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LOW-INPUT TECHNOLOGY FOR MANAGING OXISOLS AND ULTISOLS IN TROPICAL AMERICA

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I. INTRODUCTION

The outcome of the race between world food production and population will largely be determined in the tropics, where most of the world's undernourished people live. During the decade from 1965 to 1975 food production increased at a slightly faster rate than population in food-deficient countries (IFPRI, 1978). This achievement is due to a number of factors, among which the predominant agronomic one is the development and adoption of high-yielding varieties of several crops with improved agronomic practices. Most of these varieties were selected for their ability to produce high grain yields under conditions of little or no soil or water stress. Not surprisingly, their adoption has been most successful when grown on fertile, high base status soils with sufficient fertilization and a reliable water supply. The elimination of soil constraints by applications of the necessary amounts of fertilizers and amendments can be considered as *high-input soil management technology*. Its basic concept is to change the soil to fit the plant's nutritional demands. This high-input approach is largely responsible for our present world food production levels and undoubtedly must continue where economic conditions permit.

The applicability of high-input soil management technologies, however, diminishes in marginal lands where soil and water constraints are not easily overcome at low cost. The rising price spiral of petroleum-related products since 1973 has further limited the economic feasibility of soil management technologies based on the intensive use of purchased inputs, particularly for farmers with limited resources in the tropics. Many research efforts in the tropics are now directed towards developing *low-input soil management technology*, which does not attempt to eliminate the use of fertilizers or amendments but rather attempts to maximize the efficiency of purchased input use through a series of practices. The basic concept of low-input soil management technology is to make the most efficient use of scarce purchased inputs by planting species or

varieties that are more tolerant to existing soil constraints, and thus decrease the rates of fertilizer applications while attaining reasonable, but not necessarily maximum yields.

Although basic knowledge about plant adaptation to acid soil stresses has been available for decades (Levitt, 1978), systematic research for developing technology based on this concept began only a few years ago (Foy and Brown, 1964; Spain *et al.*, 1975; NCSU, 1975; Foy, 1976a; Salinas and Sanchez, 1976; Wright, 1976; Foy and Fleming, 1978; Loneragan, 1978). These efforts have caused considerable