in Tables 3 and 4. Biological systems of soil surface management are advocated for subhumid and semiarid regions with structurally stable soils. Mechanical measures of structural improvements may be needed for regions where soils are naturally compacted and have massive structure.

Improved Technology

Experiments conducted at IITA (Lal and Kang 1982, Lal 1983), in tropical America (Sanchez et al. 1982), and elsewhere have indicated that gradual improvements in the shifting cultivation system is preferred over methods that involve drastic and abrupt changes. The basic principle is the least disturbance of the soil-plant-climate equilibrium. This can be achieved by replacement of a forest canopy by a ground cover such as mulch or a cover crop, which will permit food crop production without exposing the soil to the vagaries of the weather. A package of cultural practices to help achieve this includes:

1. Increased production on existing lands, thereby reducing the need to clear new lands for farming.
2. Manual clearing of land over mechanical clearing. If land is cleared mechanically it is advisable not to:
   a. Remove litter, roots and stumps,
   b. Scrape off the surface soil,
   c. Compact the subsoil, or
   d. Drag trees and stumps over long distances.
3. Maintaining a continuous supply of organic additions to the soil surface through one or a combination of the following agronomic practices:
   a. No-till or reduced tillage systems with crop residue mulch,
   b. Leguminous/grass crop covers in the rotation to produce *in situ* mulch,
   c. Growing seasonal/annual food crops in association with deep-rooted woody perennials by practices such asalley-cropping, agroforestry, etc.
   d. Integrating livestock with food crop production.
4. Effective use of water, nutrient, and light resources through appropriate crop sequences and crop combinations. A continuous ground cover that

will use these limited resources and to protect the soil from rain and sun can be maintained through:

a. Mixed cropping,
b. Relay cropping,
c. Multistoried crop association,
d. Ley farming (resting the land in a grass fallow).

For small landholders in the tropics and subtropics it is vital to minimize the dependence on agrochemicals and other capital intensive inputs. While it is true that high yields cannot be achieved without these inputs, agronomic practices should be developed that can drastically reduce the fertilizer and chemical (herbicides, pesticides, etc.) needs and yet maintain good yields. These techniques have proven successful on research farms and research-managed on-farm plots. Their effectiveness needs to be evaluated for a wide range of ecologies by adaptive problem-solving research. Improved cultivars and chemicals are easily wasted if effective conservation measures are not adopted.

Conclusions

About 15 years of research in tropical agriculture conducted at IITA and other national and international centers supports the conclusion that most tropical soils can be intensively cultivated and can produce high levels of economic yields without severe degradation of the soil and the environment. This is based on the soil and crop management techniques developed specially for this ecology and that have been evaluated and proven successful under the socioeconomic conditions of the small landholders in the tropics. Some of these potentially useful agronomic techniques listed in the previous section need to be evaluated and adapted for a wide range of soils and environments. The best production potential of the tropics can be explored and food production can be dramatically increased.

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Efficient Use of Phosphorus Fertilization in Acid Tropical Soils

Manuel Arca*

Summary

Acid soils of the tropics are often very deficient in phosphorus, and those with loamy or clayey topsoil textures often fix large quantities of P. There is a need to increase the efficiency of fertilizer-P utilization. This paper reviews the prospects of doing so by (1) improvements in soil test interpretations, (2) utilization of phosphate rocks either in their natural state or with partial acidulation, (3) selecting the most appropriate rates and methods of application, (4) the use of lime to increase P availability, and (5) the enhancement of mycorrhizal associations.

Phosphorus Constraints in Tropical Soils

Acid soils of the tropics are usually deficient in available P. This is the result of low P reserves and the dominance of occluded and organic forms over more active forms of P.

Fairly constant ratios are reported among the various forms of P for highly weathered tropical soils (Dabin 1980): active forms account for 10–20% of the total P; organic forms account for another 10–20%; and occluded forms account for 50–80%.

The potential for increasing P availability by water-soluble phosphate application is limited by the high P-fixing capacity of highly weathered soils of the tropics with topsoil of loamy or clayey textures. Although utilization of fixed P by plants following P application depends on the nature of the chemical and mineralogi-

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cal species formed, it is generally accepted that "fixed" P availability to plants is limited. Biological immobilization of P also occurs as a result of P incorporation into microbial bodies and parts of living plants, but this process is reversible and contributes to increased P availability upon decomposition.

Another factor that contributes to limited use by plants of P reserves in acid soils is the limited volume of soil explored by roots of nonacid-tolerant species. This is mainly the result of the practical difficulty of deep lime incorporation necessary for a good root system development. Moreover, due to high ambient temperature and udic soil moisture regimes often encountered in tropical environments, high crop growth rates cause high P requirements during part of the growth cycle. To meet the requirements of fast-growing crops, a rather large pool of soil P must be present, with a potential for fast rate of transfer of P from the soil surface to the soil solution.

Interpretation of Soil Tests for Efficient P Fertilizer Recommendation

The amount of P fertilizer required by crops and pastures when P-poor soils are put into production can be deducted from experiments performed at other sites with similar soil conditions. Surface soil properties are expected to be quite similar in soils of the same series, in their natural state. After several years of cropping and fertilizer application, topsoil properties are intensively modified and fertilizer rates required for annual or perennial crops might be quite different from those determined for virgin soils. Then soil tests for available P become important.

Because of the variation in surface soil texture and mineralogical properties found in tropical soils, soil test procedures and interpretation should be adapted to the soil variability of the region in which they are used.

Some soil test procedures widely used in many countries extract very little P in acid tropical soils and do not allow clear interpretation. Adaptation of presently used soil tests or development of new procedures has been found necessary in some tropical regions for better assessment of available soil P and fertilizer recommendations (EMBRAPA 1982, CIAT 1983).

The increased use of phosphate rock as a source of P for crops and pastures in acid soils of the tropics imposes more limitations to soil test interpretation. For instance, it was found that the Mehlich I procedure extracted considerably more "available" soil P than the Olsen and Bray I methods in field plots in which phosphate rock had been applied 15 months before sampling (Yost et al. 1982). The amount extracted by Mehlich I in plots receiving ordinary superphosphate was lower than in plots receiving phosphate rock. With other extractants, the situation was reversed. Results emphasize the need for a soil test procedure that works independently of previously applied sources of P or for separate interpretation of soil test results for samples obtained from plots with different fertilizer source history.

Phosphate Rocks

Direct use of nonwater-soluble phosphates as a means to diminish important P fixation in acid tropical soils has been advocated. The reactivity of phosphate rocks from different sources, however, is extremely variable depending on origin and structure.

Where highly reactive phosphate rocks are available at price competitive with other sources, there is no reason for utilization of other sources of P. Phosphate rocks available throughout tropical America present different reactivity, the most reactive being the one from the Bayovar deposits of the northern coast of Peru. Low reactive phosphate rocks require higher rates of total P applied and a long time of contact with soil to be comparably efficient to water soluble sources of P.

The agronomic efficiency of several phosphate rocks measured in greenhouse studies is shown in Table 1. Some phosphate rocks become more efficient with time, possibly being as efficient as superphosphate after 3 or 4 years.

Partially acidulated phosphate rocks have been proposed for use in acid soils with high P-fixing capacity. The potential use of these products to reduce P fixation and to increase agronomic values of phosphate rocks appears attractive. It has been found that there is an additional solubility of phosphate, as a result of the presence of the untreated fraction of phosphate rock and the water-soluble phosphate produced by the partial acidulation (Mokwunye and Chien 1980), but results must be tested under field conditions (Fig. 1).

The selection of the most attractive option as a source of P depends on the kind of phosphate rock available in the region, its agronomic effectiveness, and its price in relation to more efficient sources of phosphate. Considering phosphate rocks as a nonrenewable resource of which there are limited reserves on earth, maximum efficiency in their use should be made in selecting the method of utilization.

Table 1. Relative agronomic efficiency of phosphate rocks in an Oxisol with *Panicum maximum* in a greenhouse experiment. (After Chien and Hammond 1978.)

	Relative agronomic efficiency (%) of applied phosphorus at rates of:		
Rock phosphate	100 mg kg^{-1}	200 mg kg^{-1}	400 mg kg^{-1}
Fosbayovar	132	110	103
North Carolina	100	100	100
Gafsa	106	89	89
Florida central	69	64	61
Hinla	63	49	50
Pesca	36	36	33

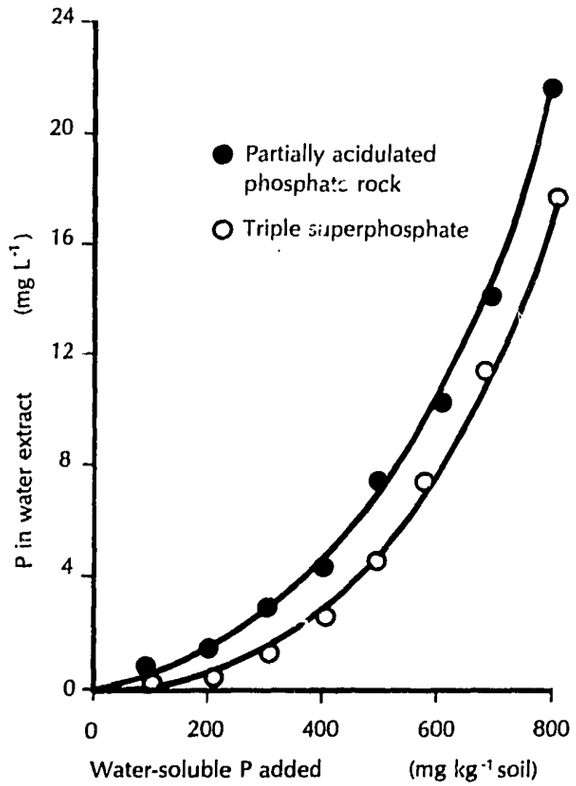

Fig. 1. Water-extractable P in the Gaviotas soil (Oxisol, *Llanos orientales*, Colombia) after shaking at 20°C for 1 week with equal amounts of water-soluble P as CSP or partially-acidulated phosphate rock. (After Mokwunye and Chien 1980.)

Rates and Methods of Application

A considerable amount of work has been conducted in acid tropical soils to determine plant response to applied P and optimum rates of application. Although results are site specific, when soils are well characterized in terms of chemical, physical, and mineralogical properties, a reasonably accurate extrapolation can be expected.

Lower rates of P could be used if the best method of fertilizer application is used to minimize P fixation and optimize P uptake by plants. In soils with high P-fixing capacity, banded application of P fertilizers has been recommended as a way to reduce P fixation. However, it has been shown that banded P fertilizer, applied on maize growing in extremely P-deficient Oxisols could reduce yield when soil water availability is limited (Yost et al. 1979). Combining broadcast and banded applications increased efficiency of low rates of P applied as ordinary superphosphate as well as phosphate rock as measured by soybean yield growing in *Cerrado* soils (Smyth and Sanchez 1982).

These and other results obtained in acid soils of the humid tropics show the potential for improved P efficiency by developing optimum rates and methods of application best suited for the most common farming systems used on soils with high P-fixing capacity.

Effects of Lime on Phosphorus Availability

It is well known that the P-fixation capacity of Al hydroxides present in acid tropical soils is greater at lower pH values. Increased plant response to applied P in the presence of lime has been reported in many experiments, the results being attributed to reduced P fixation at increased pH values and greater P availability. It has also been suggested that liming enhances the availability of native phosphorus as a result of increased mineralization of organic matter (Lathwell 1979).

The beneficial effect of lime on plant productivity and increased response to applied P has not been limited to acid-sensitive species. Similar effects were observed with moderate amounts of lime on acid-tolerant grasses, without a measurable increase in available P in the soil (CIAT 1981, Couto et al. 1985).

An adverse effect of lime on P availability has also been reported (Stoop 1983), suggesting that the presence of Ca^{++} in liming materials counteracts the effect of increased pH due to the formation of calcium phosphates.

The discrepancies between these findings show that not enough is known about phosphorus fertilizer reactions in highly weathered soils and lime interactions. More research is necessary for assessment of the role of lime on increased efficiency of P fertilizers.

Mycorrhizal Effect on P Uptake

It has been suggested that mycorrhiza control the evolution of roots and that many crops cannot take up sufficient P from low-P soils unless their roots become infected with efficient strains of mycorrhiza. These fungi form an extensive system of external hyphae through which they absorb P from soil solution outside the P-depletion zone around roots.

Although the role of mycorrhizal fungi in improving nutrient uptake and plant growth in nutrient-deficient soils has been well established, the influence of edaphic factors on the mycorrhizal symbiosis is less well understood. The soil conditions

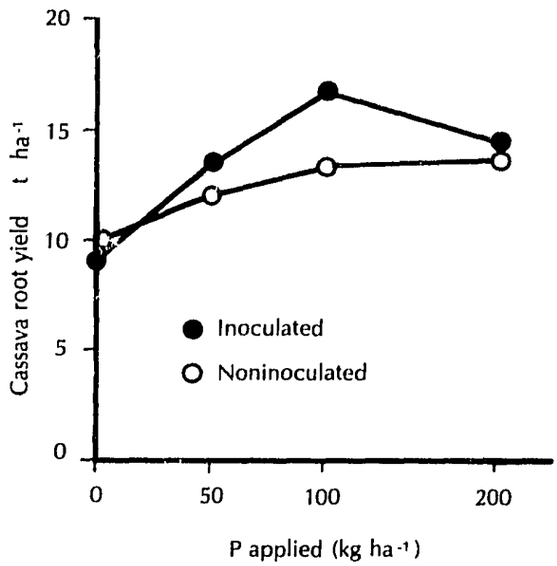

Fig. 2. Effect of various levels of P and mycorrhizal inoculation on root yield of cassava in an Oxisol of the *Llanos orientales* of Colombia. (Howeler and Sieverding 1983.)

most suitable for maximum mycorrhizal growth must be identified if plant growth response to mycorrhizal inoculation is to be predicted under field conditions.

It has been said that in nature the mycorrhizal condition is the rule and the nonmycorrhizal condition is the exception (Gerdemann 1971). Even though about 90% of plant species form endomycorrhiza, there is a wide range of plant responses to vesicular arbuscular endomycorrhiza (VAM). It has been shown consistently that plant species differ in their nutrient requirements and that VAM-infected plants show higher uptake of phosphorus nutrients than nonmycorrhizal plants. Hence, it can be expected that plants requiring higher P fertilization would benefit from the VAM mycorrhizal symbiosis more than plants having a low phosphorus requirement.

The VAM fungi can have marked effects on maize, wheat, *Stylosanthes*, clover, and *Macroptilium atropurpureum*. Cassava (*Manihot esculenta*) is an example of a crop that has been amply demonstrated to be highly dependent on a mycorrhizal association for P uptake from low-P soils. Trials with sterilized soil in the greenhouse have shown a marked response to VAM inoculation.

A study in Colombia of the potentials and limitations of mycorrhizal inoculation in field-grown cassava (Howeler and Sieverding 1983) showed that in a soil

with low native VAM population, mycorrhizal inoculation with the fungus *Glomus manihots* increased yields significantly. They concluded that there may be a potential to increase yields or decrease the P fertilizer requirements of cassava through field inoculation with effective VAM isolates in the vast areas of acid infertile Oxisols and Ultisols with low native VAM fungal populations.

Inoculation in cassava resulted in a more uniform root infection and thus a more uniform growth of the whole plant population. The inoculum consisted of material infected roots of cassava or maize, or soil on which these two crops had been grown. The soil-root mixture of maize contained 14 spores per gram and that of maize 29 per gram. The fungi *Glomus manihots* and *Enthrophosphora colombiana* were found to be most efficient species for cassava grown on acid low-P soils. According to results, fertilizer P application is required to stimulate the effectiveness of the VAM inoculation.

Inoculation with chopped-up infected cassava roots increases yields 64% over the uninoculated control. Inoculation with roots from other species increased yields consistently but not significantly. Unfortunately cassava is not a very good species for inoculum production because of the relatively small amounts of roots produced and the increased possibility of transmitting root diseases when inoculum of the same plant species is used.

Mycorrhizal inoculation either increased yield at 100 kg P per ha or decreased the fertilizer requirements (Fig. 2). The application of 50 kg P ha^{-1} with inoculation resulted in the same yield as 100 kg P ha^{-1} without inoculation.

Agricultural Practices and Efficient Use of P Fertilizers

Besides the improved efficiency in P uses that can be obtained by selecting the best sources and rates of P fertilizers and the most efficient method of application, considerable gains could be obtained by developing farming systems that make more efficient use of fertilizers.

Since the amount of P extracted from soil by most common crops is only a rather small amount of P applied, emphasis should be given to farming systems that better utilize residual fertilizers or provide opportunities for recycling of P in plant residues.

The use of perennial crops probably provides the best opportunity for P recycling in humid tropical environments as a result of the continued addition of plant residues to the soil and the consequent addition of P and other nutrients. In addition, grazed pastures can be expected to contribute to P recycling and efficient use of residual P fertilizers in both the humid tropics and acid savannas. Crop-pasture rotations could offer good opportunities for better use of fertilizers previously applied to crops and the return of important quantities of P to soil by grazing animals or pasture plant residues.

Intercropping annuals and perennials or forest trees offers other alternatives for maximum efficiency of P fertilizer use.

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Management of Soil Acidity

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Summary

Generalizations about food crop response to liming of acid soils in the tropics are illustrated. Current methods of extrapolating and interpolating experimental results to other soils and crops are examined, and none are found to be universally useful. Future network actions should include the following:

a. Interested countries should be encouraged and supported to collect and summarize their in-country data on management of soil acidity, including current research and an appraisal of research needs. There should be an effort devoted to collecting and summarizing these reviews.
b. There is need for 5 to 10 long-term lime experiments with careful attention to measuring critical soil and crop parameters so that results of all experiments can be compared and used for purposes of extrapolation and interpolation.
c. There is a need for two basic research projects: one to describe in detail the reactions and chemistry in the root-soil interface, and another to describe the long-term changes in chemical properties throughout the soil profile following liming. These two projects are essential to using our experimental data for all economic, soil, crop, and climatic conditions.

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Introduction

Soil acidity is only one of many factors that must be managed in order to increase food production on acid tropical soils; however, unless acid soils are managed correctly, sustained production of food crops will not be feasible. This paper (1) reviews selected aspects of present knowledge about food-crop response to lime on acid soils and (2) proposes a comprehensive research program for soil acidity. Similar reviews have been published by Pearson (1975), Lathwell (1979), van Raij et al. (1983), and Adams (1984).

Generally, the focus is on well-drained acid soils, and the emphasis is on food crops. We concentrate on experiments in which nutrients (other than lime) were at levels appropriate for high production, and we do not discuss interactions with other nutrients to any great extent.

One aspect of the utilization of acid soils not discussed here includes situations in which land area relative to population is large and high yields of food crops per unit area are not critical. In some of these situations, pasture production with acid-tolerant species and small additions of Ca are sufficient to increase and sustain beef production. Food crops can be produced in rotations when the nutrients are carefully conserved during crop growth and when a deep-rooted crop is grown periodically to recover any nutrients that have been leached below the rooting zone of the food crops. Periodic additions of nutrients, including Ca, are usually necessary to sustain production, but these additions of Ca are not always referred to as liming in the usual sense of the word.

We do not use the term "lime requirement" except when it refers to the relationship between amount of lime added and degree of amelioration of soil acidity. In general, others use "lime requirement" to describe the recommendations made to farmers; this use implies an economic judgment has been made, which means that as one travels around the world the amount of lime recommended in any given situation changes with differing economic situations. Because this review is aimed at an international audience, we restrict our discussion to the biological input-output relationships (e.g., yields vs. lime inputs) so we can avoid the ambiguities associated with "low input" vs. "high input," "developed" vs. "developing," "poor" vs. "rich," "large" vs. "small," etc. Because the role of agronomists is to provide the biological input-output relationships necessary to any rational economic and social analysis, we must be sure to provide the output possibilities for the whole range of inputs—from none to those required for maximinum biological yields. If we do this, then our data can be used in all economic and social strata, including "large" and "small," "rich" and "poor" farmers.

Example of a Well-Planned Lime Experiment

In 1972 a lime experiment was initiated at CPAC (Planaltina, Brazil) on a virgin soil recently cleared from native *Cerrado*. In the Brazilian soil classification system it is called *Latossolo vermelho escuro* (CPAC 1976), and according to the U.S.

Soil Taxonomy it is classed as a Typic Haplustox, fine, kaolinitic, isohyperthermic (Salinas 1978). Some characteristics are listed in Table 1.

The treatments included 0, 1, 2, 4, and 8 t ha^{-1} of lime, and each was mixed to depths of 15 and 30 cm. Phosphorus, N, K, S, and micronutrients were added in amounts judged sufficient to eliminate these nutrients as important factors limiting yield. Yields of crops were measured each year for 10 years, and soil samples were taken at intervals of time for laboratory analyses (CPAC 1976, 1979, 1981, 1982). Figure 1 illustrates the accumulated yields of the first three crops of maize (two wet-season crops and one irrigated dry-season crop) for the different lime levels and the two depths of incorporation. Additions of more than 4 t of lime per ha gave only small increases in yield when lime was incorporated to the 30-cm depth; yields decreased slightly where more than 4 t of lime was incorporated to the 15-cm depth.

The superior yields at the 30-cm depth of incorporation were shown in associated research to be the result of more favorable root growth in the soil below the plow layer (Gonzalez et al. 1979). Because the soil acidity is so intense, the roots of aluminum-sensitive plants do not penetrate the subsoil layers and do not use water and nutrients below the depth of incorporation of lime in the initial year or two of cropping. As a consequence, yields are improved by deeper incorporation of lime since the crops have more water and nutrients available for use during prolonged periods without rain (Bouldin 1979; Gonzalez et al. 1979).

This experiment was continued in succeeding years using different crops. In the later crops, differences in yields between the depths of incorporation of lime gradually disappeared. Field observations and chemical studies of soil confirmed that

Table 1. Selected properties of the fine, kaolinitic, isohyperthermic Typic Haplustox at the experimental site for lime experiments at CPAC, Planaltina, Brazil, after the virgin soil was cleared from *Cerrado*. (From Salinas 1978.)

Soil property	Depth of sampling (cm)		
	0-20	20-40	40-60[4]
Clay (%)	45	51	—
Silt (%)	20	17	—
Sand (%)	35	32	—
pH (1:1 soil:H_2O)	4.7	4.6	4.5
Exch. Ca + Mg (cmol kg^{-1})[1]	0.15	0.15	0.15
Exch. Al (cmol kg^{-1})[1]	1.04	0.90	0.92
Effective CEC (cmol kg^{-1})[2]	1.25	1.10	1.09
Aluminum saturation (%)[3]	83	82	84
Available P (Mehlich I method) (kg mg^{-1})	1.9	1.0	Trace

1. Extracted with 1*N* KCl, 1:10 soil-solution rates.
2. Σ Ca + Mg + K + Al.
3. (Al/Σ Ca + Mg + K + Al) × 100.
4. Dashes indicate data not determined.

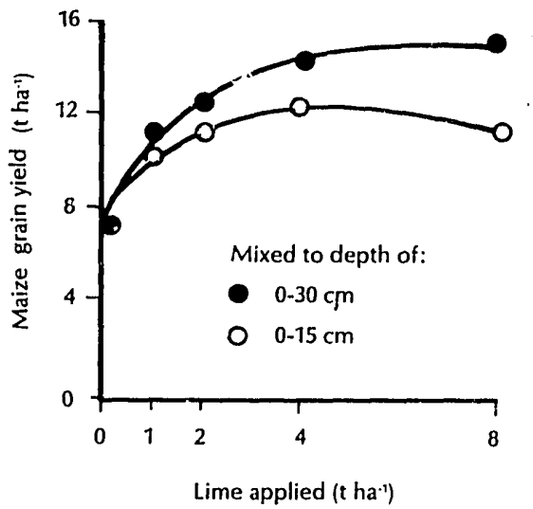

Fig. 1. Accumulated maize grain yields from the first three crops after lime application to an Oxisol from the *Cerrado* of Brazil in 1972. (After CPAC 1976.)

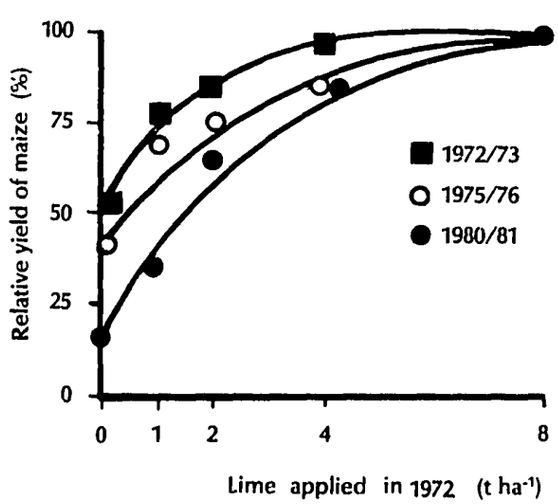

Fig. 2. Residual effects of lime applied in 1972 on maize on the same soil as Fig. 1. Each point is the average of the 0-15 and 0-30 depth of mixing. Lines are for reference purposes. (After CPAC 1976, 1979, 1982.)

as cropping continued the beneficial effects of liming gradually moved into the soil below the depth of incorporation: root penetration and water use extended to over 1 m in depth several years after liming. In addition, gypsum, as a component of ordinary superphosphate, speeded the process of improving deep root growth (Ritchey et al. 1980). In a similar study in Africa carried out by IITA, there was no evidence that the leaching process neutralized extractable Al in the soil below the depth of lime incorporation after 3 years under 2500 mm of rain annually (Friesen et al. 1982). On the other hand, others have reported changes in subsoil properties several years after liming the cultivated layer (Chaves et al. 1984, Quaggio et al. 1982). The explanation for the differences among locations is not evident.

These studies by CPAC show that the ability of the crop to extract subsoil water increases with time after liming because the rooting depth is extended, and thereby the impact of prolonged periods without rain on crop yields is reduced. This is extremely important because it means that the yield potential of the soil increases with time after liming. The data from CPAC also demonstrate that deep incorporation of lime increases crop yields during the first few years of cropping; thus, the economic feasibility of deep incorporation (compared with incorporation only by normal cultural practices) will depend on local economic conditions. Furthermore, the beneficial effects of deeper incorporation of lime can be obtained, providing one is willing to wait a few years. To date, no one seems to have developed a good means to predict rates of amelioration of subsoil acidity as influenced by soil properties and climate.

Relative yields of maize as the experiment progressed are shown in Figure 2. Two points are illustrated: (1) the residual effect of lime is considerable and (2) without lime, yields decrease from even their low initial level, presumably as a consequence of further acidification of the profile (CPAC 1982).

For this latter reason, care should be used in proposing that selection of crops tolerant to acidity is a universally viable alternative to liming or additions of Ca. As shown in Table 1, the total Ca and Mg in the top meter of soil is only a few hundred kg, and this small amount can be quickly depleted by crop removal and accelerated leaching likely to accompany food-crop production. Selection of crops tolerant to acidity is useful when the cultivated layer is limed, but the subsurface layers remain acid when there are more ample supplies of Ca and Mg than in soils similar to those described in Table 1. As an additional precaution, perhaps some attention should be given to the possibility that the Ca and Mg content of crops tolerant to acidity may not supply sufficient Ca and Mg for the human/animal diet.

The experiments described provide input-output data for several crop cycles, data on residual effects over several years, and information on amelioration of acidity throughout the soil profile. Several other experiments furnish the same kind of information (Friesen et al. 1982, Chaves et al. 1984, Quaggio et al. 1982). With these data economists can carry out a detailed study of the benefits of different rates of liming, crop sequences, and residual effects, and they can project the economic benefits of different liming programs under different crop prices and dif-

ferent interest and inflation rates. With these calculations, the data can be extrapolated to any economic situation. This is the kind of input-output data agronomists should supply to farmers, extension workers, economists, bankers, public planners, and so on so they can make informed decisions about lime as an input.

Extrapolation and Interpolation

For all practical purposes, the experiments we have described are history at one location for a fixed set of weather conditions and management variables. How can we extrapolate the results to other soils, to other crops, to other varieties of the same crop, to other climates, to other management regimes, to a multitude of economic and social regimes, etc.? How can we compare the data with those from other experiments?

To accomplish these more ambitious objectives, we must know more about many soil, crop, and climatic factors. The factors that appear to be most important to these objectives are the following: Al toxicity, Ca deficiency, crop response to each of these factors, interactions of crop variety/species with Al and Ca, the buffering capacity of the soil with respect to liming, the rate of amelioration of acidity throughout the profile, soil physical conditions, and the intensity and duration of the residual effects. In the following sections we review the current knowledge about some of these factors.

Soil Chemical Measurements

Soil pH. Soil pH is the easiest parameter to measure. All one needs is pH-sensitive indicators or relatively inexpensive electronic equipment.

A vast amount of research has shown that Al toxicity (Foy 1984) and Ca deficiency (Clark 1984) are two major factors determining crop response to soil acidity. Both are related in indirect ways to pH (Thomas and Hargrove 1984). Thus, the simplicity of pH measurement has proved to be useful, although it is a fairly imprecise guide to crop behavior. Pearson (1975) concluded that pH does not appear to be as useful a guide in the tropics as in the temperate regions. Some of the following are more often used with acid soils in tropical settings.

Neutral salt extractions. Commonly, cations extracted with a neutral salt (such as *N* KCl) are useful to estimate the toxic effects of Al, Ca deficiency, lime requirement, and the effective cation-exchange capacity.

Extractable Al. Commonly, two parameters are based on 1*N* KCl-extractable Al: the percentage of Al saturation and the lime requirement. Percentage of Al saturation is usually defined as the ratio of extractable Al to the sum of extractable cations, expressed as percent. The utility of this parameter is illustrated by a number of experiments (e.g., Kamprath 1984); an example is shown in Figure 3 using the CPAC data referred to above. Figure 3 illustrates that this parameter is often better correlated with crop response than is pH.

Kamprath (1984) cited several experiments where the percentage of extractable Al was correlated with yield. However, when the relationship between percentage of extractable Al and relative yield is compared from several experiments, the relationship differs among locations, as illustrated with maize grown in Brazil, Africa, and Puerto Rico (Fig. 4). Presently we can only speculate about why the different relationships were found at the different locations. Possibilities include differences in Al tolerance of the varieties, differences in laboratory techniques, differences in soil properties, and differences in absolute yields. Clearly, yield of maize is not a single-valued function of the percentage of Al saturation.

Extractable Al has also been found to be a useful guide to lime requirement (the amount of lime that must be added to achieve a given yield potential). However, the soil contains constituents other than Al that react with lime and, as a consequence, the reaction of 1 equivalent of lime does not reduce the extractable Al by 1 equivalent. In general, between 1.5 and 3.3 equivalents of lime must be added to reduce *N* KCl-extractable Al 1 equivalent (Kamprath 1984). The size of the factor increases as the organic-matter content increases (Kamprath 1984). It has been reported that other salts extract an amount of acidity so that the lime requirement is approximately equal to the amount of Al extracted (Oates and Kamprath 1983a, 1983b).

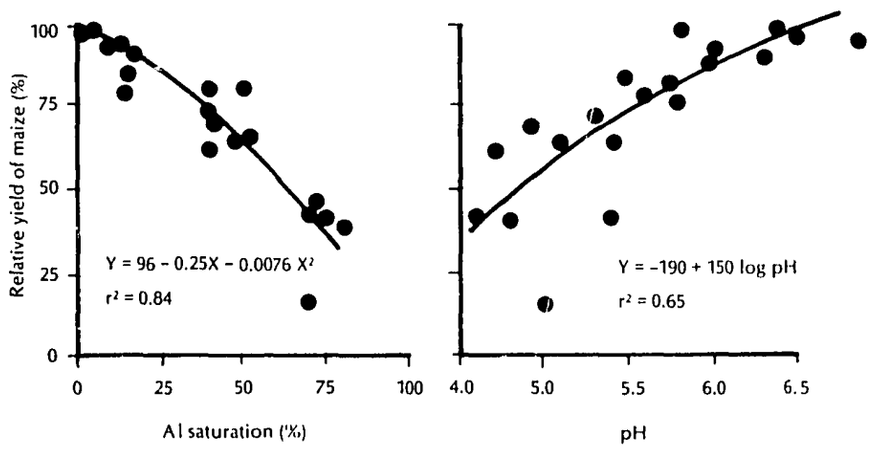

Fig. 3. Effect of aluminum saturation and pH on relative yields of maize for 1972/73, 1973/74, 1975/76, and 1976/77. The percentage of aluminum saturation and the pH of soil samples were taken the year the crop was grown.

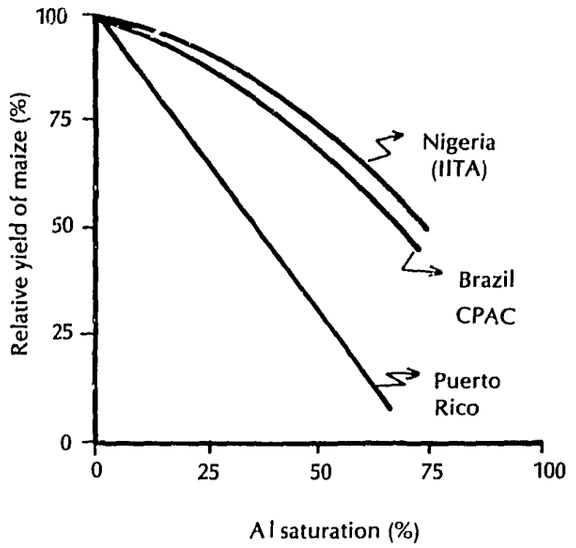

Fig. 4. Regressions of relative yield of maize on percentage of aluminum saturation from three experiments on different tropical soils. (After Friesen et al. 1982, Pearson 1975, CPAC 1976, 1979, 1981.)

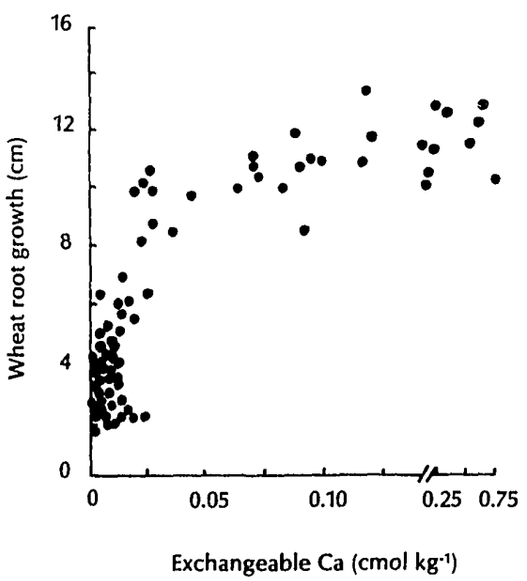

Fig. 5. Relationship between growth of roots of wheat in 4 days in greenhouse tests and exchangeable calcium in the soil. (From Ritchey et al. 1983.)

Exchangeable Ca. Generally Ca is not translocated within plants toward growing root tips of annual crops. As a consequence, the Ca required for root growth must be obtained from the soil immediately adjacent to the root. As might be expected, Ca is so low in some soils that root growth is limited by Ca deficiency in localized regions of the soil even though the plant is well supplied with Ca taken up in other portions of the soil (Ritchey et al. 1982). An example of such a situation is illustrated in Figure 5. Note that the parameter correlated with root growth was exchangeable Ca and not Ca as a percentage of exchangeable cations.

Soil solution composition. Recently considerable work has been done on the relationship of the various species of Al present in solutions and in soil solutions to plant response. For a long time soil chemists have recognized that polymeric forms of Al as well as several monomeric species exist in solution (e.g., White et al. 1976). Two recent studies (described in the next paragraph) illustrate the importance of the different Al species to plants.

The response of coffee to different lime levels in greenhouse culture was studied, and the correlations between relative root growth and various soil acidity parameters were determined (Table 2). The best correlation was between Al activity in the saturation extract and relative root growth in six soils, each with several levels of added lime. Later nutrient culture studies with soybean demonstrated that the activity of monomeric forms of Al in solution were best correlated with relative root growth (Fig. 6). These results make clear what soil chemists have been telling agronomists for years: the solution chemistry of Al is exceedingly complex. Now we must study the relationships between this complex chemistry and crop response.

Interactions. The preceding studies on the effects of Al species in solution on plant response raise some important questions on how to interpret observed interactions between Ca, Mg, Al, S, and P. Some of the interactions are probably

Table 2. Correlation between relative root growth of coffee and soil chemical parameters in a greenhouse experiment with six soils, each limed to several levels of exchangeable Al. (From Paven et al. 1982.)

Soil acidity parameters (variables)	Regression equation	Correlation coefficient
Relative root growth (%) vs.:		
Exchangeable Al	$Y = 95.6\ e^{-0.18x}$	−0.73
Percentage of Al saturation	$Y = 97.8\ e^{-0.01x}$	−0.81
Concentration of Al in soil solution	$Y = 99.0\ e^{-0.08(10^5)x}$	−0.82
Concentration of Al^{+3}	$Y = 98.3\ e^{-0.12(10^5)x}$	−0.92
Activity of Al	$Y = 97.1 e^{-0.2(10^5)x}$	−0.97

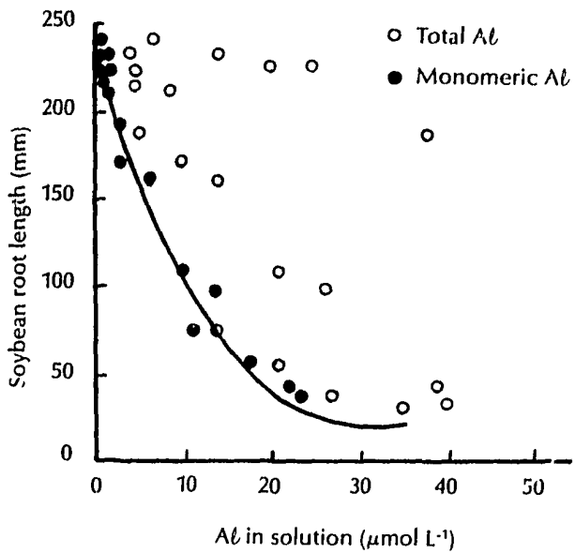

Fig. 6. Relationship between soybean root growth in nutrient solution and total aluminum in solution or monomeric aluminum in solution. Points are experimental observations; line is regression of root length on monomeric aluminum in solution. (After Blamey et al. 1983.)

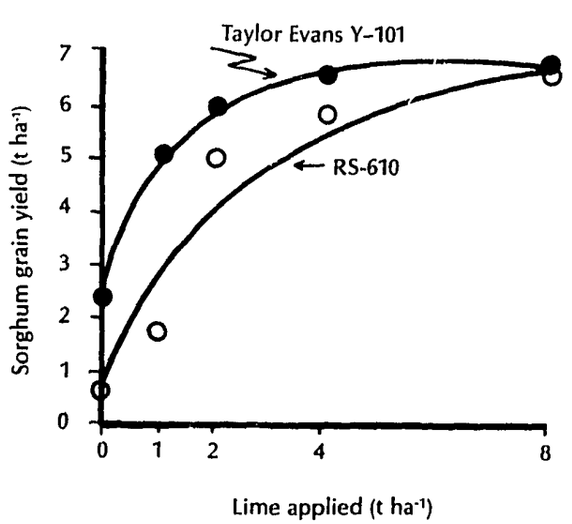

Fig. 7. Response of two grain sorghum varieties to lime application. Points are experimental observations; lines are regression equations fitted to the data. (From Salinas 1978.)

the result of solution chemistry and not interactions with the physiology of the plant. However, in soils where Ca levels are low, there may well be important plant physiological interactions.

Summary of soil chemical studies.

a. Each of the above parameters has been demonstrated to be useful under specific conditions.
b. We will probably not obtain a single-valued function between relative yield and any one soil chemical parameter if the range of soils, crop varieties, and climates is wide enough.
c. As we increase the number of parameters measured, we will probably increase the confidence in our predictions. The degree of refinement that we should seek depends to some extent on what is an acceptable level of uncertainty.

Methods of Evaluating Variety/Crop Tolerance of Soil Acidity

The ultimate test of crop tolerance is field trials. Illustrated in Figure 7 is a classic example of one field experimental trial (Salinas 1978). There can be little doubt of the differences between the two varieties.

There are a large number of studies in the literature reporting results of nutrient solution and soil cultures in the greenhouse that illustrate differential tolerance of cultivars to Al toxicity and/or Ca deficiency. In some cases these greenhouse studies have been shown to be correlated with yields in field experiments and, hence, they are useful tools for the plant breeder and can be used to give relative rankings to different varieties. It is not clear to us whether these procedures are precise enough to be useful for interpolating among lime experiments nor whether they are precise enough for purposes of predicting input-output relationships.

Along with agronomists, most plant breeders have not availed themselves of the knowledge of Al chemistry. Consequently, the results of many of the nutrient-culture studies cannot be compared with each other in any clear fashion.

Amelioration of Subsurface Acidity and Duration and Pattern of Residual Effects

The amelioration of subsurface acidity and the duration and pattern of residual effects are related in that they both depend upon leaching phenomena. Leaching rates are influenced by supplies of soluble anions (such as nitrate, chloride, and sulfate) plus the amount of water moving through the soil. Soil chemical factors are also important. Studies in the literature document the changes in contents of extractable Ca, Al, and other ions with depth after different periods of time following treatment of the superficial layers with lime (e.g., Ritchey et al. 1980, Friesen et al. 1982, Quaggio et al. 1982, Chaves et al. 1984). We could not find

an example where these data had been interpreted for use in predicting leaching phenomena under a range of conditions; we do not yet have a model useful for these purposes.

Summary of the State of the Art of Interpolating among Lime Experiments

Both Al toxicity and Ca deficiency reduce root growth and thereby reduce crop yields because of water deficits and nutrient deficiencies; a major consequence of liming is to provide more favorable levels of both these factors. Tolerance to these factors varies greatly among crops and varieties.

In many regions of the tropics, irregular distribution of rainfall, low available water-holding capacity, and excessive subsoil acidity require more than amelioration of the acidity in the cultivated layer; subsoil acidity must also be ameliorated so that crops can use subsoil water.

In both temperate and tropical regions there is a reasonable body of experimental field data that serves as a basis for recommendations in the locality where the experiments were run and for current local economic conditions. However, many experiments do not include a wide enough range of treatments nor enough chemical measurements to serve as a basis for evaluating a wide range of management options with respect to liming. They cannot be extrapolated through time and space to different economic, soil, crop, and climatic conditions.

Most of the soil and crop relationships are based on statistical correlations, and few have any status as cause-and-effect relationships. For example, the percentage of Al saturation referred to earlier is not likely to be the real variable, but, because it is related in an indirect way to both Al toxicity and Ca deficiency, it is correlated with crop response under a restricted set of conditions. As the range of conditions is widened, the degree of correlation weakens.

Future Research Needs

In our judgment, we should strive to improve our ability to explain the differences among experiments. We have pointed out several important discrepancies that need attention, and surely there are others. Until we can explain the differences among experiments, we cannot be very confident about any extrapolations we make. Many of the most used relationships are based on statistical correlations and not true cause-and-effect relationships. We should strive to establish the true cause-and-effect relationships, however, because extrapolations are not likely to be reliable until we do so. We also need complete response curves and residual effects so that the results can be extrapolated to all economic situations.

Following are our recommendations for future research.

Synthesis of What We Know and Do Not Know

Individual countries should be encouraged and supported to do a comprehensive in-country review of past, present, and needed research on the management of soil acidity.

A working group of 10 to 15 soil and crop scientists should be established to examine the available experimental data and:

1. Identify conclusions consistent among experiments that apply to all present data;
2. Identify conclusions that vary among experiments;
3. Based on the above analysis, develop hypotheses for future study;
4. Develop the hypotheses into requests for donor support and requests for proposals from scientists and institutions.

The working group should be encouraged to develop hypotheses of a size suitable for a thesis project or a 1- to 3-year study leave. The study leaves could be used to facilitate exchange among complexes of research groups, soils, crops, and climates and perhaps could be on an exchange basis (e.g., scientists from stations A and B exchange places for 1 to 3 years).

Our recommendation for the composition of the group is as follows:

- A chairman who can devote perhaps a total of 4 months to the project over the next 12 to 18 months.
- The following who can devote 1 to 3 months to the project over the next 12 to 18 months:
  - Four agronomists/soil chemists: one who has access to the data at CPAC and Brazil in general; one who has access to the data at IITA and Africa in general; one who has access to the data at Puerto Rico, CIAT, and South and Central America (except Brazil); and one who has access to the data in Asia and southeastern Asia.
  - One crop physiologist who has experience with physiological aspects of crop response to soil acidity.
  - One soil chemist who has experience with acid soils.
  - One soil physicist who has experience with leaching of soil constituents.
  - One soil taxonomist who is familiar with soil classification in the tropics.
  - One economist who is familiar with interpretation of agronomic input-output data.
  - One soil chemist/soil fertility person familiar with modeling the root-interfacial zone.
  - One editor-manager who will be able to spend 6 months working on the necessary editorial-management aspects.

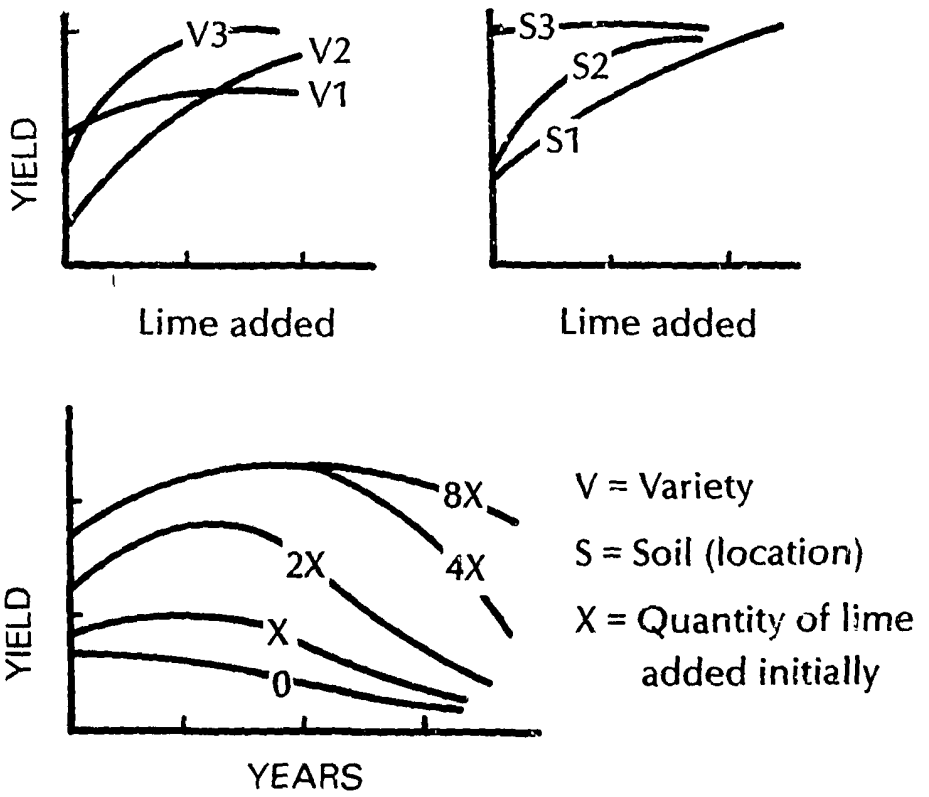

Fig. 8. Influence of liming on crop yields, by variety, location, and quantity of lime added initially.

Future Field Experiments

Either the group described above or a similar group should design 5 to 10 comprehensive, long-term experiments for carefully selected soil-climate complexes. Essential features of the design are the following:

1. Provision of careful studies of soil chemical and physical properties at each site during the duration of the experiment through a depth of 1 to 2 m. Addition of fertilizers at appropriate levels to insure high yields. Characterization of lime and other amendments with respect to chemical and physical properties, and storage of samples for possible future studies;
2. Provision of detailed climatic records for the experimental period and analysis of the historical records (one criterion for each site should include availability of historical data);
3. Careful selection of crops and varieties to insure that genetic variability and stability are such that (a) adequate supplies of seed are available for the experiment, (b) current and subsequent physiological studies can be carried out, and (c) comparisons among crops and varieties at the different sites are facilitated.
4. Provision of seasonal measurements of crop development, nutritional status, and water stress.
5. Paying careful attention to the design and conduct of the experiments to provide comprehensive evaluation of the hypotheses developed by the group described in the preceding section.
6. Inclusion of lime added by variety, soil, and year in the output of the above at each experimental site (Fig. 8).

Project Proposals

One or both of the preceding groups should design project proposals to establish the following two special projects, which in many respects should serve to summarize and integrate the foregoing recommendations.

1. A comprehensive model describing the root-soil interfacial zone including mass-flow and diffusion as transport agents and the impact of differential anion-cation uptake by roots as factors modifying the chemistry of the root-soil complex.
2. A comprehensive model describing changes in the chemistry throughout 1 to 2 m of soil following incorporation of lime into the cultivated layer. The result would be a valuable tool for predicting changes in rooting depth and residual effects of lime.

If the correct measurements of soil/crop/climate variables are made at a new and different site, we should be able to interpolate the results of the experiments to that

site. Thus we could describe lime response for any soil, climate, crop, or economic condition.

As agronomists we will have provided the information needed to evaluate liming under any socioeconomic condition and, hence, the data may be extapolated through time and space. Although the program outlined is ambitious and expensive, this is the sort of project IBSRAM should sponsor. If we do no more than review and analyze the synthesis of what we do and do not know, as described above, we will have accomplished a worthy objective.

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Reclamation of Degraded Acid Tropical Soils in Indonesia

F. Rumawas*

Summary

Land that has suffered from man's mismanagement can become degraded. Discontinuing these harmful activities alone does not necessarily restore the land to its former condition, especially when the stress conditions have exceeded the system's homeostatic ability. Years of research and experience have resulted in sufficient knowledge to overcome chemical, physical, and biological constraints and to reclaim degraded acid tropical soils. The most decisive factor dictating the success or failure of land reclamation, however, is socioeconomic.

Introduction

This paper covers mainly some experiences in land reclamation in Indonesia, but it seems that there is commonality across countries in dealing with acid tropical soils. Two recent reviews (Sanchez and Salinas 1981, Goedert 1983) sum up the problems faced in Latin America. General principles of proper soil management are often applicable over a wide range of soils and climatic zones.

The total land area of the Indonesian archipelago is approximately 191 million ha, of which 14 million are used for food crop production and another 7 million are devoted to perennial estate crops such as rubber, oil palm, coffee, and tea. Most of the soils are acid. Table 1 shows their regional distribution. It is clear that the weathered Red Yellow Podzolic soils cover vast areas of Sumatra, Kalimantan, and Irian Jaya (Fig. 1), and therefore it is fair to say that the archipelago as a whole is not as fertile as one is led to believe (Fig. 2). The most fertile islands of Java and Bali are already badly overcrowded, and increasing numbers of landless families

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This paper was invited but not presented at the Workshop.

Table 1. Estimated area[1] (x 1000 ha) and distribution of soils in Indonesia. (Adapted from Muljadi and Soepraptohardjo 1975.)

Classification										
USDA 1938	Soil Taxonomy	Java/ Madura	Bali	Sumatra	Kalimantan	Sulawesi	Irian Jaya	Nusa Tenggara	Maluku	Total
Organosols	Histosols	25	—	6,781	6,469	—	10,875	—	—	24,150
Alluvial soils	Entisols	2,550	31	6,238	5,644	1,363	2,575	281	488	19,170
Regosols	Entisols, Inceptisols	1,431	219	831	150	294	—	688	294	3,907
Rendzinas	Mollisols	38	—	394	—	138	369	13	719	1,671
Grumusols	Vertisols	1,481	—	—	—	56	—	263	—	1,800
Andosols	Inceptisols	844	—	2,725	1,225	156	—	94	12	5,056
Mediterranean soils	Alfisols	1,625	56	—	—	2,938	106	3,068	50	7,843
Latosols	Inceptisols, Oxisols	2,831	250	6,788	4,469	2,856	356	313	519	18,382
Red Yellow Podzolic soils	Ultisols	325	—	15,950	14,525	1,494	12,001	—	3,231	47,526
Podzols	Spodosols	—	—	931	4,081	—	—	—	—	5,012
Complex soils	Mostly Podzolic	2,069	—	6,725	17,437	9,800	15,313	2,319	2,162	55,822
Others		—	—	—	—	—	605	—	—	605
Total		13,219	556	47,363	54,000	19,095	42,200	7,038	7,475	190,946

1. Dashes indicate amount is negligible.

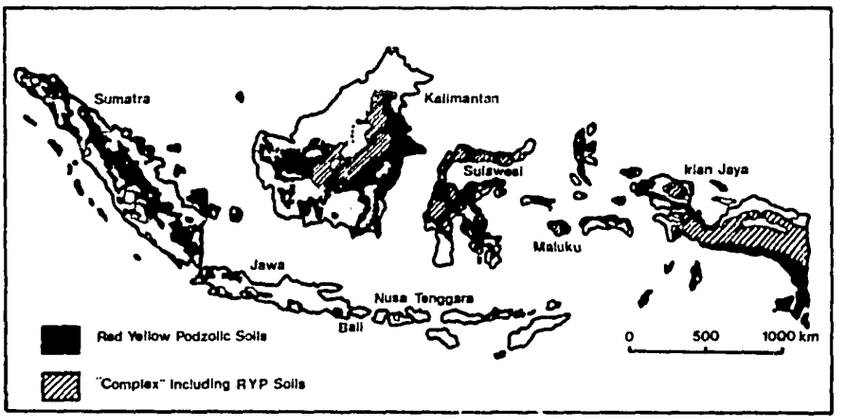

Fig. 1. Regional distribution of Red Yellow Podzolic Soils in Indonesia. (After Driessen and Soepraptohardjo 1974.)

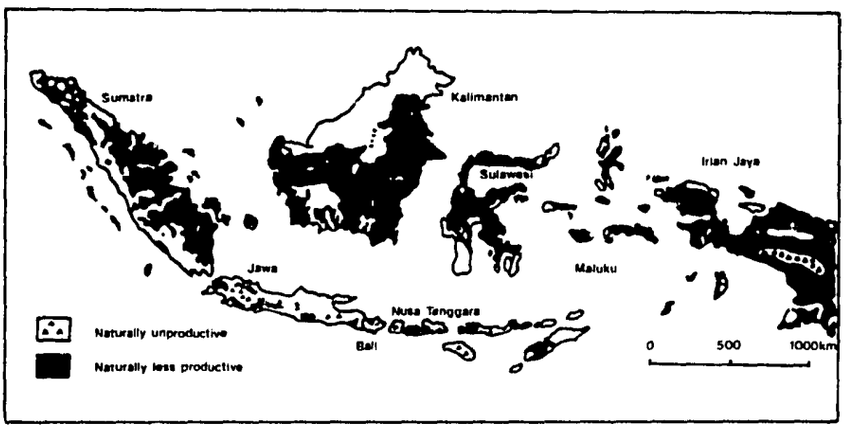

Fig. 2. Regional distribution of less and unproductive land for agriculture. (After Muljadi and Soepraptohardjo 1975.)

are being transmigrated to acid soil areas in Sumatra, Kalimantan, and Irian Jaya. Currently, serious soil fertility and conservation problems are encountered in many of these new settlements. It is therefore certain that soil degradation will be more serious in the future unless drastic countermeasures are taken.

In 1975 an estimated 42 million ha of land were stripped of its forest cover, 20 million ha of which are classified as critical (degraded or "waste") lands (Suranggadjiwa 1975). Land reclamation is negligible, and the critical land area is estimated to be increasing at an annual rate of 1 to 2%. A total of 22 million ha of degraded land in Indonesia in 1985 is thus a conservative estimate. Most experts agree that the main causes of land degradation are (1) population pressures resulting in a gradual change from a generally stable shifting cultivation into the "bush fallow" system (Ruthenberg 1980) and (2) a disregard for soil conditions, carrying capacity, and soil conservation in rainfed agriculture (Suranggadjiwa 1975).

Different aspects of land reclamation are discussed separately; in reality, however, it is often not possible to consider one independently from the others. The most common approach is to first determine and try to resolve the main limiting factor(s), then remove the secondary constraints.

Physical Factors

The most common forms of physical land degradation in the humid tropics are excessive soil erosion and compaction of surface or subsurface layers. Bush fallow systems and especially permanent agriculture on steep lands invariably result in soil degradation. It was calculated that without soil conservation measures, a more stable Citayam latosol (slope 3–25%) lost 129 t of soil per ha in 4 months with a surface runoff of more than 25% of precipitation (Suwardjo and Kurnia 1982). In Ultisols, compaction of lower soil horizons is often observed due to migration of clay from surface layers downward. With only 3 years of cultivation, bulk densities of over 1.3 g cm^{-3} were observed on a podzolic soil, which caused yield reductions in maize and rice (Hakim and Santoso 1982).

Land reclamation on steep land usually starts with erosion control. This can be achieved by making different types of terraces. Terraces can also be developed by planting grass or a dense stand of shrubs following contour lines, but in some cases land has been damaged to such an extent that plant growth is not possible. On a larger scale, check dams may be constructed, which in time fill up with soil and become suitable for agricultural use. A fine example is found in the Gunung Kidul area (Central Java). Runoff is also slowed by the construction of a series of small earthen dams. This method has been successfully tried in undulating terrain in Lampung, South Sumatra. This system also supplies crops, animals, and humans with water in the dry season, and large ponds that do not dry up are stocked with fish. Javanese and Balinese farmers reclaim land by making rice paddies where irrigation water is available or where rainfall is abundant. Irrigated rice production has proven to be one of the most acceptable conservation techniques to Indonesian farmers.

Chemical Factors

Soil chemical conditions have been investigated extensively, because many plants do not grow or produce satisfactorily due to chemical constraints. Highly weathered tropical soils developed in a humid climate are usually acid, low in available phosphorus, and low in exchangeable bases; they have low base saturation, low CEC, medium to high levels of both exchangeable Al and Al saturation, and, in some cases, excessive levels of Fe and Mn.

To reclaim these soils for agricultural use, chemical inputs are necessary. A rather extreme case is shown in Table 2 from a paper outlining difficulties in reclaiming land in Sitiung, West Sumatra: these soils are very poor and extremely erodible (Sudjadi 1984). The same conditions were described in a review of soil survey results in West Sumatra and Jambi provinces (Riley and Harding 1979), where smallholder rubber plantations yield around 350 kg ha^{-1} y^{-1}. On these soils, for rice production, liming and phosphorus applications gave good results (Rumawas 1983, 1984; Wade et al. 1985), as shown in Table 3. It was also found that plants absorbed high to excessive levels of Mn when not limed (IPB 1981). Application of phosphate rock, superphosphate, and K improved maize and peanut yields (Rumawas et al. 1980). Development of the root system, however, was very poor, resulting in wilting during short dry spells. From the very beginning it was already concluded that reclaiming this land would require high inputs (Rumawas 1980). Rochayati et al. (1985) also reported a good response of maize and soybean to liming and P application on an Ultisol in Rangkasbitung, West Java. On a Typic Paleudult in Nakau (Lampung) where the former Benchmark Soils Project was located, inconclusive results were obtained from a liming experiment (Sudjadi et al. 1985). This soil is higher in base status than other Ultisols in similar areas.

No response to liming was obtained on slightly acid young alluvial soils with low levels of exchangeable Al. One example is an experiment in Luwu, South Sulawesi, where only chicken manure and P increased maize yields (Djamaluddin 1983).

Reclamation of acid tropical soils for irrigated or rainfed paddies often results in bronzing during the first rice crops. This iron-induced K deficiency can be relieved by applying high levels of P, and in some cases additional K is needed. Another method is leaching and alternately inundating and drying the soil. Lime and organic matter applications do not seem to cure this physiological disease.

Biological Factors

De Jongh (1941) was one of the first scientists in Indonesia who noticed that in some soils *Rhizobium* spp. on legumes failed to develop. This observation is currently further pursued because of a renewed interest in biological N fixation. We found that on the unimproved Sitiung soil, soybean nodulated poorly and in some cases yielded less than the noninoculated plants. Others were able to show that liming acid soil is absolutely necessary (Prihatini and Adiningsih 1985). Addition of P, K, and Mg increased absorption of nutrients and soybean yields dramati-

Table 2. Chemical characteristics of the Red Yellow Podzolic soil in Sitiung, West Sumatra. (Adapted from Sudjadi 1984.)

Horizon	Depth (cm)	pH		O.C.	Total N	Exchangeable cations					Effective CEC	CEC at pH 7.0	Al sat. (%)	Available P (HCl 25%) (g kg^{-1})
		H_2O	KCl	(.... %	....)	Ca	Mg	K	Na	Al	(.....	.....)		
						(.....	.....	.....	cmol kg^{-1}	.....				
A1	0-4	4.3	3.6	3.13	0.24	0.2	0.1	0.1	0.1	6.26	6.56	26.4	95	0.1
B21	4-22	4.7	3.7	1.55	0.16	0.2	0.1	0.1	0.1	6.31	6.81	22.3	95	0.1
B22	22-45	4.9	3.8	0.86	0.12	0.1	0.1	0.1	0.1	5.49	5.89	20.0	93	0.1
B3g	45-82	4.9	3.9	0.55	0.08	0.1	0.1	0.1	0.1	8.35	8.65	20.2	95	0.1
BC	82-117	4.9	3.8	0.34	0.06	0.1	0.1	0.1	0.1	9.05	9.45	25.0	96	0.1
C	117-200	5.0	3.7	0.22	0.03	0.2	0.1	0.2	0.1	4.85	5.45	23.4	89	0.2

cally (Table 4). It may well be that other soil microorganisms are similarly affected by these treatments.

In low-input agriculture, organic matter is often regarded as the major input to improve soil conditions and crop yields. Although a list of plants that can survive under acid soil conditions was compiled (Sanchez and Salinas 1981), it is clear that many crops or ground covers cannot be established unless some corrective measures are taken. Establishing *Leucaena leucocephala* hedges or *Paspalum notatum* strips to stabilize the soil is often only possible after liming and P fertilization. Acid-tolerant cover crops such as *Calopogonium* spp. and *Centrosema pubescens* can be established in many acid soils only when P is included in the package.

Crops are also known to differ in their ability to conserve the soil (Lal 1975). Ground cover is one of the main features of a "good" crop. This is why the most stable rainfed agricultural system in the tropics is perennial crop production (Ruthenberg 1980).

Table 3. Rice yields (t ha^{-1}) due to P fertilization and application of residual lime, sixth crop. (From Rumawas 1983.)

Lime applied (t ha^{-1})	TSP applied (kg P_2O_5 ha^{-1})					Mean
	0	50	100	150	200	
0	0.44	3.33	3.48	4.60	4.03	3.20
1	1.86	3.59	4.30	3.91	4.51	3.63
2	2.33	4.80	4.80	4.58	4.56	4.21
4	3.66	4.74	4.93	4.55	4.90	4.58
8	3.95	5.40	5.45	5.04	5.36	5.04
Mean	2.45	4.36	4.60	4.53	4.68	—

Table 4. Nutrients absorbed and yield of soybean grown on limed Podzolic soil. (Adapted from Prihatini and Adiningsih 1985.)

Treatment	Nutrients absorbed (mg pot^{-1})					Yield (g pot^{-1})
	N	P	K	Ca	Mg	
Control	47.6	1.4	18.3	18.7	4.7	7.2
Urea	40.1	1.2	12.8	15.3	3.8	8.3
Nitragin[1]	40.5	1.6	16.4	17.8	4.2	8.4
Nitragin + P	72.3	4.4	35.7	31.9	9.5	16.5
Nitragin + PK	90.2	6.0	54.7	41.6	10.5	16.1
Nitragin + PKMg	87.1	5.5	66.1	43.9	12.5	15.4

1. *Rhizobium* inoculant.

Socioeconomic Factors

Many countries face progressive degradation of their land and water resources, in spite of technological know-how and in many cases available credit. From the many, often unpleasant experiences, we can draw the conclusion that in some way or other, farmers fail to participate in soil conservation and soil reclamation programs. Some believe that traditional land rights, poor education of smallholders, the lack of off-farm employment, and poor extension services are to be blamed (Partadiredja 1975). In many instances, this line of reasoning explains many failures, but other people tend to discard this opinion and suggest that peasant farmers in low-income societies are trapped in a technical and economic equilibrium featuring (1) little change in technical, social, and economic conditions, (2) equilibrium in supply and demand and allocative efficiency, and (3) low productivity and slow growth (Stevens 1977). This situation for subsistence farmers has been described as a low productive steady state (Ruthenberg 1980), and this condition may be the main reason why rural training and extension, small-farm credit and development of new institutions, reclamation programs, and increasing land holdings, have not resulted in the expected improvements.

Since the subsistence farmer's goal is to produce enough for himself and his family (Ruthenberg 1980), he will only increase his inputs if his needs increase, with only a small disposable income. Capital formation is therefore next to zero. Increased production without access to a suitable market may even hurt the farmer. It is no wonder that in many cases credit schemes degenerate into mere give-away programs.

There will be no capital investment including land reclamation as long as the farmer remains in a subsistence economy. It is not necessary to introduce peasant farmers into the market economy through their main crop. Often it turns out that an entirely different commodity becomes the catalyst. It is said that Japanese farmers started improving their rice culture 150 years ago, after the silkworm was introduced. In many new settlements in Sumatra and Kalimantan, Javanese rice farmers became prosperous by growing coconuts or citrus. They in turn are able to purchase inputs for their other agricultural activities. In Timor, subsistence maize farmers are now able to reclaim large areas of useless land by row planting *Leucaena leucocephala*, not because they can grow more maize, which they do, but because of the cash they earn from fattening cattle with grass mixed with *Leucaena* leaves. Even Irianese stone-age sweet potato growers from the Anggi Highland are willing to walk for 3 to 4 days to market the 30–40 kg of garlic they can carry each time. It is a strange sight, indeed, to see these half-naked men deposit their earnings in a modern bank.

If changing individual farmer's attitudes is difficult, land reclamation on a regional basis involving smallholders is next to impossible, unless certain conditions can be utilized or created. Reforestation and many land reclamation schemes have practically failed. Pangoedijatno and Mangoensoekarjo (1975) mention only a few of the many programs gone wrong in North Sumatra.

From the few success stories to be mentioned below, one can invariably see that strong, even charismatic, leadership and participation of a highly motivated farming community are imperative. In Sikka (Isle of Flores) around 20 000 ha of degraded land were reclaimed under the leadership of a priest (Metzner 1982), and a formerly impoverished populace is now vigorously switching over to a market economy by growing estate and fruit crops beside their traditional staple food (maize). The changes brought about by contour planting of *Leucaena leucocephala* on the appearance of the region and especially on the people are astounding. The same leguminous shrub was used in the reclamation of seriously degraded land in Amarasi (Isle of Timor). Land previously infested by *Lantana camara* and short grass is now supporting cattle and maize production. Here traditional land regulation is enforced by local government (Metzner 1983). Grazing land is separated from forest and arable land and vigorously enforced. The owner of cattle that stray out of these assigned areas pays stiff fines to the village treasury. Here is a case where traditional (*adat*) law is instrumental in land reclamation even with an influx of outsiders. In the Gunung Kidul area (Central Java) farmers have been successfully reclaiming their degraded land after the local government succeeded in coordinating different agencies. Sand traps (check dams) were constructed, tube wells drilled, leguminous trees (*Leucaena* and *Glyricidia*) planted, and pastures established. Improvements are still being made, and here too the changes are dramatic. In conclusion, it can be said that even in densely populated areas, land reclamation is possible.

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Environmental Characterization of Acid Tropical Soils

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Summary

Environmental characterization of acid tropical soils deals not only with the pedon, but also with the three-dimensional soil mantle organization, at the scale of eco- and agrosystems. Every time lateral and vertical differentiation is taken into account, it has been shown that most physical properties are ordered in the landscape. These properties appear to be particularly important considering that many of the driving forces governing pedogenesis and fertility depend on the rates and vectors of chemical and water transport. Under these conditions, sequential testing seems to be the most appropriate approach for obtaining a direct correlation of soil properties with plant response.

Introduction

According to Glinka (1927): "Soils are conceived to be independant natural bodies, each with a unique morphology resulting from a unique combination of climate, living matter, earthy parent materials, relief, and age of landform. The morphology of each soil, as expressed by vertical section through the differing horizons, reflects the combined effects of the particular set of genetic factors responsible for its development."

This approach leads logically to the concept of the pedon, defined as "the smallest area for which we should describe and sample the soil to represent the nature and arrangement of its horizons and variability in the other properties that are preserved in samples" (Soil Survey Staff 1975).

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It is thus implied that there is a one-to-one connection between the environment and a pedon or a group of pedons representing a given soil series (polypedon). According to this approach, environmental characterization allows us to determine within which limits the knowledge acquired by the study of a pedon or polypedon may be extrapolated to a landscape surface. In an environment that is supposed to be homogeneous, the polypedon thus represents a soil that is within the limits of physical, chemical, and mineralogical variability of a given soil series.

This definition of the soil in relation to its environment seems to allow an extrapolation to be made of the knowledge acquired through agronomic experiments on a group of polypedons to all the surfaces containing a similar group of pedons represented as a mapping unit. Therefore, soil maps appear to be very useful for those who manage agricultural development projects.

The environmental characterization of acid soils of tropical regions may be summarized as follows:

- Rainfall appears to be crucial: the limits of acid tropical soils in IBSRAM documentation nearly coincide with the 1000-mm isohyet;
- Mean annual temperatures are in the range of 20 to 27°C;
- Water balance for these soils is usually positive for at least part of the year;
- The soil moisture regimes may vary greatly depending on the nature of the soil. They range from aquic to ustic;
- The soil temperature regimes are usually isothermic and isohyperthermic;
- The natural vegetation is evergreen forest, deciduous subtropical forest, or savanna. When this vegetation is destroyed for cultivation, the surface soil moisture and surface temperature regimes are altered;
- Soil fauna is extremely dependent on vegetation and on the soil climate;
- Parental materials are diversified (sediments, weathered crystalline rocks);
- Landform and geomorphic elements are specific to the tropics; it has been shown that these elements are closely related to the distribution of different soils in the landscape.

Such environmental characterization requires an interdisciplinary approach, mainly based on the study of the interactions and interdependences of dynamic processes in physical surroundings (Kilian 1975).

Whereas all these environmental characteristics relate to lower categories in Soil Taxonomy (family, series), this paper deals with the problem of spatial and temporal variability at the much smaller scale of eco- and agrosystems. Specific examples are presented.

To describe the dynamics of key fertility parameters, Sanchez et al. (1983) chose three fields, ranging in size from 1 to 2 ha, and approximately 300 m apart from each other, having the same soil (classified in the same family, series, and phase), and the same geomorphic position and standing vegetation. They noticed that "the time at which nutrient deficiencies appeared and the amount of fertilizer or lime

needed to correct them, varied substantially between the three fields." For instance, aluminum toxicity (more than 60% Al saturation in the topsoil) was apparent after 1 month in field I, after 45 months in field III, and has not yet appeared in field II, after 8 years. Having established this site variability, the authors concluded that "These differences are probably related to the longer time between cutting and burning in fields II and III, and perhaps to the quality of the burn itself, depending on when it rained last." It is therefore necessary to consider not only the intrinsic properties of the pedon but also the management history.

Wilding and Drees (1984) write the following: "Landscape variability is the very essence of pedology" and "Inability to adequately cope with spatial variability remains a major obstacle to interpretation of field research." According to them, "Spatial variability can be grouped into two broad categories, random and systematic. Random variability includes changes in soil properties that cannot be related to a known cause. When the soil system is investigated in greater detail, a part of the variation considered random may be recognized as systematic. Systematic variation is a gradual or marked change in soil properties as a function of landform, soil forming factors and soil management by man." They add that in many agronomic experiments, "Variance due to soil parameters is extracted as blocking or as replication error and given little attention. Under these conditions, sequential testing appears to be more appropriate to direct correlation of soil properties with plant response." However, the topography is not a sufficient criterion to explain variability of crop behavior. It is necessary to know the spatial pattern of the soil mantle and its dynamics.

Let us now turn to our main example, a description of the soil mantle on old offshore bars. The chosen site is situated on prelittoral bars at the border of the Guiana Shield. These old offshore bars have flat or rounded tops, are 200–500 m wide, and are parallel to the seashore. They are composed of Pleistocene marine sediments. Their soils range from Oxisols to Spodosols, yielding considerable variability in the soil mantle (Turenne 1977; Boulet et al. 1982, 1984). Given the extensiveness and agronomic interest of these soils, and in spite of their variability, we have studied selected sites and carried out agronomic experiments.

Analysis of the Three-Dimensional Structure of the Soil Mantle

The aim of structural analysis is to determine spatial variability in three dimensions of the soil mantle of elementary landscape units, so that pedogenesis and soil behavior may be easily visualized.

The elementary landscape unit, in this case, is a section of the old offshore bar. It has been studied by means of transects oriented perpendicularly to changes in soil patterns following landscape features, changes that depend on the orientation of the bar. By drilling bore holes it is thus possible to recognize and compare the main pedological materials. After the limits of the various pedological volumes encountered in the bore holes are included in topographical maps, the inventory of

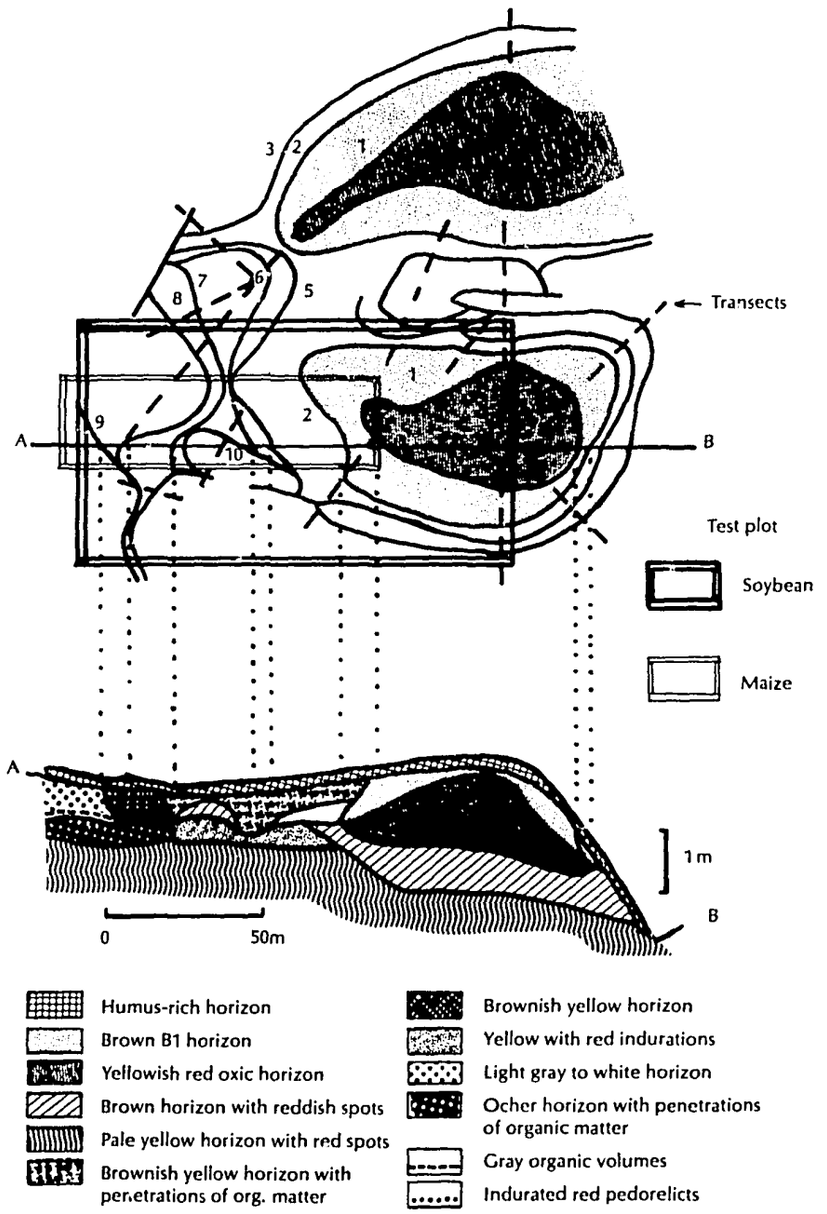

Fig. 1. Section and map of the experimental site showing transects and the location of test plots.

these samples is then set up by using simple descriptive terms (color, texture, porosity, moisture at a given time). By making additional bore holes as needed, it is thus possible to draw the accurate geometry of the various soil bodies that have been observed.

In the present case, a dozen materials may be distinguished on this section that differ by their color (yellow red, brown, yellow, light grey), their texture (from sandy-clay to sand), the presence of red volumes that are differently indurated, by penetration and accumulation of organic matter, and by ocher patches around the voids (Fig. 1). Soil pits are then dug at appropriate sites to observe in detail the materials and to sample the principal horizons that are specific to this pedological mantle.

To draw the map, one can use first the most important lateral variations that can be accurately determined, such as the appearance and disappearance of horizons and variations of some of the above characters. Then, back in the field, variations are checked along secondary transects. By appropriately placing additional bore holes, we can accurately determine the limits of the horizons and of their properties. On the map, points representing the same stage of pedological differentiation are then linked by a continuous line. These continuous lines are called "lines of isodifferentiation."

The principal features that can be distinguished in the present example (see Fig. 1) are:

- On the side of the shoulder is the unit characteristic of an oxic horizon that is clayey and most permeable; to the left are horizons that are progressively lower in clay content and which are deeply penetrated by organic matter; corresponding soils are delineated by unit 7 on the map.
- Starting with unit 5, the bottom of the same horizons have grey organic volumes; and we have seen that, during the rainy period, considerable moisture accumulated due to the decrease in internal drainage.
- To the left of unit 7 the soil in the upper horizons is a pale yellow color and extremely low and very sandy. The lower limit of these horizons is sharp; the bottom of these horizons, during the rainy season, has a seasonally perched water-table.
- Beyond line 9, the top horizons are bleached and permeability is very low.

Sequential Testing of Plant Response in a Given Landscape Unit

The experiments presented here were carried out by agronomists from IRAT and ORSTOM (Godon 1981; Worou 1983). The first trial involved two successive cycles of soybean. The test plot was rectangular and comprised most of the pedological variability that had been studied. Measurements were made according to

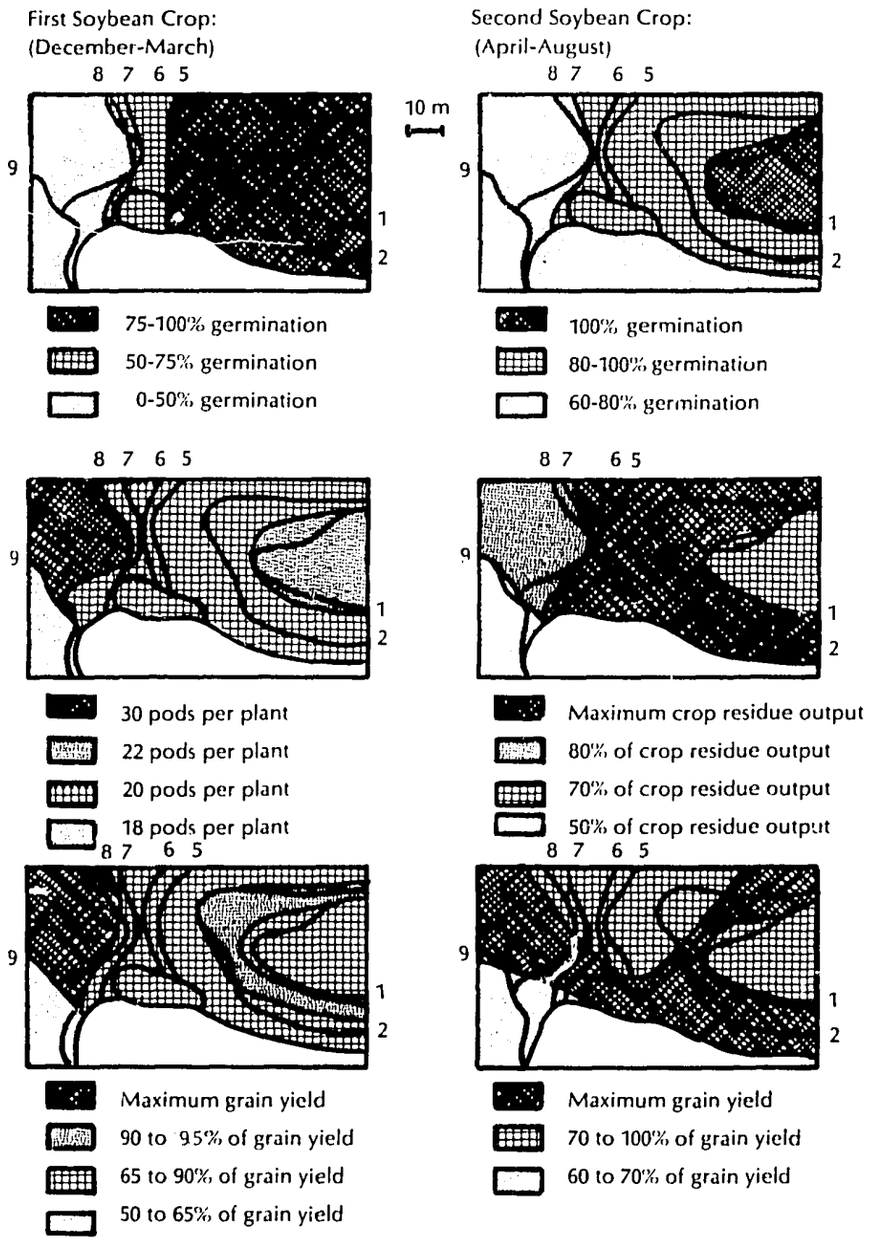

Fig. 2. Soybean behavior during two successive crop cycles.

a grid 1 m wide; they included number of seedlings per m^2 (percentage of maximum), number of pods per plant, volume of crop residues, and grain yield. The first cycle, from December to the end of of March, gave the results presented in Figure 2.

Germination occurred under favorable rainfall conditions. The best results were found wherever drainage was sufficient. An excess of moisture, linked to a decrease in internal drainage, was clearly visible to the left of line 7, precisely where the seasonally perched water-table was observed.

In some places, the number of pods per plant compensated for low plant density. In the area between lines 8 and 9, low plant density and the considerable water reserves (caused by the low permeability of the deep horizons) favored soybean pod development when a drought took place in March. On the other hand, to the left of line 9 an excess of water limited soybean production. To the right of line 7, the normal density of plants led to pod counts of lower than 20 pods per plant. Better water retention in the more clayey Oxisols delineated by line 1 accounted for the higher pod counts in this area.

As for grain yield, the high number of pods per plant between lines 8 and 9 largely compensated for poor germination and resulted in a maximum yield of 1.4 t ha^{-1}. The yield was lower on the right side of line 8 because of lack of water; nevertheless, it was a little over 90% of the maximum in between lines 1 and 2, where conditions were favorable at the end of the cycle. On the left side of line 9, the combination of low density and limited number of pods resulted in a minimum yield (0.7 t ha^{-1}).

The second cycle, from the end of April to the end of August, gave the results shown in Figure 2. Germination occurred during a period of heavy rains. The results are like those of the previous crop but shifted toward the better-drained soils (Oxisols, delineated by line 1). Nevertheless, maximum germination obtained in this trial was only 23 plants per m^2, in comparison with 41 plants per m^2 during the first cycle. The worst results occurred on the left side of line 8, exactly as in the previous crop.

The amount of crop residue (see Fig. 2) is once again in accordance with the soil properties. Better rainfall distribution explains why the maximum residue amount is attained, for this trial, between line 1, which delineates the oxic soil unit, and line 7, which delineates the area lower in clay content.

The grain output is maximum (2.1 t ha^{-1}) in the area limited by lines 9 and 1. Low germination was more than compensated by the number of pods per plant (data not shown). Grain yields overlap to the left of line 1, but do not correspond to any predictable soil limit. This may be due to an unknown event during maturation.

This field test demonstrated the importance of compensation phenomena that are so typical of soybean cultivation. Thus, it was necessary to carry out more experiments, with maize, which is less prone to compensation. In addition, to appraise soil resistance to root penetration, different types of tillage were compared:

with a heavy 60-cm disk harrow, with a tooth scarifier, and with a 4-disk plow. The limits of the field test are shown in Figure 1. The data are shown in Figure 3.

At the first stage of cultivation (28 days) the distribution of plant height correlates very well with the way in which the soil was prepared. This influence is clearly marked by the horizontal patterns. The tooth scarifier gave the best results through the whole pedological sequence.

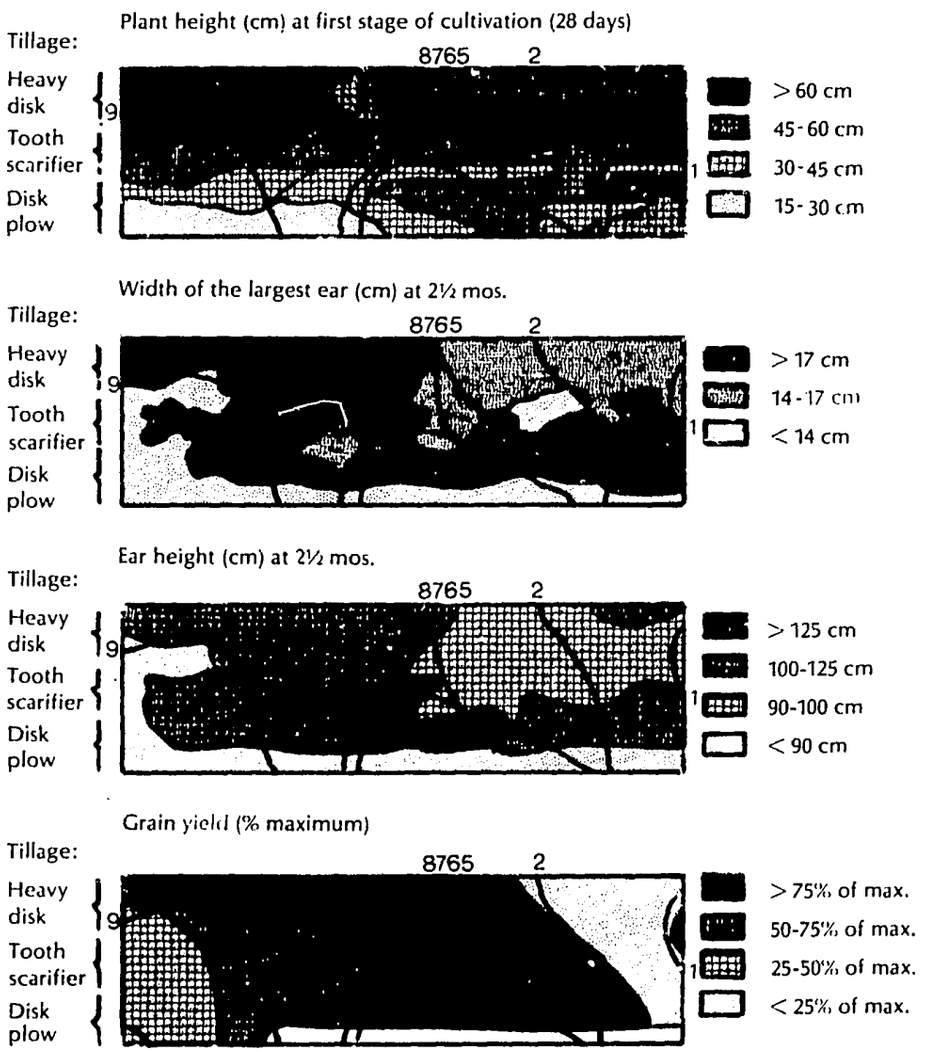

Fig. 3. Maize behavior as affected by soil mantle variation and tillage treatment.

As time went on, the influence of the pedological properties became increasingly important, as measured by the width of the largest ear and ear height at 2½ months. The soil that is low in clay, located between lines 7 and 9, which had produced the best results for soybean, appeared to be most favorable at this stage of maize cultivation.

Highest yields were obtained in the area limited by lines 2 and 9, that is, on the soils that have brown to yellow horizons, are low in clay, and are deeply penetrated by organic matter.

Concluding Remarks

Through these tests, marked changes in plant response appear directly correlated with pedological gradients. Thus, agronomic experiments have to take into account changes in soil properties linked to pedogenesis. These soil properties that are found on typical landscapes of old offshore bars (that cover hundreds of thousands of hectares), thus offer accurate and reliable guidelines for extrapolation of results of agronomic trials from the test site to similar sites.

Given the existing interactions between soil and climate, it is necessary to replicate these trials during different seasons, so as to derive partial but accurate predictions for each growth stage as a function of climatic condition.

Let us not forget that in these acid tropical soils, natural chemical fertility is low, whereas physical properties greatly vary from one site to the other. This is why we have stressed morphological and physical properties of these soils. These properties appear to be particularly important, considering that many of the driving forces governing pedogenesis and fertility depend on rates and vectors of chemical and water transport (Wilding and Drees 1984).

It should be clear that it is not only in the specific case of the old littoral bars that physical properties are ordered in the landscape, a fact understood by native populations, who prefer to locate their small fields in specific areas in close agreement with pedological patterns.

One final remark is worth adding: all variations in the environment, no matter whether they are caused by natural conditions (climatic, tectonic) or by human action (deforestation, cultivation), trigger transformations that show an orderly pattern in time and space. We simply have to discover this orderly pattern, instead of negating the existence of variations or regarding them as artifacts of the analysis.

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Socioeconomic Considerations in Acid Tropical Soils Research

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Summary

Socioeconomic considerations are relevant to the management of acid tropical soils, primarily because the term "management" refers to the behavior of farmers toward crops and soils. This behavior, in turn, is a function of (1) past behaviors, (2) current constraints of land, labor, capital, and technology, and (3) the opportunity costs of the individual household.

Populations may or may not have precise knowledge of their soils or their management, due to the voluntary or forced resettlement of people. When a population is able to be sedentary in a given physical area for a generation or more, it is likely to have considerable precise knowledge—what we may call an integral system. By contrast, dislocated populations are likely to practice what may be called a pioneer system. A pioneer system is more likely to resemble the agricultural requirements of the area of origin than those of the area of resettlement. An example of an integral system was reported in H.C. Conklin's Hanunoo Agriculture *(1954). Examples of pioneering systems are many, among them E.F. Moran's* Developing the Amazon *(1981).*

Pioneering systems in the first decade after resettlement tend to be characterized by subsistence agriculture because of poor infrastructure development, scarcity of labor and capital, low yields, and the dominant role of the market for land. Thus, emphasis in the early years of frontier settlement ought to be on baseline research, both agricultural and socioeconomic, rather than on credit, extension, and crop commercialization. After the first decade, the area's potential is clearer, land speculation may decrease, and a growing number of farmers arrive to produce crops—a population more receptive to

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agricultural technology and production than the earlier one. These conclusions are based on a comparative analysis of the U.S. frontier in the 17th and 19th centuries, and on the Amazonian frontier of the past 2 decades. There is evidence that it may apply to Africa and Asia, but few cases from those areas have been analyzed.

Introduction

Social scientists generally do not conceptualize their research in terms of agroecological zones, such as the humid tropics, and certainly not in terms of their soil characteristics. A growing number of social scientists, however, like myself, are defining their long-term research interests by studying the potential of the humid tropics for intensive agriculture. This potential has considerable significance for both agronomy and anthropology, for anthropology especially because much of the existing literature suggested that the humid tropics could not support human societies above the level of the small, isolated village (Meggers 1954, 1971 being the most prominent advocate of such a view). In my own case, the plans of Brazil to build a major highway across the Amazon Basin, the Transamazon Highway, and to attract settlers from throughout the country to farm the Amazon seemed to provide an ideal setting to study just this hypothesis. To carry out this research, I studied soil science, agricultural economics, and biological ecology, in addition to social anthropology.[1]

This paper illustrates the value of attention to the interaction between people and the soils and plants they manage. This value lies not only in facilitating final acceptance of technological packages that might be proposed to farmers, but also in providing a faster flow of information from farmer to soil scientist that may be worth experimenting with.

Until recently, only very little social science research in the humid tropics has had obvious and direct relevance to the work of soil scientists. The first study to document in a convincing manner the management expertise of preindustrial populations was that for Hanunoo agriculture (Conklin 1954). In a later publication Conklin (1963) made an important distinction that I will follow and elaborate upon: he contrasted *integral* with *pioneer* systems of shifting agriculture. Integral systems were those used by populations who for long periods of time held rights to land in an area that they had come to know with great preciseness of detail. In contrast, pioneer systems were those in which the populations were recent settlers and in which the social organization and integrity of cultural knowledge had been

1. More and more social scientists have sought this dual training that we might call "agricultural anthropology." Most of them emphasize training in agricultural economics alongside their anthropology. A few have emphasized crop science, and a smaller number still have sought competence in soil science. An organization of researchers with this competence now exists, the Anthropological Study Group on Agrarian Systems. They publish a newsletter, Culture and Agriculture, and organize interdisciplinary symposia at national meetings of various societies, in both the social and agricultural sciences.

disrupted by either external or internal forces. Evidence for such disruption could be seen in the simplification of shifting cultivation practices, the shortening of fallows, and the declining rates of intercropping.

This distinction between integral and pioneer systems did not have much impact upon subsequent work in the social sciences. Anthropologists have tended to take the position that native peoples know their physical environment and that it is unnecessary to test the accuracy of native knowledge. Although still dominant, such a view is increasingly being questioned. Now it is seen that most native peoples' traditional forms of social organization, cultural knowledge, and familiarity with the environment have been disrupted by resettlement and adoption of nonnative knowledge and technology, which has resulted in the loss of traditional expertise. It is important to note that native systems of knowledge are embedded in complex behavioral systems that require ritual, musical events, folk tales, and other forms of transmitting agricultural information to remain viable through regular use. With the arrival of radios, tape recorders, and other technologies, time is taken away from traditional forms of communication. Moreover, participation in seasonal wage labor disrupts the normal investment of individuals in maintaining traditional knowledge. Thus, the integrity of native knowledge becomes a question to be investigated rather than assumed.

This leads to the realization that native peoples, and any other population that has had extended residence in the same area, have important adaptive knowledge about land-resource management, about adaptive varieties, and about coping with local ecological constraints. The accuracy of their knowledge varies a great deal, however, depending on the integrity of their institutions, especially those responsible for transmitting information about production and for assuring the esteem of those individuals who are the repositories of expertise. The rule of thumb to use to determine whether such knowledge deserves particular attention by scientists is the length and stability of residence of the population in the region. The longer the residence, the more likely they are to have important insights into the constraints presented by a region and information about how to cope with them. Because many, but not all, of these populations may not be well integrated into market systems, they are unlikely to have selected for high yield in their plant varieties. Instead, they are more likely to have selected for, say, coping with aluminum toxicity, acidity, or low levels of potassium. Thus, their selected varieties are likely to have desirable characteristics for reducing the cost of inputs and still intensively managing the acid soils of the tropics. It will be rare to find among these populations crop selection for high-yielding varieties.

Evidence for the Knowledge of Some Native Populations

The Hanunoo Study

The classic study by Conklin (1954) is not the most relevant to our workshop since the soils of the Hanunoo population in Mindanao, the Philippines, ranged in pH

between 5.8 and 7.8, had a high base content, and contained no major nutrient deficiencies. However, it is relevant that this population had cultivated the same area for over 100 years with a population of at least 4 persons per km^2, and the crops were carefully matched to minute differences in soil characteristics. For their native system of soil classification, the Hanunoo considered moisture content, sand content, rock content, general texture, firmness, structure in the dry season, stickiness in the wet season, and color. Permanently muddy soils and those characterized by fine silty gravel were never selected for shifting cultivation; most fields chosen for this purpose had firm soils. But the Hanunoos avoided soils too hard or too loose, the latter likely to result in erosion. Soil sample data in Table 1 reflect the quality of the soils selected. In addition, the population paid close attention to slope (average shifting cultivation field slope is 46%) and native vegetation on the locality. Most areas cleared were fallowed for no more than 12 years, and there was an elaborate system for judging the preferred types of forest vegetation to be looked for in selecting an area.

Thus, it is evident that, all things being equal, the more complex the criteria for soil and crop selection, the more likely that this is an integral system rather than a pioneering one—and the more likely that there is a wealth of knowledge to be acquired and tested. Of course, today we are most liable to find less complex systems that, nevertheless, have sufficient expertise to benefit agronomic research.

The Hanunoo cultivated 92 different rice varieties and about 280 recognized plants in their shifting cultivation fields. Any given field in 1 year only had a fraction (about 40–60) of the available varieties, but such diversity is still remarkable since the average field was only 0.5 ha. Grains planted tended to be classified by how long they took to mature, and farmers attempted to plant maize that matured in 4, 5, or 6 months. Whether this reflected a labor bottleneck or a preference for fresh maize is not indicated in the study; however, I suspect some constraint was at play here. After grain cultivation, the field was planted with root crops and then with perennial tree crops.

The amount of labor invested in shifting cultivation was considerable: a minimum of 2200 man-hours per ha. The diversity of intercropping, in addition to the

Table 1. Soil samples taken from Hanunoo shifting cultivation plots in the Philippines. (Adapted from Conklin 1954.)

Property	Mean value	Range	N
pH	6.92	5.8-7.8	54
Clay (%)	45	16-62	24
Available P (kg mg^{-1})	22.4	tr-50	54
Available K (kg mg^{-1})	86.03	tr-200	54
Available Ca (kg mg^{-1})	12,289	1500-40,000	54
Available Mg (kg mg^{-1})	252.2	50-750	54

high labor investment, led to continuous production: 16 to 35 different cultivated food plants were harvested each month on a year-round basis. The efficiency of production in this system was high, according to Conklin. For every man-hour of labor invested in rice cultivation, 2.5 kg of rice resulted, a figure that compared favorably with those available for other parts of Asia in the 1950s (Gourou 1966). Thus, we can note some features of such integral systems: a high labor investment, relatively small areas to manage intensively, and high yields per unit of land.

At the conclusion of his study, Conklin noted that pioneer systems were less efficient and more environmentally destructive than integral systems such as those of the Hanunoo. However, at the time there had been little documentation to permit a controlled comparison between these two types of system.

The Transamazon Study

While my research in the farming communities along the Transamazon Highway was not designed to compare the agricultural system of Amazonian *caboclos* (the term for rural poor in the Amazon) with that of the newcomers, it did not take long for this problem to become an obvious and important dimension to my research (Moran 1979, 1981). After several months of taking soil samples in the farms of the Transamazon migrants, we noticed that the Amazonian *caboclos* seemed to have selected soils with similar color and similar texture. When we compared our data with the soil samples previously taken and analyzed, we discovered that the soils selected by the *caboclos* were also remarkably superior in base status and pH, with practically no aluminum—in contrast to most of the soil samples taken on the dominant Oxisols and Ultisols of the region.

When soil fertility is visualized by the size of the hexagon using the system developed by Alvim and Cabala (1974), the remarkable fertility of *caboclo* soils is evident, contrasted with the soil fertility of plots selected by newcomers (Fig. 1). Newcomers to the Amazon, like newcomers to almost any significantly different area, lack criteria for soil selection based upon species growing on given soils, color, or desirable moisture levels to meet the needs of plants given the microecological conditions of the new site. In the absence of accurate criteria, pioneers or newcomers tend to turn to oversimplified criteria, the most common of which in forested environments tends to be the girth and/or height of the trees. This was as true in the 17th century in the United States as it is today in this and other areas of the Amazon where I have carried out field research. For this area of the Transamazon settlement scheme, the criteria of tree height and girth was associated with poorer soils.

The Amazonian *caboclos* picked the superior soils due to familiarity with the tree species associated with those soils in that particular area (Table 2). The ability to extrapolate that knowledge from place to place depends upon the patchiness of the environment and upon the pattern of species dispersion and endemism. I found, in fact, that only *caboclos* who had been farming, hunting, and fishing for the past 20–30 years in the immediate area (i.e., Belo Monte), had accurate knowledge (see

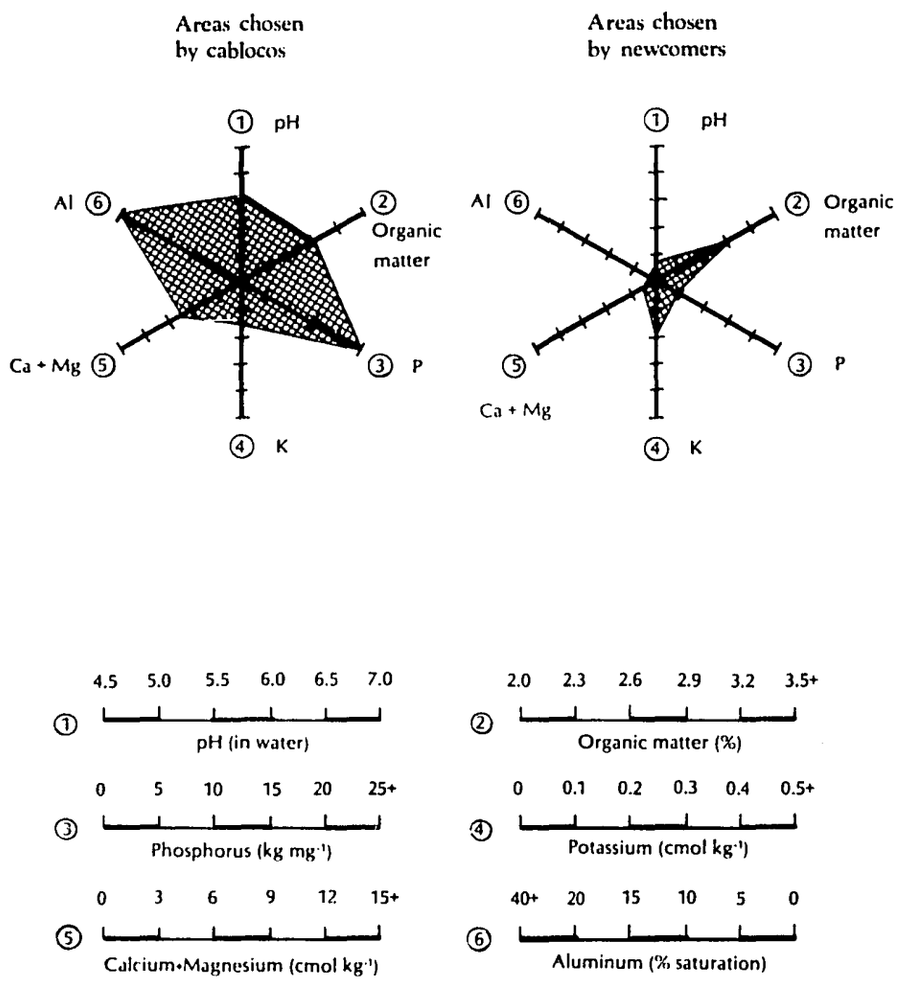

Fig. 1. Soil fertility of farms chosen by local and nonlocal settlers in the Transamazon settlement scheme.

Figure 2 for the range of this population and thus for the accuracy of their developed criteria). Amazonian *caboclos* from the state of Amazonas, an area at considerable distance from the Altamira colonization scheme, chose acid, low-nutrient status soils just like non-Amazonian newcomers. Thus, in saying that natives have precise knowledge, it must be made clear that we must get beyond labels that may be used to stereotype a socioeconomic group but that lump together those with accurate expertise of local agroecological systems and those who are as new to the local constraints as the pioneers and the scientists. In this case, knowing that someone was a *caboclo* was insufficient to know whether the individual might know the soils of an area of interest. Rather, the crucial information is to know how long they have lived in the immediate area, how much they have gotten around the area during the period (i.e., what was their territory), and whether they have found good soils in the area. Only then might one proceed to the next step of collecting a soil sample to test the accuracy of these local systems of soil identification.

The local *caboclos* not only picked superior soils but also managed them more intensively and in a more intercropped pattern than did newcomers. Yields per ha were higher for *caboclos* than for newcomers (Moran 1981, p. 142), in part because they had better soils and in part because they planted their own varieties rather than the still poorly tested ones introduced from outside. In addition, they cleared smaller areas for cultivation (6.3 vs. 8 ha for newcomers) and allocated the

Table 2. Species of trees used by *Caboclos* to select agricultural land and forest vegetation indicating poor agricultural soils. (From Moran 1981.)

Scientific name	Local Brazilian term
Indicating good agricultural land	
Bauhinia spp.	Mororó
Emmotum spp.	Maxarimbé
Euterpe oleracea Mart.	Açaí
Orbignya martiana	Babaçú
Piptadenia spp.	Faveira
Tabebuia serratifolia D. Don.	Pau d'arco *or* ipê (yellow variety)
Tabebuia vilaceae Hub.	Pau d'arco *or* ipê (purple variety)
Unidentified	Pinheiro preto
Indicating poor agricultural land	
Alexa grandiflora Ducke	Melancieira
Anacardium giganteum Engl.	Cajú-Açú
Caryocar microcarpum (or *Villosum* Pers.)	Piquí
Ceiba pentandra Gaertn.	Sumaúma
Holopyxidium jarana Ducke	Jarana
Lecythis paraensis Linn.	Sapucaia
Manilkara huberi (or *Mimusops huberi* Ducke)	Massaranduba
Vouacapoua americana Aubl.	Acapú

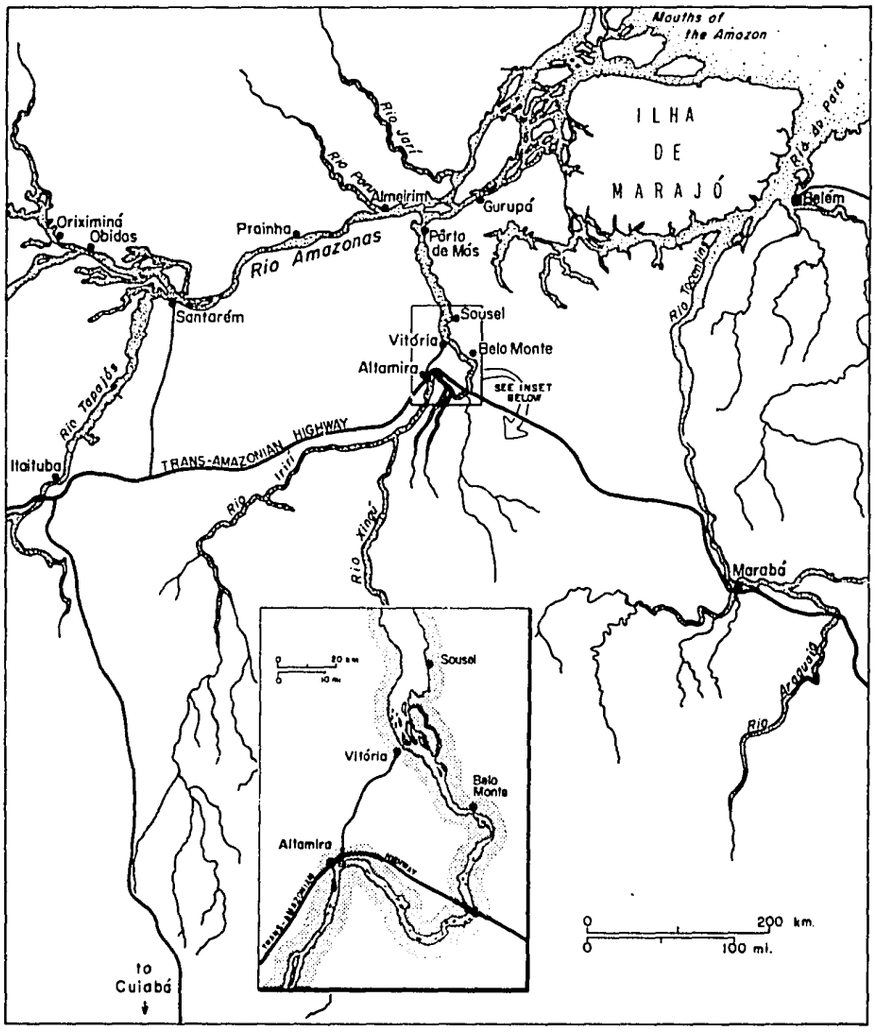

Fig. 2. Range of *cabloco* population in the Transamazon settlement scheme (darkened areas in inset).

additional labor into managing their farms and earning off-farm wages, resulting in more than twice the available income from these noncereal crop activities.

This brings us to an important socioeconomic dimension. From a comparative analysis of frontiers in a wide range of areas carried out during the past year and still on-going, I am coming up with recurrent similarities in the behavior of pioneer settlers in the early stages of frontier occupation. These findings may be of some interest to you given that so many areas being opened up for settlement today in Latin America, Africa, and Asia are precisely on acid tropical soils.

Human Behavior in a New Frontier Zone

The considerable similarities that exist among frontier areas during the early stages of occupation result from the following similarities: (1) who moves to the frontier during the first decade, and (2) which strategies are preferred by the early frontiersmen in coping with the abundance of land, the lack of labor, the lack of capital, and the lack of infrastructure to facilitate marketing (Curti 1959, Bogue 1963, Swierenga 1970, Lemon 1972, Nelson 1973, Moran 1981).

Only a small proportion of early frontier migrants are serious about farming and have backgrounds to suggest that farming is their primary occupation. This small minority, in the 10 to 20% range, tends to pick better soils from the start than do the majority of migrants—although factors such as the degree of freedom in site selection and the adequacy of roads to market might alter the soil selection strategy. Experienced farmers will tend to ask the local or native population about how they choose soils for agriculture, or they will use scientific criteria or careful assessment of the soil itself (as opposed to using vegetational criteria in an area unfamiliar to them).

The early frontier can best be characterized as a "speculative frontier" (Swierenga 1970). Frontier development generally takes place in societies where population is increasing, where political leaders encourage economic expansion through incorporation of as-yet-undeveloped geographical areas, and where mineral finds bring about spontaneous flows of people. But frontiersmen enter such pioneer societies at very slow rates, primarily because of the perception of high risk involved, the lack of clarity as to what strategies will work, and not knowing whether political leaders will really aid and reward those who undertake such a move.

During this early stage, migrants come primarily from the upper lower and lower middle class. Few, if any, come from the upper and upper middle classes because for them the early frontier offers little attraction; their interest in the frontier develops later, when the potential of a given frontier has been assured and they can determine if their realm of economic activity is likely to benefit from frontier activities. Nor is the early frontier a haven for the poorest of the poor: they generally lack the capital resources to undertake a long-distance move and find it difficult to be freed from indebtedness in areas of origin. This generalization is undermined, however, by the growing frequency with which governments plan colonization schemes to give them priority. Such government-directed schemes have

a poor track record because they tend to recruit a population with even less capital and farm-management experience than those more self-selected populations in situations where government has a lesser presence (Nelson 1973). But even in these projects, one will find greater diversity in background than one would expect to find if one took the government selection criteria seriously (Moran 1981).

Most early migrants aim to maximize the area of land they control or have title to, rather than engage in farm-making (Bogue 1963, Swierenga 1970, Gates 1973), which is the chosen strategy of only relatively few. Evidence from frontiers as diverse as 17th-century Pennsylvania (Lemon 1972), the 19th-century Midwest (Curti 1959), the 20th-century Amazon (Moran 1981), and others are consistent in the low levels of farm management present in the early settlement of each frontier and in the tendency to buy more land than can be managed with available labor.

In a study during 1984 in the Carajás colonization area of Brazil, it was notable that after 3 years of settlement there had been 620 lots sold, but only 62 had farmers residing; of these 62, no more than 50 had carried out any farming activity on the land (Fig. 3). Of these 50, less than 6 had built any significant storage areas or sheds for farm equipment, put up fences, or engaged in other normal farm-making activities.

Early migrants, in addition to buying up or claiming more land than they need, also hire themselves out because of the relatively high wages paid in frontiers. Wages have tended to be 100 to 300% higher in early frontiers than those in areas of origin of migrants. This wage differential attracts to the frontier a significant

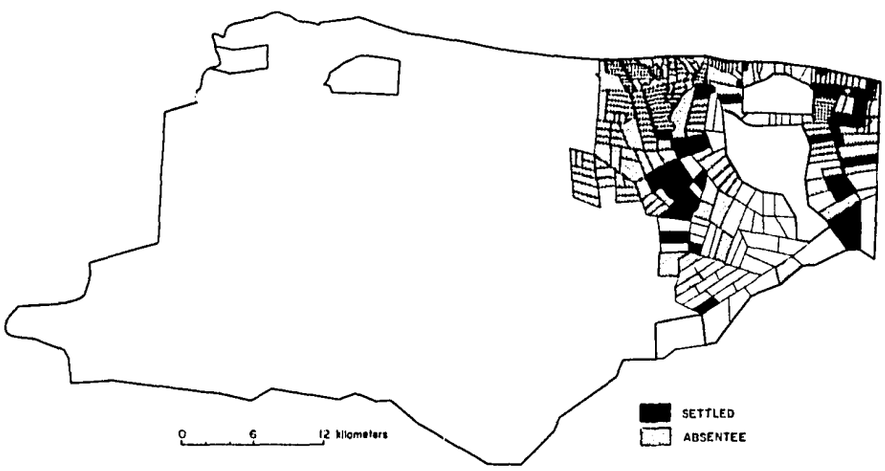

Fig. 3. Lots sold vs. lots actually farmed after 3 years of settlement in the Carajás area of Brazil. (Moran 1984.)

proportion (30–40%) of craftsmen and urban wage earners. It also attracts labor away from farming and into a broad array of activities—petty trading, transportation, fence-making, and town-building. Many of these activities are related to efforts to increase the value of land and of the region as a whole, so that the land-maximizing strategy pays off. Thus, the frontier attracts about a third non-farmers, about a sixth of experienced farmers, and the rest composed of low-level professionals, rural wage earners, and some upwardly mobile sharecroppers. They tend to be younger (28–35 years old, mean age head of household) than those who stay behind, but they tend to have less education than those who migrate into the city (i.e., rarely more than 4 years). In both the Transamazon settlement and the Carajás scheme, the ability of households to avoid indebtedness was due to wage labor. The difference between nonfarm income and yearly profit is shown in Table 3. It is essentially wage labor. Even the small proportion of farm-makers allocated at least one member of the household to off-farm employment. A much larger proportion allocated practically all their labor to wage labor and carried out minimal subsistence agriculture, if at all (cf. Chuta and Liedholm 1979 on the importance of nonfarm employment in rural sector development).

Regardless of background, settlers emphasize subsistence production in their agricultural activities, in part because of the inadequate road and marketing fa-

Table 3. Economic indicators of resettlement schemes in Brazil. (Moran fieldnotes 1972-74, 1984.)

Basic indicators	Transamazon (1973)	Carajás (1984)
Beginning capital (US $)	275	4000
Previous mobility	4.6	1.9
Previous credit (%)	21	73
Previous title to land (%)	20	57
Previous education (years)	3.2	6
Urban experience (%)	30	75
Previous social class (%)	96 "lower"	87 "middle"
Area of origin	30% north; 31% northeast; 23% south; 14% central west	80% south; 20% central west
New location performance		
Sick days/year	11	12
Number of cattle	2.3	5.4
Number of pigs	2.7	6.9
Number of chickens	21.6	42.5
Farm income (US $)	720	2000
Nonfarm income (US $)	2000	2500
Yearly profit (US $)	1700	1500
Grain yield (kg ha^{-1})	950	900

cilities but also because of the diversion of labor from farming to off-farm employment. Indeed, this may be the correct strategy since there appears to be a recurrent problem of low yields from farming efforts in forested frontiers during the early period. Within 10 years, yields at least double (whether in 17th-century Pennsylvania or the contemporary Amazon). It is unclear whether this has to do with labor investments in farm management practices (i.e., weeding), or whether it is due to some chemical soil-plant interaction that remains poorly understood.

Early frontier settlers rely for their survival on their subsistence farming and on off-farm employment, the proportion of the latter depending on the availability of capital, the rate of development, and the availability of labor within the household. Net income is invested not in farm-making but, rather, in either consumption or additional land purchases. Besides the minimum subsistence activities, settlers emphasize activities that increase the market value of land rather than its productivity. The former is most often achieved by clearing as much forest as possible—thereby transforming a relatively free good into an economic one that will gain in value as the frontier develops. In the Carajás settlement scheme, bank financing was highly correlated with rate of forest clearing ($r = 0.74$, $p = 0.0001$). This means that practically the entire loan went to maximize area cleared, and practically nothing was left for other facets of the agricultural cycle such as planting, harvesting, or weeding. The result was inadequate management of the area cleared, areas that are overrun by secondary succession, but which gain in value because they no longer have forest on them. The value goes up even faster if pasture grasses are seeded at the time of clearing to reduce the vigor of the successional process.

What all this implies is that most settlers in the early frontier period go there aware of the potential gains to be derived from the development of the area, but have no certainty as to what might happen. The environment is unfamiliar, the social system is absent and requires negotiation for nearly all social positions, the economic value of the region is undemonstrated, and the national leaders may or may not link the region to existing markets – thereby contributing to the development or underdevelopment of that frontier region.

A minority strategy tends to be to look for good land near roads and markets, to invest household labor in clearing areas that can be managed with that labor, to invest net income in farm equipment, buildings, and livestock, and to help build social and political institutions through participation. The majority strategy, in contrast, is characterized by clearing more land than can be worked, by allocating portions of the household labor in salaried occupations to capitalize on the high wages available, by a lack of concern with soil quality than with maximizing areas cleared and other practices that would enhance the market value of land, by investing net income in either consumption or more real estate, and by investment of available time in activities other than the building up of local social and political institutions.

Can we find any socioeconomic or cultural features that might characterize these households practicing the minority strategy of farm-making? It is not uncommon for government to presume that good farmers come from given regions, such as

southern Brazil, which *as regions* have attained greater agricultural modernization. However, one needs to remember two factors in this regard:

1. Those who go to new frontier areas will rarely be the better farmers. The better farmers will have done well in areas of origin and would be reluctant to leave profitable operations for highly risky situations in a new frontier.
2. In any given region there is a highly variable array of farming abilities, and any given region is unlikely to have a monopoly on good managers. In fact, stagnant agricultural areas are more likely to export good managers to a frontier area than are progressive areas where opportunities for these persons are abundant.

If it is not region of origin that can be used to predict success, what might one use? I would argue that the precise criteria would have to be based on the agrarian history of the given country (Moran 1979). For a country like Brazil, I have found that having owned land in the area of origin is a predictive index of the management capacity of the head of household (Moran 1979). In the Transamazon settlement scheme such households had higher net incomes and invested more of their net returns in farm-making than did households that lacked such previous experience (Table 4); they also tended to pick better soils than did the others. Given their interest in farming, they paid more attention to this resource and in most cases did better in this regard. In the Carajás settlement scheme, the same thing hap-

Table 4. Economic status of Vila Roxa farmers, Transamazon resettlement scheme.[1] (Adapted from Moran 1981.)

	Previous land owners		Nonowners	
	Entrepreneurs	Independent farmers	Artisan-farmers	Laborer-farmers
Beginning capital	571	97	243	20
Average debt to bank and INCRA	5391	1785	949	750
Salaried income per year	6857	800	2610	643
Farm income per year	714	1257	536	381
Gross income per year	7571	2057	3146	1024
Expenses	3429	1157	1313	1153
Net income per year	4143	900	1833	−129
Liquid assets accumulated	7214	1143	53	63

1. Based on a 50% sample of Vila Roxa households (N = 25). Figures in 1974 U.S. dollars.

pened. Most of those with the best soils in the area had low rates of previous residential mobility and about 20 years of ownership experience with a small property (average of 23 ha). They translated these holdings into more than 100 ha on the frontier and into reasonable yields (Fig. 4: asterisks indicate farmers with the above characteristics) as compared with the low yields of the population as a whole (950 kg ha^{-1}).

By contrast, the majority of the population lacks experience in land ownership, and in more than 30% of the cases in agriculture itself. Soil selection by this group tends to be rather random and based more on proximity to friends they know or to distance to available employment. Those with the worst soils in the Carajás settlement scheme were mostly urban households trying out their luck (urban households are data points with triangles). Some picked reasonably good soils also, given that the scheme is located in one of the patches of Alfisols in the Amazon region. Yields on even relatively fertile soils by this group ranged between 230 and 700 kg ha^{-1}. Yields such as these, given the availability of reasonably good hybrid seeds, and extension service advice, can only be explained by the quality of the clearing and burning, or by the lack of management (analyses of selected soil samples from the scheme are shown in Table 5).

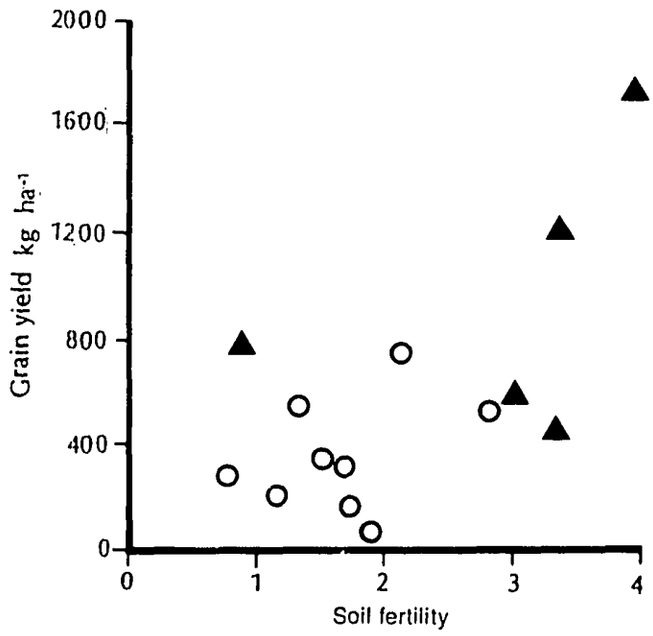

Fig. 4. Soil fertility level and yields in Carajás. (Moran 1984.)

Within the first decade, anywhere from 20 to 60% of the early settlers will have sold or abandoned their holdings, depending on the speed with which the frontier developed and the price of land went up. The faster the price of land goes up, the faster they will sell their original holdings—either to settle in the developing frontier town or to go on to newly settled frontier areas to buy up more land with the gains made in the current frontier.

Thus, it is incorrect to presume that land abandonment is necessarily a measure of failure—as is common to assume in social-science writings on frontiers and in development-agency evaluation studies. Selling current land holdings may be simply a rational and profitable way to convert one's labor investment and to achieve a considerable improvement in one's relative economic position. This latter consideration brings us to one of the most overlooked aspects of socioeconomic research on frontiers: one of the goals of most individuals in any stratified society is the enhancement of his relative social position. Given that the national stratificational system is so vast, individuals tend to view their goal as that of improving their relative rank in their community of residence. However, over time most communities develop ways of restricting access to the limited number of positions that carry prestige and authority. One of the few opportunities available to individuals in social systems to change their relative position is by movement to a frontier during its formative stage.

Table 6 illustrates just such a situation in a frontier county of Wisconsin in the 1860s. Note that it is only in the first decade that migrants under 30, and those with total property of under US $1000, can hope to achieve major leadership positions. After the first decade, the income and age requirements of leadership become higher. Moreover, it is these very same early settlers who remain in those leadership positions and who prevent even wealthier late arrivers from achieving local political authority. Only 6 out of the 24 leaders in the 1880s had come after the 1860s—suggesting a locking in of leadership by a small early arriving group.

Table 5. Soil analyses from a Carajás colonization area. (Moran 1984 soil sampling.)

Property	Mean value	Range	N
pH	5.76	4.20-7.30	23
Clay (%)	19.90	3.69-43.18	23
Available P (kg mg^{-1})	4.50	2.00-10.00	23
" K (cmol kg^{-1})	0.20	0.08-0.46	23
" Ca (cmol kg^{-1})	4.14	0.49-12.72	23
" Mg (cmol kg^{-1})	0.95	0.30-2.60	23
Available Exch. Al (cmol kg^{-1})	0.38	0.00-4.43	23
Available ECEC (cmol kg^{-1})	5.66	1.86-15.49	23

Early frontiers offer one of the few opportunities for lower middle and upper lower class people to achieve a significant change in their relative social position in their lifetime. Most of the important local social and political leadership positions will be occupied by early settlers. Thus, while settlers arriving in later decades may come with more capital and achieve greater total wealth, only a small proportion of them will be able to make major gains in relative social rank. Most people, including the better off, will probably end up at roughly the same relative social position. However, it is the potential for mobility that makes early frontiers so attractive to myth makers and nation-builders, and why it is used to increase the pace at which population would engage in what is a high-risk strategy.

Relevance for Research on Acid Soils of the Tropics

The above discussion highlights the benefits to be derived from an appreciation of socioeconomic variables in the design of research on agricultural development in general, and of soil science research in particular. In testing the value of native varieties, for example, one needs to find out how integral the total life of the population has been in a given area and not be deceived by the apparent antiquity of current practices. The fit between current behaviors and knowledge and the current environment being exploited may no longer be present. In addition, finding

Table 6. Age, occupation, and property of 201 leaders elected to office in Wisconsin, USA, in the 1860s. (From Curti 1959.)

	Major leaders		Minor leaders		All leaders	
	Pre-1860	Post 1860	Pre-1860	Post 1860	Pre-1860	Post 1860
Age						
Under 30	23	0	31	27	29	25
30-39	42	67	45	39	44	41
40+	35	33	24	34	27	34
Occupation						
Agriculture	62	33	83	67	77	65
Professional	15	17	5	10	7	10
Business	4	33	3	12	4	15
Artisan and labor	19	17	9	10	12	10
Total property owned (US $)						
Under 100	0	0	13	8	10	7
100-999	11	0	33	22	29	20
1000-2999	44	67	38	34	39	37
3000-4999	28	17	10	21	14	21
5000+	17	16	6	15	8	15

that a particular village or individual is no longer in precise attunement to the environment does not necessarily mean that the next village or individual may not be.

In addition, the choices made by local populations about soils and crop choices are the result of a complex calculus that includes agronomic considerations, nutritional needs of the household, the need for cash in the household, and social/religious obligations. Thus, the selection of given soils or crop varieties in pre-market or areas poorly articulated to markets is rarely based on the primacy of yield and more on the need to get security of yield under existing constraints at the lowest possible labor cost. Thus, it is inappropriate to test native varieties against newly introduced varieties using yield as the measure. Rather, the proper measure should be how the two varieties perform in fulfilling these multiple needs of households at low levels of input—and perhaps moving the population toward greater security of income. We know, for example, that native Amazonians plant their fields 90% with cassava (*Manihot esculenta*) and that they plant very small areas in maize and beans. Such a choice reflects the better performance of cassava in acid soils of the humid tropics and the well-known agronomic problems in achieving acceptable yields for maize and preventing disease and insect infestations in beans of the genus *Phaseolus*. The crops chosen also acknowledge the difficulties of providing fertilizers and lime at reasonable cost in most of the Amazon region.

Many suggestions can be made for insights to be derived from the frontier studies I have mentioned. It is doubtful that any government policy will be successful in preventing the migration of young, speculative lower middle and upper lower class individuals to the frontier. There is also very little that is likely to be effective in providing a break to their strategy of maximizing area claimed or bought. However, it may be possible to slow down the rate of deforestation associated with the strategy of increasing land value by reducing the availability of credit during the first 5 to 10 years of frontier settlement. This will not stop the process, but it will slow it down enough to perhaps give time to soil scientists and other scientists to carry out the baseline studies necessary to have adaptive varieties available and crop mixes that might provide a foundation for the development of agriculture in the area. Thus, it seems to me that resources that currently are dispersed between agricultural credit, extension, and agronomic research should be focused totally on agricultural research during the first decade. Only then will there be sufficient knowledge tested under local microecological conditions to provide a foundation for a viable farm sector. While the availability of this knowledge will not in itself prevent the speculative processes of frontier development, it would provide a more viable farm sector option than exists normally during the first decade. The poor results of agriculture during the first decade simply provide a logical basis to further deforestation and land speculation, labor investment in nonfarming activities, and available capital going to other activities. Greater adaptive knowledge about farm management and the nonsubsidization of speculative activities through credit could very well change the course that frontier development has had for centuries.

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Transfer of Acid Tropical Soil Management Technology

José R. Benites*

Summary

Soil scientists need to know whether the technologies that appear promising at primary research sites are viable in other humid tropical environments. On-farm and on-station research done by trained local scientists will provide much-needed feedback to soil scientists. At the international level, a research network would be a successful mechanism to test new technologies such as the low-input crop-production system developed at Yurimaguas. The most important constraints to technology transfer include a high degree of covariance among soil properties and climate, lack of on-site trained personnel, research institutions organized into several commodity and disciplinary programs, lack of cooperation between research and extension, high operational costs, and complicated logistics. Some ideas on how to remove institutional constraints for technology transfer are presented. In addition, some examples of successful soil management technologies and their transfer are given.

Introduction

In the last 20 years there has been an increasing awareness of the strategic role of soil management in agricultural development of the humid topics. Research from Yurimaguas, Peru, and other areas of the humid tropics is addressing the fundamental problem in tropical agriculture of maintaining land productivity and preventing soil degradation (TropSoils 1985). The technology that has grown from this research is already having an impact. Improved land-clearing methods, selec-

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tion of acid-tolerant crop cultivars, identification of soil constraints, monitoring of soil dynamics, and development of improved grass-legume pastures, managed fallows, and soil management options for the Peruvian Amazon have improved productivity and should be applicable to other countries (Sanchez and Benites 1983). However, many of these findings need to be tested throughout the humid tropics to assess their validity and determine the necessary modifications for specific physical and socioeconomic situations. Attempts at such testing have identified the lack of on-site trained personnel as one of the major constraints to the validation and transfer of technology. This paper provides an approach for the transfer of acid tropical soil management technology.

Extrapolation as Related to Soil Fertility

Extrapolation, as related to soil fertility, assumes that soil and crop management technology from one area can be used in similar soil-crop-climatic areas (Buol and Nicholaides 1980). Dependent on a high degree of covariance among soil properties and climate, such extrapolation is necessarily imperfect to varying degrees (Isbell 1985).

Technical soil classification systems may aid in extrapolating soil fertility research results to users. The Fertility Capability Classification (FCC) system (Buol et al. 1975) uses physical, chemical, and mineralogical properties from the upper part of the soil profile to classify soils based on their management properties. Within groups, similar fertility management responses are expected. Management responses are predicted to be different between groups, while the basis for extrapolating management systems exists within groups.

Since the FCC system is designed to provide responses to soil management practices, data showing response curves related to rate of fertilizer application are of specific value if the initial level of "available" nutrients has been determined by soil test methods. Experiments relating results or benefits from band vs. broadcast methods, preplant vs. side-dress fertilizer placement, subsurface drainage vs. surface drainage, and any other experiments that compare management techniques on identified soils are of value in documenting the usefulness of the FCC in technology transfer (Buol and Sanchez 1985).

Farming Systems Approach to Research Planning

In most tropical countries, research institutions cannot generate all the technologies required to overcome the spectrum of acid soil management problems with which they are now faced. In spite of a steady increase in the number of scientists, such situations arise from several causes: frequent reorganization of research institutions; poor reward systems for scientists; lack of trained manpower; inadequate facilities; and budgetary restrictions, which are particularly acute with regard to operational funds.

Much of the generated technology has not been entirely appropriate to farmers' circumstances, particularly small-scale farmers, who constitute the bulk of the population and depend mostly on their own food production to satisfy family needs. Too often, ideas proposed for extension fail: such ideas were not adopted or were adopted only partially or in modified form. Failures have been numerous: many improved crop varieties, tillage, fertilizer, or plant protection recommendations, grazing management or stock-feeding proposals, all technically sound, have failed when tested at the farm level (Simmonds 1984).

The induced commodity-oriented research strategy may be partially responsible for the gap between research results and the adoption of recommended practices. In most government structures, research and extension agencies are usually separate organizations. Hence, it is not uncommon to find personal rivairies between researchers and extension workers. All these factors affect the transfer of technology from research programs to extension agents and finally to the farmers. Recognition of this problem has led to the application of a farming systems approach to research planning. The concepts and principles partially responsible for the farming systems methodology are valid for generating appropriate acid tropical soil management technologies.

The leading principles of on-farm research are described by Perrin et al. (1976), Byerlee and Collison (1980), Zandstra et al. (1981), and Shaner et al. (1982). Simmonds (1984) summarized the procedures as follows:

1. There is a multidisciplinary team which:
   - identifies the "target" areas or "recommendation domain" and
   - analyzes its technical/economic structure.
2. The team
   - identifies economically sensible innovations and
   - does research on them, on the experiment station, on a few selected farms, or on more numerous farms, according to circumstances.
3. The experiments are monitored and analyzed economically, and, if successful, they lead to recommendations for the extension system to disseminate.
4. There is a continual feedback of information to the research and extension components.
5. The national research institutions assume a responsibility for training and network development.

On-farm research, which is different from commodity or disciplinary on-station research, starts from the precept that only farmer experience can reveal to the researcher what the farmer really needs. On-farm research involves research and extension, together with the farmer, and serves the interests of both services in their nation's agriculture and development program.

As shown in Figure 1, in moving through the sequence from experiment station results to extension and farm production, the complexity of the trial (num-

ber of treatments and replications) at each location diminishes, and plot size and the number of locations increase. As these changes take place, the extent of farmer management of the trials also increases and the need for researcher management decreases (making possible the larger number of locations). Concomitantly, the capability and need to control sources of variation decrease, while the need and possibility of measuring the sources of variation increase. As the above changes occur, biological precision and discrimination among variables decrease while the ability to test socioeconomic interactions under farmers' conditions increases. All the above changes increase the number of farmers involved in formal research and increase the direct investment of farmers in that research. Finally, as the number of involved farmers increases, the interaction of extension with research is enhanced (Hildebrand 1976).

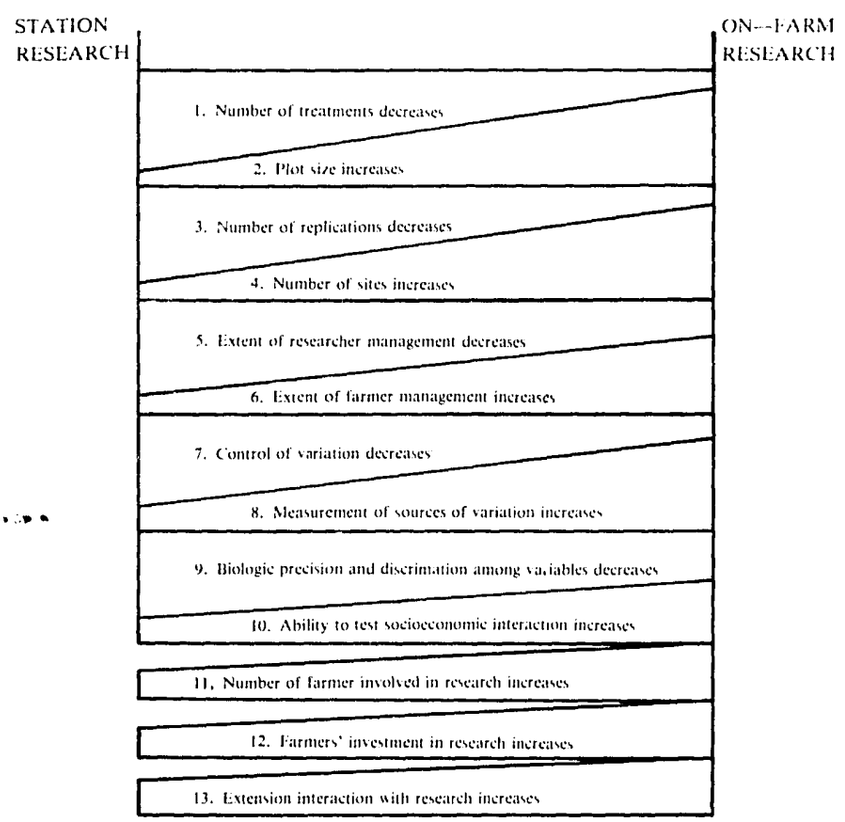

Fig. 1. Characteristics of on-farm and on-station research.

Constraints to On-Farm Research

The institutions responsible for the generation of new acid tropical soil management technologies require researchers who are able to work with farmers under limited facilities. On-farm research often concentrates activities on farmers' fields in or near villages where there is little infrastructure and the availability of only a few services, such as lodging, meals, and laundry. Consequently, experienced researchers may not want to live there. The solution is to hire B.S.-level research officers who are willing to work in isolated environments, and who are more interested in gaining experience than in receiving high salaries. With some support from experienced researchers, such systems may be successful. Training of national cadres should be systematically coordinated with processes leading to the design of soil management research projects.

On-farm research requires a different mix of support staff, facilities, and equipment than experiment station research. Regional on-farm research programs succeed or fail on the strength and reliability of transportation and timely financial support for fuel, materials, salaries, and the like. In order to reduce costs and logistical problems, such research, at least in the early stages, should only include small geographical areas with no more than 5 to 15 farmer-managed trials, 8 to 12 site-specific or regional trials, and the collection of crop records from 5 to 10 farmers.

Networking appears to be an appropriate operational model with which to face the lack of on-site trained personnel and the high operational costs and logistic problems of technology transfer of soil management with an on-farm approach.

The research network is a successful mechanism that has served to validate CGIAR-generated technology throughout the world. Examples of succesful networks are INSFFER, coordinated by IRRI and IFDC, CIAT's Cassava and Pasture Networks, and several others.

Examples of Successful Soil Management Technologies and Their Transfer

Intensive Crop Rotations

In 1978 the Tropical Soil Research Program of NCSU/INIPA began a series of demonstration plots with several three-crop-a-year rotations on selected shifting cultivators' fields near Yurimaguas, Peru (Bandy et al. 1980). The plots were cultivated according to the farmers' resources, using improved agronomic practices without lime or fertilizer, and using improved agronomic practices with moderate liming (1 t $CaCO_3$ equivalent $ha^{-1}y^{-1}$) and fertilization (60 kg N ha^{-1} for rice and maize only, 35 kg P ha^{-1} per crop, and 22 kg Mg ha^{-1} per crop). We considered this last system equivalent to the "complete" treatments developed at the Yurimaguas Experiment Station, although the on-farm fertilization rates were somewhat lower. The rotations were planted on slash-and-burn forest clearings on

land that had lain fallow up to 10 years; the soils were similar to, and somewhat more fertile than, the station's.

The results, summarized by Nicholaides et al. (1985), were impressive. In the first rotation, cumulative grain yields using the "improved technology" ranged from 7.9 to 11.4 t ha^{-1} y^{-1} (Table 1). The shifting cultivators' yield usually ranges from 1 to 1.5 t ha^{-1} (Smith 1981). Soil nutrients were depleted in the traditional system by crop removal and diminuation of the ash effect after three consecutive crops. In that system, soils become more deficient in P and more acidic, with exchangeable Al increasing and Ca and Mg decreasing; organic C also decreased. Nutrient depletion was reflected in declining maize and soybean yields in the respective maize-peanut-maize and soybean-rice-soybean rotations. In the second year, yields declined even further in the unfertilized system as depletion of soil nutrients became more severe. An economic evaluation was made for the maize-peanut-maize rotation, which gave the highest net revenue per hectare, exceeding a 600% return (Bandy et al. 1980); this technology and rotation on a 15-ha farm, using US $180 (half borrowed at 64% interest) and the labor of the farm family alone provided an annual net income of US $2797. The average farm family's net income in the Yurimaguas area is US $750.

Table 1. Average cumulative grain yields (t $ha^{-1}y^{-1}$) of 11 small farmer-managed continuous cropping demonstration trials from July 1978 to June 1979 near Yurimaguas, Peru. (After Bandy et al. 1980, Nicholaides et al. 1985.)

Crop rotation	Production System: Unimproved shifting cultivation	Improved, no lime or fertilizer	Improved, with lime and fertilizer
Maize	2.44	3.81	5.12
Peanut	1.10	1.36	1.62
Maize	1.77	2.73	4.06
Total	5.31	7.90	11.40
Peanut	0.97	1.22	1.49
Rice[1]	1.91	3.56	4.53
Soybean	1.34	1.98	2.75
Total	3.53	6.76	8.77
Soybean	1.43	2.09	2.73
Rice[2]	1.91	2.25	2.53
Soybean	1.51	1.89	2.22
Total	4.49	6.23	7.48

1. Rice in the traditional system is the traditional Carolina variety; in both improved systems, it is IR 4-2.
2. Rice in all systems is the traditional Carolina variety.

After the first year, all initial farmers in the project used improved seeds and insecticides. Ten adopted plant-spacing techniques, six adopted weeding at critical times, five said they would be willing to use fertilizer, and none adopted lime. The results of this project are important, but they do not provide all the answers for changing the region's predominant agriculture practice from shifting to permanent cultivation. The fertilizer-based technology will need strong support to provide the essential communications, materials and supplies, marketing, research and extension services, credit, and seeds.

Low-Input Cropping

Innovations must either fit the farmer's economic circumstances or those circumstances must be changed to make the innovations work. Generally, the simpler and cheaper the innovation, the more likely its adoption. In this regard, the low chemical input crop production system could be a more appropriate starting point for addressing some of the more pressing problems of shifting cultivators. The low-input technology developed at Yurimaguas consists of an upland rice-cowpea rotation with zero tillage, absence of lime, proper plant spacing, small rates of N, P, and K, and adequate weed control.

The results of a 1-ha field cleared of a 10-year-old secondary forest on an Ultisol with pH 4.6 after burning are shown in Table 2 (Benites and Nureña 1985). The field included a fertilizer differential, either zero or 30 kg N ha^{-1}, 50 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1} applied to each rice crop except the first one. The results show high yields in six consecutive crops harvested without a significant response to fertilizer application. Such results are quite different from the check plot yields, which dropped to practically zero after the second consecutive crop. The check plot was tilled but was not fertilized or limed. The combination of acid-tolerant cultivars, zero tillage, and complete residue return may be responsible for the difference.

Table 2. Productivity of a 1-ha low-input system after slash and burn of a 10-year-old secondary forest in an Ultisol at Yurimaguas during the first 29 months (September 1982-January 1985). (After unpublished data, Benites and Nureña 1985.)

		Grain yields (t ha^{-1})	
Crop sequence	Planting date	No fertilizer or lime	Fertilized crops 2,4,6
1. Rice cv. Carolina	Sept. 1982	2.44	2.44
2. Rice cv. Africano	Feb. 1983	2.99	3.11
3. Cowpea cv. Vita 7	Sept. 1983	1.09	1.24
4. Rice cv. Africano	Dec. 1983	2.77	3.22
5. Cowpea cv. Vita 7	May 1984	1.19	0.94
6. Rice cv. Africano	Sept. 1984	1.84	2.02
Total grain yield in 29 months		12.32	12.98

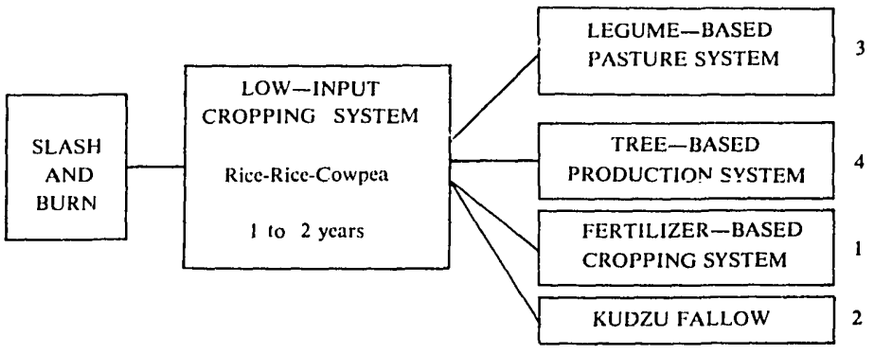

Fig. 2. Alternative uses of a field after the third year of a low-input cropping system.

Fig. 3. Network trials established in Peru (1982 - 1984) through the National Selva Program.

Productivity may last for 2 or 3 years but then a decision will have to be made about the permanent role of the field. Alternatives are: (1) high chemical input cropping, (2) managed fallows, (3) grass-legume pasture, or (4) agroforestry, depending upon soil, landscape position, and infrastructure conditions. A detailed description of the low-input technology sequence is shown in Figure 2. A testable hypothesis would be that "A low-input cropping system consisting of a rice-rice-cowpea rotation will increase the farmer's overall output per unit of land and facilitate the transition from shifting cultivation to permanent agriculture."

Before other attempts to implement the low-input technology are made, testing should be conducted through site-specific trials. Testing should include crop species, varieties, rotations, planting dates, and different fertilization and liming rates.

Extrapolation Program Beyond Yurimaguas

The Tropical Soil Program received many requests for assistance in the Selva of Peru. It was necessary to validate the results first to make sure that local adaptations could be incorporated. It became apparent that research workers needed prior training to validate and transfer the results in a sound manner. Participants in the 1983 Tropical Soil Management Course designed validation trials, using specific soil management options which the participants considered appropriate for their localities. These trials were then established throughout the Selva and are now incorporated into INIPA's newly established National Selva Program (Fig. 3). NCSU staff has assisted INIPA in the development of two additional components of the National Selva Program: the National Tropical Pastures Network and the Agroforestry Project.

In 1980 an agreement was reached between EMBRAPA, IICA, and NCSU to locate an NCSU senior scientist at EMBRAPA's Manaus Station to test some of the Yurimaguas experiences in the different environment of Central Amazonia.

In 1984 a similar agreement was signed with the Proyecto Especial Pichis Palcazú (PEPP) with funding from the Interamerican Development Bank to post a soil physics specialist and a pasture specialist in the Pichis Valley of the Central Selva of Peru. A series of trials have been designed to test the Yurimaguas results under this environment.

Additional opportunities for site-specific collaboration may be possible in other Amazonian countries through REDINAA and in acid tropical soils worldwide through IBSRAM.

The overall linkage system of NCSU's TropSoils Program is shown in Figure 4. A distinction is made between sites with an active research program that have NCSU staff on-site and those that have a formal linkage with cooperative institutions. The figure also indicates informal working linkages of a different nature. The one with IITA is one of exchange of information and germplasm. Given IITA's extensive networks in tropical Africa, this link could be strengthened to extrapolate TropSoils results to this area, and vice versa. Linkages with CEPLAC, and with ESAT at Cardenas, Tabasco, Mexico, consist of designing experiments on soil

management in their area of action. Strengthened linkages with IBTA (Bolivia), ICA (Colombia), INIAP (Ecuador), and FONAIAP (Venezuela) are anticipated with the initiation of the REDINAA soils network.

Soil Management Research Network for the Humid Tropics

Many national research institutions are sharply increasing their efforts in tropical soils research. Some are perfectly capable of conducting systematic research within their boundaries. International networks that directly address soils in the humid tropics are in the process of being developed. Such networks should:

1. Develop inter-institutional cooperation *within countries* by working on different aspects of a particular technology (e.g., low-input cropping) and *among countries* by focusing on the generation of different soil management options according to their priorities (e.g., paddy rice cultivation on alluvial soils, intensive mechanized crop rotations, low-input cropping systems, legume-based pastures, and agroforestry);

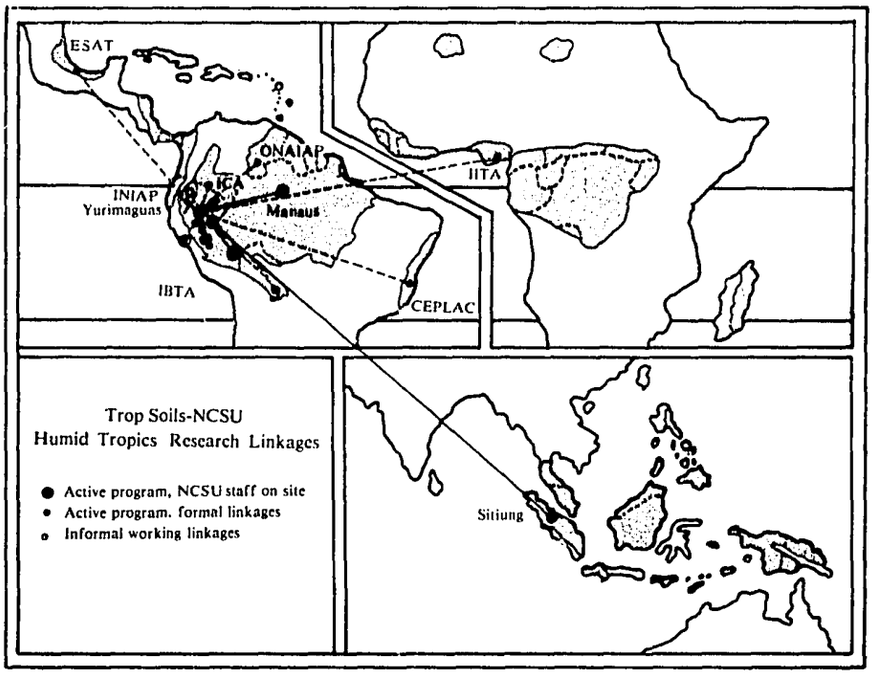

Fig. 4. Linkages in humid tropics research.

2. Train collaborating country personnel, by exposing them to a spectrum of different soil management options;
3. Facilitate a more comprehensive development and testing of research methods and techniques; and
4. Concentrate external assistance and national resources, both of a technical and financial nature, on regions or topics that are expected to have a larger national impact.

An outline of the proposed network activities is shown in Table 3. The general project objectives are:

1. To validate and extrapolate available soil management technologies to other countries beyond primary sites.
2. To develop the capability of collaborating country personnel to conduct, interpret, and report user-oriented soil management research.

Network participants will consist largely of B.S.-level research officers of national institutions who are stationed in humid tropical areas of collaborating countries and are responsible for conducting field research. During the first years, work will be limited to Spanish, Portuguese, and English speakers, to be arranged in two groups. French capability is envisioned later. Examples of potential collaborating countries and their national institutions with a considerable likelihood of willingness to collaborate are listed below according to language groups. Those marked with an asterisk have USAID Missions.

Spanish/Portuguese-speaking:

Bolivia*	Instituto Boliviano de Tecnología Agropecuaria (IBTA)
Brazil	Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA)
	Commissão Executiva do Plano da Lavoura Cacaueira (CEPLAC)
	Instituto Nacional de Pesquisas Amazonicas (INPA)
Colombia	Instituto Colombiano Agropecuario (ICA)
Costa Rica*	Ministerio de Agricultura y Ganaderia (MAG)
	Centro Agronómico Tropical de Investigación y Enseñanza (CATIE)
Dominican Republic*	Ministerio de Agricultura (MA)
Ecuador*	Instituto Nacional de Investigaciones Agropecuarias (INIAP)
Honduras*	Ministerio de Agricultura (MA)
	Escuela Superior Agrícola El Zamorano
Mexico	Instituto Nacional de Investigaciones Agrícolas (INIA)
	Escuela Superior de Agricultura Tropical (ESAT)

Table 3. Outline of proposed soil management research network activities for acid soils areas.

Activity	Methodology	Objective	Product
Selection of target areas	Landscape and geomorphology characterization. Technical soil classification system (FCC)	Dividing a given area into land types and identifying major soil constraints	Land types map, FCC soil map
Problem identification	Agroeconomic survey Recommendation domains	Identification of research priorities by multidisciplinary teams	Report Work plan
Planning and design	Exploratory trials On-site trials	Technology generation	Best alternatives
Evaluation of technologies	Regional agronomic and agro-socioeconomic trials (network)	Verification of homogeneity within the recommendation domains	Best alternatives
Acceptability	Farmer-managed trials Index of acceptability	Individual evaluation of acceptability by the farmers themselves	Recommendations of the acceptable technologies
Extension	Experimental production plots	Promotion of acceptable technology	Adoption of technology
Training	Soil and crop management in-service training	Improving technical knowledge and research capability of each team member	Well-trained research officers of national institutions who are responsible for conducting field research within the network

Panama*	Instituto de Desarrollo Agropecuario (IDIAP)
Peru*	Instituto Nacional de Investigación y Promoción Agropecuaria (INIPA)
	Other participating institutions in the National Selva Program
Sao Tome*	Ministerio da Agricultura (MA)
Venezuela	Fondo Nacional de Investigaciones Agropecuarias (FONAIAP)
	Instituto Venezolano de Investigaciones Científicas (IVIC)
English-speaking:	
Belize*	Ministry of Agriculture
Cameroon*	Center for Soils Research
Ghana*	Soils Research Institute
Guyana*	Ministry of Agriculture
Indonesia*	Center for Soils Research (CSR)
	Institut Pertanian Bogor (IPB)
Jamaica*	Ministry of Agriculture
Malaysia	Malaysian Agricultural Research and Development Institute (MARDI)
	Rubber Research Institute of Malaysia (RRIM)
	Institute Pertanian Malaysia
Liberia*	Ministry of Agriculture
Sierra Leone*	Ministry of Agriculture and Forestry
Surinam*	Ministry of Agriculture
Trinidad*	Caribbean Agricultural Research and Development Institute (CARDI)

Selection of participants will be done via the national institutions. Cost of participant training will be borne by donor agencies or national institutions. Figure 4 shows current linkages and other third-world countries that potentially might join the network.

In-Service Training

A group of up to 20 selected participants will take the Soil Management course to be held at the training center of the Yurimaguas Station once a year. The course will last 6 weeks; both theoretical and practical aspects will be taught. The theory portion should include lectures on basic climatology, soils, land clearing and preparation, crop management, experimental design, economics, communications, and research results on different soil management options. Individual consultation with TropSoils and INIPA scientists on-site will also form part of the theory portion of the course. Practical training includes landscape and geomorphology

characterization, soil classification, laboratory analyses, land clearing, land preparation, fertilizer management practices in the field, and microcomputer use.

Training of national cadres will be systematically coordinated with processes leading to the design of soil management research projects. As project implementation activities are phased in, manpower development will turn from training on research planning to training on experimental methods and techniques for field research on soil management.

Field Research

Prior to the conclusion of the course, participants will design on-farm and on-station trials that will be installed upon their return to their institutions. The focus is likely to be the low-input management option as a starting point for addressing the more pressing problems of shifting cultivators.

The low-input technology developed at Yurimaguas may be the first option to be validated. The research hypothesis can be formulated as follows: "A low-input cropping system will increase the farmer's overall output per unit of land, facilitating the transition from shifting cultivation to permanent agriculture."

A variety of research activities could be adapted. Particularly useful will be surveys, on-station research, researcher-managed trials, farmer-managed tests, and component trials.

- *Surveys.* The *sondeo* methodology (Hildebrand 1976) will be used, in cooperation with the University of Florida's Farming Systems Support Program, as well as soil constraint analysis using the FCC system.
- *On-station research.* Research stations in selected areas will test the low-input technology under local conditions and evaluate its potential.
- *Researcher-managed trials.* Researchers will manage experiments on farmer's fields. These trials will help the team more precisely define the characteristics of the research area and recognize the gap between current and potential yields. Finally, they will provide means for selecting technology according to its suitability for different types of farmers and conditions.
- *Farmer-managed trials.* Farmer-managed trials provide an excellent means for evaluating how new technologies fit into the farmer's system and how farmers react to the proposed changes. For best results, farmers need to manage these tests using resources normally available to them. Plots need to be large enough to permit accurate measurements of the farmers' activities, particularly the use of family labor. The last step will be farmer-managed tests on commercial-scale plots supervised by the extension workers.
- *Component trials.* Component trials combine the methods of researcher-managed trials and farmer-managed tests to examine technologies for a range of conditions. These trials tend to be single-factor experiments—that

is, fertilizer treatments superimposed on farmers' ongoing activities or on farmer-managed tests.

Follow-up and Feedback

A series of activities is designed to provide the necessary follow-up that makes a real research network. It includes site visits by the network coordinator, annual meetings of cooperators that have established trials, developing a data base of results adaptable to microcomputers, and monitoring tours by leaders of the different national institutions.

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Donor Agency Involvement with Agricultural Research Networks

A.D.R. Ker*

Summary

This paper describes the involvement of the International Development Research Centre (IDRC) with agricultural research networks in developing countries. IDRC policy has emphasized assistance to developing-country scientists and institutions to conduct research on their own problems. Over 100 research networks have been supported as part of this assistance.

Although networks take many forms in response to the needs of participating scientists, key organizational components for any one network include:

1. *Common objectives agreed by all network participants.*
2. *Willingness of all participants to adjust research programs to and invest resources in network activities.*
3. *An appropriate level of coordination by a coordinator possessing unusual qualities.*
4. *A level of interaction among participants appropriate to the complexity of the research being undertaken and the needs of the participants.*
5. *Linkage mechanisms, which may include workshops, advisory committees, consultants, training programs, and publications.*

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Introduction

Substantial advances have been made in agricultural production in many countries in recent years. For example, from 1950 to 1970 the world output of grain nearly doubled. In the developing countries, this increase was due almost equally to an increase in the area planted and to yield improvement (Wortman and Cummings 1978). Although it is difficult to quantify the relative contributions of different factors to these increases, it is generally accepted that scientific research has made substantial contributions to yield improvement in many crops. For example, the large increases in wheat and rice yields in the developing countries in the 1960s were largely due to the high-yielding varieties bred at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, and the International Rice Research Institute (IRRI) in the Philippines, combined with improved management practices, including irrigation, fertilizer application, and others.

Although these high-yielding varieties were bred by scientists in the international agricultural research centers (IARCs), the essential adaptation and selection for local conditions was performed by scientists working in national agricultural research centers. It is these national agricultural research systems that appear to hold the key to a major part of the further improvement of agriculture in the developing countries. They and only they, together with the national extension services, are in the position to maintain sufficiently close contact with the enormous numbers of small farmers and livestock producers who are the only people who can increase agricultural production in those countries. Although international organizations, such as the IARCs, can provide valuable support and back-up for these national research systems, there is no way in which they can be a substitute for their activities, except perhaps on a very limited scale.

Scientists in national agricultural research organizations have many difficulties to contend with; these commonly include limited resources in terms of equipment, staffing levels, operating funds, and information availability. There is also the problem of relative isolation—being located far from other scientists working on similar problems.

Scientists worldwide have usually found it essential to discuss their problems and compare notes with other scientists working on similar problems. This is often done on an informal basis at scientific meetings, or by individual contacts, but one of the reasons for the enormous acceleration in the rate of scientific progress in recent years appears to have been the formation of more formal types of networks of cooperating scientists.

In the developing countries, these formal networks appear to be even more important than in the developed countries, because of the limited opportunities for many developing-country scientists to interact with their colleagues, to obtain access to the latest scientific information, and to update their own skills. Also, although in the larger countries internal networks may supply most of the scientists' needs, in the smaller countries only one or two scientists may be working on a par-

ticular problem or in a certain discipline, so that interaction with other scientists working on similar problems has to be international. These appear to be some of the reasons for the considerable growth in international agricultural research networks among developing-country scientists in recent years. Following are some examples of such networks and their impact.

International Crop Testing Nurseries

IDRC prefers the definition of G. Banta (unpublished paper, IDRC, 1982) that a network is "A voluntary association of research organizations with sufficient common objectives to be willing to adjust current research programs and invest resources in network activities in the belief that they will meet their objectives more efficiently than conducting all research alone."

Although networks can take many forms, depending on the needs of the scientists involved, a number of the larger international nurseries in the developing world have been organized by the IARCs. For example, both CIMMYT and IRRI organized testing of their improved wheat and rice varieties in over 75 countries. Such international nursery programs allow scientists in these countries to compare improved varieties from the IARCs and from other countries with their own varieties, and to contribute their own best varieties to the testing programs. They form an important part of the exchange of germplasm and information, which is an essential component of modern crop-breeding programs. Many similar networks have been established by the other IARCs, and somtimes by national scientists themselves.

Plucknett and Smith (1984) have indicated that problems can arise with networks of this type. For instance, national programs sometimes find they are expected to test enormous numbers of varieties, many of which do not contribute much to their own programs, so that they end up primarily serving the interests of the international centers. They point out that these kinds of networks can be counterproductive, and national scientists may complain about and even withdraw from them.

Although these germplasm testing programs are obviously important and should be organized so that all participants benefit mutually, the better types of networks appear to be those in which scientists from national programs fulfill important roles in establishing, organizing, and guiding the network. For example, seven countries in Latin America collaborated in the Regional Cooperative Potato Network to undertake research on potatoes, led by the International Potato Center (CIP) in Peru. Nine major potato-growing problems in the region were identified, and each country took responsibility for research on a different set of problems. This type of collaborative approach allows a more efficient use of resources than if each national program tries to undertake research on all the problems. The friendly collaboration of all scientists involved at regular workshops allows interchange of ideas, research results, and plans for the future, which has the effect of improving all the research programs.

IDRC-Supported Networks

A few words of explanation on IDRC may be appropriate here. The International Development Research Centre (IDRC) was created by an Act of the Parliament of Canada in 1970, largely as a result of Lester Pearson's leadership of the Commission on International Development, which was the predecessor to the Brandt Commission. The Act established the Centre under the control of a Board of Governors, six of whom come from developing countries, and Lester Pearson was the first Chairman of the Board.

The purposes of the Centre were set out in the Act as: "To initiate, encourage, support, and conduct research into the problems of the developing regions of the world and into the means of applying and adapting scientific, technical, and other knowledge to the economic and social advancement of those regions."

Since IDRC is a comparatively small funding agency, it is not able to support large, comprehensive research programs such as those funded by the larger donors, including the World Bank and several others. Therefore, the Board's policy has been to concentrate its support for research in certain broad subject areas, which have been identified as high priority for the developing countries, and where the Centre has sufficient expertise in its four program divisions of Agriculture, Food and Nutrition Sciences; Social Sciences; Health Sciences; and Information Sciences. Within its limited resources, it attempts to respond to requests from developing-country institutions for support of research in these areas.

A particular feature of IDRC support—which was unusual among government-supported funding agencies in its early days, but which has since become more widely accepted—is that the great majority of its grants have been provided for developing-country scientists to carry out their own research programs, without large teams of expatriates to manage and perform the research for them. This approach appears to have given encouraging results and has certainly been greatly appreciated by the developing-country scientists involved in the projects. Almost invariably, these projects have strongly emphasized building the capacity of national research institutions to conduct their own applied research, focused particularly on solving the pressing problems of the great mass of small farmers and other poor people. This emphasis on institution-building has not been in the sense of providing bricks and mortar, but of supporting applied research and training for scientists and technicians, at all levels, and, where appropriate, training for research administrators.

Mainly at the request of the developing-country scientists themselves, an increasing emphasis has been placed on scientific linkages and information exchanges among scientists in several countries working on similar problems, and in this way research networks have grown up. These networks take a great variety of forms, as they basically respond to the needs of the participating scientists themselves; they vary from large networks, with many projects and scientists in a number of countries, to small networks, with only three or four cooperating scientists (IDRC

1980). Some of these networks have proved effective ways for locating and channeling support to the participating institutions.

IDRC's Information Sciences Division has assisted in strengthening some of these networks, particularly in the Agriculture, Food and Nutrition Sciences Division, by establishing specialized information centers, which provide bibliographic services, reprints, and, in some cases, specialized monographs and reviews of the scientific literature in the subject areas covered, to all members of the network and other interested scientists.

Up to 1980, IDRC had been involved in some 72 networks, which included 288 different projects (IDRC 1980). Since 1980, support has been provided for at least 30 additional networks, making over 100 in all. Although the IDRC mandate, as outlined in the Act, encourages the development of cooperation between scientists involved in networks, IDRC itself did not always deliberately create the networks. In some cases, the networks already existed, and IDRC provided funds to strengthen them. In others, when more than one project was developed in a particular area of research, the network developed naturally. In all cases, IDRC attempted to provide flexible and appropriate support to meet the needs of network participants.

In the early 1970s, IDRC supported a number of networks that provided collaboration between developed- and developing-country scientists. Although some of these networks gave fruitful results, a number of problems emerged. It was found that at workshops and other network activities, the developed-country participants, with their greater experience of these types of networks and backed by vastly greater resources, tended to dominate the discussions.

Therefore, for several years, IDRC concentrated on supporting networks of developing-country scientists only, with little input from scientists working in developed countries except for a few exceptional individuals. A requirement for developed-country participation was long experience in developing-country situations and the ability to relate closely with developing-country colleagues. Recently, IDRC started the Cooperative Program, which encourages cooperation between Canadian institutions and developing-country institutions, and a number of networks are developing. These are discussed below.

The Cassava Network

One of the largest networks supported by the Agriculture Division is that developed in close collaboration with CIAT (International Center for Tropical Agriculture), which has world responsibility among the IARCs for cassava research, and later with IITA (International Institute for Tropical Agriculture). This network at one time contained over 50 projects worldwide (Nestel and Cock 1976).

Most of the projects in this network were developed by the responsible IDRC program officer, but technical coordination and support are provided by CIAT, and, in the case of the projects in Africa, by IITA. An advisory committee, which meets regularly, assists in planning. In the early days, the IDRC program officer

coordinated the network, but later CIAT employed two coordinators with IDRC funding, one for Latin America and one for Asia. Consultants from both developed and developing countries also assist in coordination.

A series of workshops on specific cassava research topics have been held, and the proceedings were published by IDRC or CIAT. CIAT also developed a comprehensive cassava information service, with support from IDRC's Information Sciences Division.

A global network such as this logically divides itself into a number of subnetworks, usually covering more limited geographical areas, such as Latin America, West and East Africa, Asia, etc. This saves travel costs and enables projects at similar levels of development to be linked more easily. However, most of the regional workshops had one or two participants from the other regions in order to share experience and information. Also, more specialized workshops on particular technical problems, such as germplasm exchange, are held with selected participants from around the world, in order to get a wide spread of experience and feedback.

The Oilseeds Network

At present, the oilseeds network includes some eight different oilseeds in about 11 IDRC-supported projects in eastern and southern Africa and India. We can use it as an example of a network in which only one crop is the responsibility of an IARC—that is, groundnut is the responsibility of ICRISAT, but the other seven oilseeds are not within an IARC mandate.

IDRC has found it more difficult to plan and assist this network, due to the absence of an IARC with responsibilities for most of the crops involved.

The oilseeds network has the following features:

1. The network coordinator is particularly important. He is based with the national research program in Ethiopia, where he can interact with the national program scientists, help them when possible, and draw their support for other projects in the network.
2. IDRC's Information Sciences Division has developed an oilseeds specialized information service based on the library of the Ethiopian National Research Program, and the service provides photocopies of relevant information and computer printouts of references and abstracts of the various oilseeds to any network scientist who requests them. The coordinator produces an annual oilseeds newsletter for all participating scientists.
3. The network holds an annual workshop, with the site rotating among the various national research programs. The last one was held recently in Hyderabad, India.
4. Now that individual national programs have begun to concentrate their research on specific oilseeds, we expect the network to be able to plan its activities so that particular national programs can confront particular problems as they arise. This will enable them to complement each other and implement a comprehensive research program.

Although it is expected that various problems will arise in the coordination of activities, it appears probable that the national programs may develop more rapidly this way than if they were able to depend on an IARC.

If the national programs request a consultant with a special knowledge of a particular crop, every effort will be made to arrange a visit. Of course, training programs of varying lengths at appropriate institutions are built into each of the projects.

The Asian Rice Farming Systems Network

The Asian Rice Farming Systems Network, previously called the Asian Cropping Systems Network (ACSN), is one of the most highly developed networks with which IDRC has been involved. This network was based on research done at IRRI in the early 1970s, when it became apparent that the further spread of the high-yielding rice varieties developed there would depend on a more detailed understanding of the constraints and requirements of farmers working in the various rice-based farming systems in Asia (Banta 1982).

Although farming-systems research was not new when the ACSN began in 1975, the major achievement of the network was to develop and test a research methodology adapted to the needs of the national research programs and the small farmers of Asia (Zandstra et al. 1981). The ACSN is now recognized as one of the developing world's most successful agricultural research networks (CGIAR 1978). Banta (1982) suggests the following reasons for its success:

1. All the scientists involved had worked in standard agricultural research programs, mainly based on research stations, and all were dissatisfied with the effectiveness of their research results in improving the well-being of farmers.
2. IRRI made a definite commitment to support the national research programs wherever possible. IRRI's staff chose to be partners with scientists in the national programs rather than adopt a patron-client relationship.
3. Only those directly involved in the field research in the national programs and at IRRI were invited to take part in the various meetings and workshops. Thus there was a definite reward for those who worked, regardless of their position, and the discussions dealt with real problems and research results.
4. IDRC made a special effort to organize support for the national research programs and for the scientists and technicians doing the cropping-systems research in the field, as well as support for a high level of interaction among the scientists in the network. This funding model has been followed by other agencies who have contributed to cropping-systems research in Asia.
5. The real responsibility for organizing and managing the network lies with the Asian Cropping Systems Working Group. This is a small group of scientists from each national research program who are directly in-

volved in cropping-systems research and who normally meet twice a year to go over the previous year's results, discuss policy issues, and plan the next year's program.

6. The reports from the Working Group meetings and other relevant written information, whether it is of publishable quality or not, is rapidly photocopied and circulated to all research sites in the network. This insures a rapid interchange of information and that all researchers, however isolated, are kept up-to-date.
7. Each year a monitoring tour to two countries is held to allow young scientists who are actively working on research sites in the national programs to visit other countries and discuss research methods and results with scientists at their own levels.
8. The network coordinator, who is an IRRI scientist with an excellent rapport with the young scientists working in the national programs, visits the national research sites with the national cropping-systems leaders, reviewing the work going on and discussing technical, methodological, and operational problems. This is perhaps one of the most important and valuable features of the network.
9. The Working Group and IRRI have made a particular effort to provide appropriate training for all who become involved in this type of research, including policymakers, administrators, coordinators, and all levels of researchers. All training was done locally in Asia, and there was no training in and no visits to developed countries.

Perhaps one should add that although this network has been outstandingly successful in developing an agreed and workable methodology for farming-systems research, it has been a relatively expensive undertaking because it involves so much traveling for interpersonal interaction.

Also, although the national research programs have considered it sufficiently valuable to have adopted it in virtually all the Asian countries, the location-specific nature of farming-systems research makes it relatively expensive, and a balance needs to be found between replicating research teams in every possible farming system and limiting activities to one or two of the more important systems.

Conclusions

To sum up, networks, like farming systems, must be adapted to the needs of the participants, and therefore they take many forms. Some networks may only be planned to last for a limited period of time, and may then dissolve once their objectives are accomplished. However, most agricultural research networks can be expected to last for a substantial, if varying, period, and these are the ones discussed here.

For networks to be successful, certain principles appear to be important.

1. **Objectives.** All participants in the network need to discuss thoroughly and agree fully on common objectives and set priorities for the network.
2. **Resource allocations.** Researchable problems should be divided among participants in the network according to their research resources and interests.
3. **Coordination.** Although some form of part-time coordination may be successful in some very small networks, IDRC's experience is that in networks of any size, coordination will require a coordinator working somewhere near full-time. (It may be beneficial for this person to maintain a small research program to keep in touch with research.)

   Good coordinators have unusual combinations of gifts, including excellent scientific capability and the ability to form close and friendly relations with colleagues of all ages and levels. They also need good organizing ability and communication skills.
4. **Level of interaction.** It appears that a network dealing with a new and complicated methodology, such as farming-systems research, needs more intense interaction among its members than a network dealing, for example, with a commodity with a well-defined research methodology. This is the reason for the high level of interaction built into the Asian Rice Farming Systems Network as outlined above.
5. **Linkage mechanisms.** In addition to the coordinator, other linkage mechanisms used extensively are workshops, advisory committees, consultants, training programs, and publications. Each of these has a role in supporting linkages in the network, and all were found in the successful networks that IDRC has sponsored (IDRC 1980).

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Part 3. The Acid Tropical Soils Management Network

IBSRAM and its Network Approach

Marc Latham*

Summary

In this workshop, organized to initiate an Acid Tropical Soil Management Network, three major aspects must be dealt with:

1. *Management of acid tropical soils must be clearly defined in a multidisciplinary way, with a view to integrating environmental, agricultural, and socioeconomic factors. A common research approach needs to be developed, keeping in mind the network objective of increasing agricultural production on farmed acid tropical soils. A realistic research agenda must be prepared, considering both experimental and time imperatives.*
2. *The form of the network must be designed to be sufficiently coherent to retain the advantages of a network and sufficiently flexible to take into account local priorities.*
3. *A possible sequence of events could be:*

   - *Identification of National Cooperators;*
   - *Preparation of preproposals by potential National Cooperators;*
   - *A first evaluation and development of a network proposal by a Network Coordinating Committee (NCC);*
   - *Development of a mechanism for coordinating the network;*
   - *Submission of specific proposals by National Cooperators and reevaluation by the NCC;*
   - *Solicitations for funding.*

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Thus this workshop may propose a Soil Management Network which will:

- *Be attractive to national governments;*
- *Have appeal to donors;*
- *Result in improved use, agricultural production, and profitability from farming acid tropical soils.*

Why a Network?

We have emphasized that the goal of this workshop is establishment of a network to assist countries with acid tropical soils in applying existing and emerging knowledge regarding use and management of such soils, which will enable more productive and profitable use of such lands when they are farmed. Please keep in mind that we do not intend to embark on basic research on acid tropical soils, although some basic research may be associated with IBSRAM programs. We want to establish a network, and we want the network to assist and speed the application of existing knowledge through testing, adaptation, and on-farm validation in participating countries and in other countries that can apply the network's results.

Most of us have worked on acid tropical soils and have seen the great difficulties in their agronomic use. An IBSRAM Soil Management Network (SMN) is a cooperative way of tackling these problems and seeking practical, on-farm solutions to them. An SMN can make the best use of the scarce resources available. Three main reasons justify a cooperative effort:

- There is an urgent need to improve the production of regions with acid tropical soil ecosystems. The figures given in the preproposal and your presence here confirm that need.
- Although much remains to be learned about acid tropical soils, a great deal has already been learned, and it is now time to apply that knowledge.
- Independent efforts are too expensive in today's world. Through cooperation, we can speed the development of practical technologies so that ordinary farmers can use them.

Three Workshop Tasks

To define the basis of the IBSRAM concept of a network for acid tropical soil management, we have to deal with three main questions:

- The research problems we have to work on;
- The possible form of the network;
- The possible sequence of events.

Identify and Limit the Problem

Plucknett and Smith (1984) pointed out that the first two conditions of success for a network are that:

- The problem should be clearly defined and a realistic agenda should be drawn up;
- The problem should be widely shared.

Your presence at this workshop indicates that the problem is widely shared; however, the task of "managing acid tropical soils" may not mean the same thing to soil scientists in different regions. For example, in South America there are large areas of very acid soils where aluminum toxicity adversely affects many crops. In Africa some weakly acid soils are rapidly acidified under cultivation, and, after a few years of cropping, there is a rapid decline in yields as a result of fertility depletion and sometimes manganese toxicity. Thus, there is no one simple solution to the traditional problem of low yields and productivity of acid tropical soils.

Developing effective technologies to maintain, and preferably to increase, yields of food crops on acid tropical soils will require pedologists, soil chemists, soil physicists, and agronomists working together in multidisciplinary teams. A network enables the various specialists mentioned, and others if needed, to tackle the many aspects of the acid tropical soil problem, and it facilitates the exchange of results obtained to benefit everyone working on the problem.

The network must be concerned with three interrelated but distinct types of applied research:

- *Identification and characterization of the soils.* Acid tropical soils are highly variable. To be able to apply results obtained at a given location elsewhere, the soils must be identified by competent pedologists. In addition, the edaphic characteristics must be determined so that appropriate crops can be used.
- *Determination of agronomic practices needed.* Cropping practices will be affected by soil physical properties (structure, porosity, erosivity); by chemical toxicities (due to aluminum or manganese); by nutrient deficiencies or fixation of nutrients (such as phosphorus); by degree of acidity and existence of acid-tolerant crop varieties; and by cultivation practices. The existing limitations and best means of overcoming them and the best available management practices must be identified from throughout the network.
- *Socioeconomic acceptability and practicality.* An excellent technology will be of no use if it requires unaffordable or unobtainable inputs. Similarly, the types of work and practices to be followed must be ones that the people involved are able to perform and accept.

The network must take all these aspects into consideration as it develops a common research approach. A common approach does not mean that all the procedures will be identical. It means that we will agree on the concepts of the experiments and on the type of analyses and measurements to be conducted. In each country, the experiments will be linked to local socioeconomic constraints or priorities; that means periodic reevaluation and revision of the network program.

This common research approach must have an applied practical agricultural aim: the improvement of continuous cropping systems on acid tropical soils. IBSRAM does not intend to plan or support basic research at this time. If basic research is needed to solve a crucial problem, we will seek external cooperation to perform it.

After the problem has been clearly defined, we must prepare a realistic research agenda. Realistic means we have to consider both experimental and time imperatives. Experimental imperatives will be determined by the type of research approach employed. Time imperatives, as you know, are the most important for donors and national administrations, so we must try to get the quickest results possible. However, we must be on guard not to make shortcuts, which could later adversely affect the possibilities of interpretation of the results and transfer of the technology. A good network research program must ensure that results obtained in the individual countries of the network can be reliably compared on a scientific basis. We cannot endanger the projects to save time; we must adhere to the experimental imperatives.

Establish Structure of the Network

It is also necessary to decide on the form and *modus operandi* of the proposed Soil Management Network for acid tropical soils.

An IBSRAM network is an association with three kinds of participants:

- *National Cooperators,* which are the agencies in individual countries that will conduct the applied research in phase with the agreed-upon plans of the network working group. To do this, they may work with various cooperators, including national and international centers.
- *Donors,* who will fund part of the network costs and who will fund or otherwise assist the activities of individual National Cooperators.
- *IBSRAM,* which, through a coordinator and other IBSRAM staff, will help National Cooperators develop and execute the research program. Where necessary, IBSRAM will also act as a link between the National Cooperators and the donors.

Thus, a network entails three bodies cooperating to their mutual benefit. The contributions by each of these bodies will determine the success of the network and the benefits to each cooperator.

Many types of networks have served or are functioning in the agricultural field. Some give more strength to the international agency, others to the participants. IBSRAM is prepared to be very flexible and realistic and will avoid "trying to run

the show." The National Cooperators must determine what they want to do, but they may need IBSRAM's help in achieving their goals.

On the other hand, a too-loose link between IBSRAM, the network, and the National Cooperators will prevent attaining the benefits of the network. If each National Cooperator is concerned with only its own local priorities, it may not benefit from or contribute to the network. So we must try to find sufficient coherence to keep the advantages of the network and sufficient flexibility to allow for local priorities and conditions.

Decide Sequence of Events

If an Acid Tropical Soils Management Network is formed, it will start with a limited number of participants, preferably representing a range in agroecological and socioeconomic conditions. The sequence of events and requirements may be somewhat as follows.

1. Each country in the network will need to have a national research agency that is already involved in some way in applied research on the use of acid tropical soils. The research agency selected to represent a country, therefore, will have some facilities and staff already engaged in acid tropical soil management and will therefore be called the "National Cooperator" of the country. All such countries will be welcome in the network, but the level of involvement and support from IBSRAM will vary from country to country.
2. Each potential participant will be asked to prepare a preproposal for activities of the National Cooperator. The preproposal of 3 to 5 pages should include:
   - Agroecological description of the region proposed for the experiment;
   - Socioeconomic background of the area concerned;
   - Description of the experiment(s) envisaged;
   - Identification of the national agency and scientists responsible for the project;
   - Locally available facilities, in terms of experimental fields and equipment, vehicles, laboratories, office space, and personnel;
   - Approximate needs from external sources for equipment and instruments, expertise, training, etc.;
   - Additional information helpful to the evaluation of the preproposal.
3. An interim Network Coordinating Committee (NCC) will be formed, consisting of 6 to 8 persons as follows:
   - 2 to 4 representing prospective National Cooperators;
   - 1 to 3 international specialist(s);
   - 1 to 3 donor representative(s);
   - 1 (the IBSRAM Interim Director);
   - 1 or 2 IBSRAM members of the Board (if practical).

This NCC will draft an overall network proposal from the preposals of the potential National Cooperators.

4. The proposal developed by the NCC will be taken to the respective countries by the representatives of the National Cooperators. In each country where there is to be a National Cooperator, the specific plan and proposal of that country will be revised and developed in detail. An important part of that activity will be to prepare detailed cost estimates of the requests being made for assistance to execute the proposal. The following actions will then occur:
   - When the proposal of each National Cooperator has been approved by the government concerned, it will be forwarded to IBSRAM.
   - IBSRAM will review the proposals received from the National Cooperators in the network. If necessary, some changes or some integration of requests may be made. For example, there might be three separate requests of a generally similar nature for training; these requests might be combined into a single request to serve the three countries.
   - After IBSRAM has approved the proposals and requests described, funding will be sought, perhaps by both IBSRAM and some of the individual National Cooperators. Some donors may prefer to provide funds to IBSRAM but may specify the activities to be supported in a particular country or countries. Other donors may want to provide support to selected National Cooperators on a bilateral basis; sometimes donors may choose to support only specific projects by a particular National Cooperator and on a bilateral basis.
   - If, after several months of seeking donor support, there are shortfalls in funding for the requests made, the NCC may have to meet and work out some adjustments. If the requests made are realistic, prospects for adequate funding are considered good.
5. Once the network is established and funded:
   - IBSRAM will provide a coordinator to assist the individual National Cooperators during the initial 1 to 3 years.
   - Provided the necessary funding is available, arrangements will be worked out for the NCC to make field visits to one National Cooperator per year on a rotational basis to view work in progress and to review and evaluate the results. Such reviews and field visits may lead to adjustments in plans for the work to be done during the next year or two.
6. When the Network has been established and is successfully operational, additional countries wishing to join as active National Cooperators will have the opportunity to do so. In addition, network newsletters and other IBSRAM publications will be available to interested countries even if they are not able to join the research activities of the network.

Network Participation

There are several advantages for developing countries accepting the invitation to participate in the IBSRAM Acid Tropical Soils Management Network. The advantages include:

- The opportunity to send participants to network workshops.
- Receipt of information about acid tropical soils, their extent and variability, as well as hearing and seeing how improved management of them may increase their productivity under certain conditions.
- A chance to seek membership in the network likely to be formed and thereby to be included in:
  - IBSRAM requests to donors for funds to support applied research and on-farm investigations by National Cooperators.
  - IBSRAM information services providing the newest technical information about ways, means, costs and results of various methods (including new techniques) of acid tropical soil use and management.
  - The annual review and evaluation of results from the various National Cooperators in the network.
  - Regular visits to each National Cooperator by IBSRAM officers who will provide information, advice, and encouragement.
  - Training courses or visits by specialists, etc., which IBSRAM may be able to organize.

In conclusion, may I say that I am very confident of the prospects for establishing a network on management of acid tropical soils. It meets an urgent need, and some donors are already willing to finance the type of applied research intended. But I must emphasize that this inaugural workshop occurs at a crucial moment; the possibility of establishing the network depends upon its success or its failure. Because the Acid Tropical Soils Management Network is essential for IBSRAM, IBSRAM, the Organizing Committee, and I myself will put our best efforts forward in an endeavor to ensure the success of this meeting and to succeed in the establishment of the network. Upon that success depends the credibility of IBSRAM.

But we cannot create the network without your interest and input. I hope that those who have participated in the field trips in Peru and Brazil have found them relevant for their own interests. This week we discussed in detail the scientific approaches to be employed in seeking solutions to the problems we plan to work on. We must also decide the form of the network and try to agree on the first steps of this enterprise.

I solicit your best efforts to focus your interest on these problems and your help in developing a proposal for an Acid Tropical Soils Management Network which will:

- Be very attractive to your governments, thereby winning approval and financial support.
- Appeal to donors who as a result will support your proposals.
- Result in improved use, agricultural production, and profitability from the use of acid tropical soils management in developing countries.

My best wishes for success!

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Working Group Reports

After the formal review of geographic regions and keynote issues, conference participants formed six working groups, which, in collaboration with the 13 country representatives present, prepared formal proposals for network activities in six areas. These proposals, as follow, were presented at a general session and were accepted by conference participants for implementation by the network.

Working Group A:
PEDOLOGY AND SOIL FERTILITY

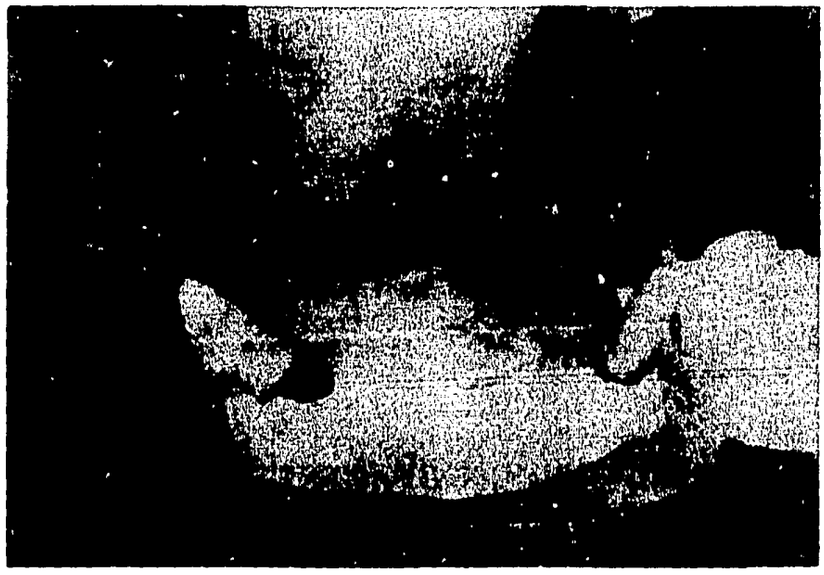
Introduction

The IBSRAM Acid Tropical Soils Management Network should essentially be concerned with soils of the humid tropics and savannas that are acid and well-drained, have a low base status, and are usually dominated by kaolinite and sesquioxides. These include the Oxisols and Ultisols of Soil Taxonomy; the Ferrasols and Acrisols of FAO; the *Sols ferralitiques désaturés* and *Sols ferrugineux tropicaux désaturés* of the French system; and the *Latossolos* and *Podzolicos vermelho-amarelo distróficos* of the Brazilian system. It is desirable to include some closely associated soils—in particular, Dystropepts in Latin America and some acid-surfaced Alfisols in Africa.

First, the network should review existing research centers currently dealing with the above soils to determine the extent of existing knowledge and the coverage of the major representative soils. Important knowledge gaps can thus be defined. Further steps should include the following.

Selection of representative research sites

Detailed attention should be paid to the selection and soil characterization of existing and new experimental sites. This is essential for better understanding and transfer of results. Climatic and vegetation factors should also be considered in selecting representative research sites. Attention must be paid to existing or likely local farming systems in the region.



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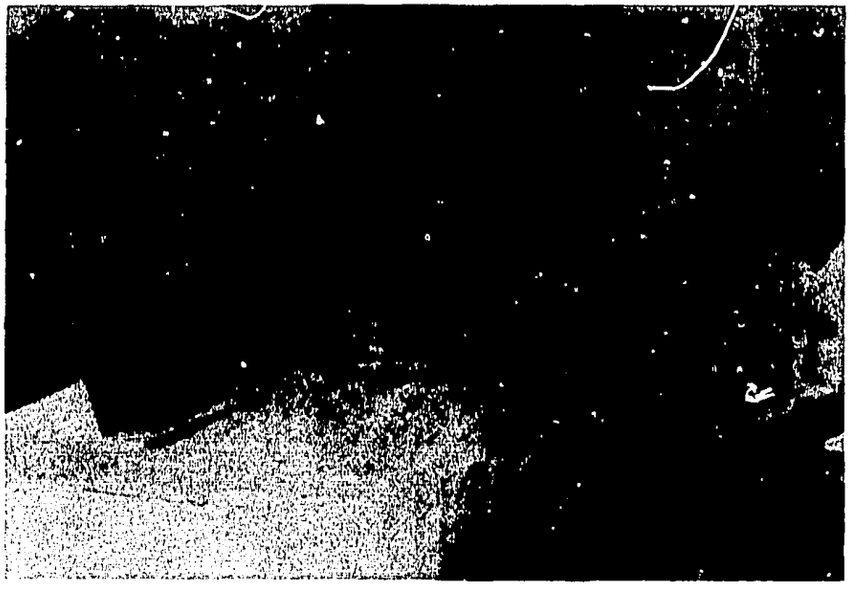

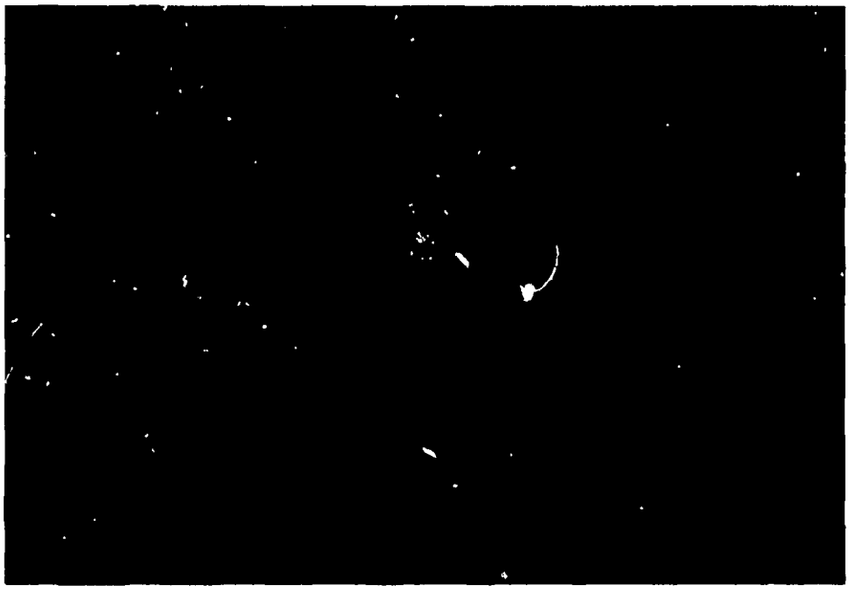

Soil characterization

In the case of major experimental sites, a detailed soil survey should be undertaken and the major soils described and sampled for laboratory analysis. Sampling will usually be by reference to morphological layers, but sampling intervals should not exceed 30 cm. Additional sampling (possibly including bulking) should be undertaken for surface (plow-layer) horizons to enable statistical estimates of variability of important soil fertility parameters. Soil samples should be stored after analysis so that if new technologies are developed the need for resampling is avoided.

Table 1. Outline of a provisional minimum data set for site characterization (not all analyses will be required on all soil horizons).

Major experimental station site	On-farm site
Site data	
Location (lat. & long.), physiography, altitude, vegetation, land use, site drainage, erosion, microrelief, stone, presence of water tables	As for major site
Climatic data	
Daily rainfall, temperature, radiation, and panevaporation	At least rainfall
Soil morphology	
Standardized soil description to appropriate depth—this may exceed 2 m.	Describe color, texture, structure, restricting layers to 1 m
Physical properties	
Particle size distribution, bulk density, moisture retention (0.1, 0.3, 2, & 15 bar)	Particle-size distribution
Chemical properties	
pH (H_2O, KCl), KCl-extractable acidity, extractable bases, CEC at pH 7, ECEC, organic carbon & nitrogen, extractable phosphorus, P-sorption characteristics, phosphate-extractable sulfate, micronutrients such as Fe, Mn, Cu, Zn, Mn, B	Will vary according to soil
Mineralogical properties	
X-ray/DTA of clay fraction	

Source: Working Group A, Acid Soils Conference, IBSRAM, May 1985.

At the major sites, a complete laboratory characterization should be made of the soils to be used for experimental purposes. Analyses should be by a standardized set of methods, which needs to be developed; this does not preclude use of any existing local methods of analyses, as correlations may need to be developed between these and some standardized methods. An outline of the kinds of analyses required is given in Table 1.

Subsidiary research sites, such as those used for on-farm trials, should be selected or characterized by a pedologist, if possible, unless a sufficiently detailed soil survey is available. At such sites fewer analytical data are usually required, and perhaps a minimum data set should be established. Again, some estimate of surface soil variability should be attempted.

Fertility evaluation

At any new site the soil characterization data should give a good indication of the likely fertility status of the soil. Some factors, however, are more difficult to assess from laboratory data—e.g., minor elements and response to phosphorus. Before extensive field experimentation is done, consideration should be given to a series of glasshouse and shadehouse pot trials to establish nutrient responses in surface soils using omission and/or factorial designs. It may also be desirable to conduct P and lime rate trials. Such information can help considerably in designing the most appropriate form of field experiment to determine actual plant performance.

Extrapolation of results

There are three possible ways of extrapolating results, using (1) analogous areas such as mapping unit, site index, or agronomic capability unit systems; (2) statistical correlation of results based on soil test information; (3) expert systems and other interactive computer systems. An expert system is defined as a computer-based procedure or set of procedures for drawing on the knowledge of a person or persons experienced in a particular field (knowledge base) and a data base for that field, using especially designed computer programs, to produce rules, guidance, and answers to questions upon the provision of a specific set of data for particular cases (e.g., soils).

Conclusions

The network should:

1. Examine the present coverage of acid tropical soils by existing research stations and recommend new stations if necessary.
2. Where possible, include other soils present in local mapping units in the experimental sites.
3. Establish an international reference base for soil characterization and soil fertility parameters. Develop standard methodologies.

4. Establish and collect minimum data sets for the major experimental stations and on-farm research sites.
5. Promote research to establish better relationships between pedological characteristics and management behavior of acid soils.
6. Promote research to develop fertility capability groupings based on farming-systems information.
7. Develop expert systems or other interactive computer systems that incorporate available information and use them as a tool for technology transfer.

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Working Group B:
SOIL ACIDITY

Introduction

Many different methods of measuring the parameters of particular interest in soil acidity characterization are currently in use by scientists around the world. A serious problem occurs because there is no "common language" available, and thus it is difficult to compare data sets. A common method for characterization of soil acidity could be achieved either directly by individual network scientists or by their providing appropriate soil samples to some core laboratories.

In addition to soil pH, extractable cations, and lime requirements for specific crops, there is a need to measure additional parameters if our understanding of the limitations to plant growth in acid soils is to progress. This includes both assessment of change characteristics in these acid soils (in which variable charge colloids often predominate) and determination of species and activities of ions in soil solution. Particular attention needs to be focused on aluminum: exchangeable aluminum and aluminum saturation have been widely used for determining aluminum status, but they have often been found wanting. Soil-solution analysis may offer a more appropriate approach.

This emphasis on new methodologies should in no way be interpreted as a replacement of current procedures; in fact, the ideal would be to continue to use both the old and the new, IBSRAM-recommended procedures. With time and experience, the recommended procedures of an organization such as IBSRAM may well change as superior methodologies are developed.

Recommendations

The group developed the following recommendations for network activities on soil acidity. The network should:

1. Assess the current status of knowledge of soil acidity.
   a. Provide support for the collection, examination, and synthesis of available information on soil acidity management, with emphasis on current experiments:
      - liming experiments;
      - traditional methods of "slash-and-burn" management of secondary forest.
   b. Foster consolidation and interchange of information among network scientists:
      - network newsletter;
      - follow-up workshops (may be regionally centered, e.g., in South America, Africa, and Southeast Asia);
      - personal interchange visits between network members.
2. Develop standardized methodologies for characterization of soil acidity in relation to plant growth.
   a. Support development and adoption of standard procedures for determining soil acidity parameters:
      - soil pH;
      - extractable cations;
      - lime-requirement determinations for specific crops;
      - general evaluation of fertility status.
   b. Direct attention toward assessment of charge characteristics and determination of species and activities of ions in the soil solution.
   c. Focus on aluminum. The characterization of soil solutions can best address the question of whether aluminum toxicity or calcium deficiency limits plant growth, or, if both, under what conditions one is a larger constraint than the other.
   d. To develop and adopt standard procedures, support a few existing laboratories that have good facilities and high quality control.
3. Promote an experimental program to ameliorate soil acidity.
   a. Determine management considerations for soil amendments and develop management practices for both surface and subsurface horizons:
      - chemical and physical properties of the soils;
      - lime requirements of specific crops;
      - physical and chemical characteristics of liming materials;
      - prediction and measurement of residual lime effects;
      - interaction with phosphorus and other essential nutrients;
      - biological activity.

b. Determine implications of liming for:
   - legume nodulation, nitrogen fixation, and plant growth;
   - organic-matter mineralization and nitrification;
   - influence of mycorrizal associations.

c. Determine management practices for use when liming materials are not available or are noneconomic:
   - crop rotations;
   - organic-matter incorporation;
   - tolerant cultivars/species.

4. Develop a methodology for characterizing plant adaptability to soil acidity and selection of tolerant species and cultivars:

a. Establish reference collections of germplasm for both pot trials and field experiments;

b. Evaluate plant indices as indicators of tolerance to soil acidity:
   - root growth;
   - biomass and product yield;
   - nutrient composition;
   - nodulation;
   - mycorrhizal associations;
   - temporal variation in sensitivity;
   - product quality for human and animal nutrition.

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Working Group C:
PHOSPHORUS FERTILIZATION

This working group considers the following topics relevant for P research on the acid soils of the humid tropics and savannas.

Recommended research topics

The network should assess the following:

Rates and methods of P application

1. Conduct field plot experiments to obtain response curves on representative soils:

a. Properly characterize experimental sites in terms of P response.

b. Standardize experimental procedures:
   - use triple superphosphate;
   - use maize as the test crop;
   - ensure uniformity of all other factors, particularly soil nutrients.

2. Compare band and broadcast methods of application.
3. Assess residual effects.
4. Calibrate field results with standard laboratory procedures:
   a. Assess routine available P-extraction techniques for selection of a reference procedure;
   b. Determine P-sorption and -desorption isotherms based on standard methods;
   c. Exchange soil samples among countries for crosschecking purposes.

Interaction of P with lime, organic manure, and green manuring

1. Conduct preliminary lab experiments on the effect of lime and organic manures on P sorption and desorption.
2. Use this information to conduct field plot experiments to measure the interactions, if necessary.
3. Assess the actual practical value of liming and manuring based on local conditions and availability of material.
4. Analyze materials used for nutrients.
5. Assess residual effects.

Sources of P

1. Characterize physical and chemical properties of locally available rock phosphate materials.
2. Compare agronomic efficiency of these materials with that obtained from triple superphosphate.
3. Assess the Ca-supplying properties of available materials (preferably in a factorial experiment).
4. Assess transformation technologies of available rock phosphate materials in relation to agronomic and economic efficiency.

Nutrient balance

Monitor the interactions of P with macro- and micronutrients as the above-mentioned experiments are in progress.

P use in farming systems

1. Evaluate phosphate use in different farming systems through on-farm trials.
2. Assess the socioeconomic factors involved.

Mycorrhiza

Encourage research in this area where facilities are already available.

Network considerations

For a comprehensive collection of current research, the following review of network activities is recommended:

1. State-of-knowledge report at beginning of network.
2. Continuing collection of data from ongoing research and circulation to participating countries.
3. Annual regional workshops in participating countries, emphasizing field visits and group discussions.
4. Individual yearly reports on progress at annual workshops.
5. Planning for following years' experiments.

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Working Group D:
MANAGEMENT OF THE SOIL SURFACE

Problems

Erosion, compaction, and rapid decomposition of organic matter result in degradation of the soil and, hence, loss in productivity. The aggravating factors unique to acid soils in the tropics include high intensity of rain (leading to erosion and compaction) and high solar radiation (responsible for high soil temperatures and rapid decomposition of organic matter). Additional factors are the poor structure of the surface soil (especially in Ultisols) and the inability of some native vegetation to regenerate and cover the soils after clearing certain savannas.

Experience in some areas has indicated possible solutions to these problems: these include the use of green manures, legume covers, and managed fallows. Both legume covers and green manuring add organic matter and nitrogen and cycle other nutrients to the soil. In addition, they protect the soil surface and provide other benefits. At the same time, it has become evident that inappropriate tillage further aggravates deterioration of the soil surface. Although limited work on preserving and/or improving soil surface properties has been carried out in a number of tropical countries on acid soils, published information is not readily available. The need for compilation of the "state-of-the-art" knowledge cannot be overemphasized.

Solutions

The best solutions involve residue management and appropriate tillage practices. The options available for residue management include rotations with additions of residue (green manures, stubble, legume covers, etc.) and alley-cropping.

Tillage management should include minimizing surface compaction (minimum-tillage systems and traffic control) and/or overcoming existing physical impediments (deep ripping). The role of amendments such as lime in ameliorating some of these constraints should also be considered.

Evaluation

The validation of existing knowledge and evaluation of new technology should be instituted in both the humid tropics and the savannas. The combined evaluation of tillage practices and residue management should be carried out on cropping systems involving annuals, whereas either residue or cover management would suffice for perennials.

These could best be done on a network basis and include the following investigations on a priority basis for each ecosystem:

Savanna
1. Residue[1] by tillage interactions
2. Pasture-crop rotations

Humid tropics
1. Perennials
   a. Cover management (nonharvested)
   b. Possible use of cover for grazing
2. Annuals
   a. Residue[1] by tillage interactions
   b. Alley-cropping (e.g., using *Inga edulis*, *Acioa barterii*, or *Flamingia congesta*)
   c. Managed fallows
   d. Pasture-crop rotations.

Priority should be given to cover crops or mulch that have food, economic, or forage value to the farm household. Low priorities should be given to moving mulch from one place to another (except where target people are small holders).

Baseline knowledge on available cover crops, legumes, mulch or tree crops (and their seeds and appropriate *Rhizobium*) ought to be sought and incorporated into the experiments. This would allow for a final assessment of the improved socioeconomic integration of local crops into the soil surface.

1. Includes green manures, stubble, and other residue.

Minimum data collection

The optimal data from experimental trials would include the following:

1. Site characterization (including climatology, plant species used, fertilizer practices, etc.)
2. Crop yields
3. Compaction
4. Organic-matter content
5. Soil temperature
6. Soil loss
7. Soil water
8. Nutrient changes and movements.

The minimum data set should cover the first five parameters.

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Working Group E:
REHABILITATION OF DEGRADED LANDS

Introduction

Large areas of land cleared for agricultural uses have become degraded as a result of various mismanagement practices. Such lands need to be reclaimed and made productive.

Some of the causes of land degradation include the following:

1. Loss of inherent soil fertility because of:
   a. Lack of, or minimum use of, fertilizers;
   b. Short fallow periods;
   c. Erosion due to surface soil exposure before crop establishment;
   d. Indiscriminate subsoil exposure through land leveling.
2. Soil compaction because of:
   a. Use of inappropriate machinery and implements during clearing and cultivation;
   b. Adverse tillage practices, including timing of operations.
3. Erosion because of lack of conservation practices on steep lands. Need for:

a. Physical conservation practices (terraces, planting on contour, etc.);
b. Biological conservation practices (cropping systems).

4. Diminished range conditions.
5. Unbalanced hydrology.

Research needs

The network should:

1. Assess various degradation features of acid soils.
   a. Compare basic relationships between different degradation features of land and several soil properties.
   b. Study relationships between soil erodibility and rainfall erosivity.
2. Develop methodologies for rehabilitation of degraded lands.
   a. Evaluate management practices to eradicate undesirable weeds and other vegetation associated with degraded land.
   b. Compare conservation-oriented tillage practices on different soil types.
   c. Study methods of reclamation of degraded pastures through legume-based pastures and the use of fertilizers.
   d. Study the efficiency of various systems for reclaiming degraded land, such as agroforestry, wooded pasture, and other cover crops, especially on steep lands.
3. Evaluate socioeconomic aspects of reclaiming degraded lands.
   a. Cost of rehabilitation.
   b. Extension methods and their effectiveness.

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Working Group F:
SOIL DYNAMICS

Dynamics is defined as the evolution of soil physical, biological, and chemical properties over time.

Objective

To maintain or improve productivity, while avoiding ecosystem degradation.

Proposed network activities

The network should:

1. Produce state-of-the-art-reviews on soil physical, biological, and chemical dynamics from currently available studies on acid soils in the humid tropics and savannas.
2. Establish trials to evaluate soil dynamics under different tillage practices.
3. Establish trials to evaluate soil dynamics under different cropping systems, such as arable and permanent crops, pastures, agroforestry, and fallow systems.
4. Establish trials to evaluate soil dynamics under different organic-matter management systems.

Proposed network strategy

1. Trials on representative soils in the humid tropics and acid savanna ecosystems.
2. Standardized methodology for each type of trial; training in the methodology initially provided for network participants.
3. As the amount of observations to be made in soil dynamics studies is perceived to be intensive, consideration should be made to provide appropriate laboratory facilities and adequately trained personnel.

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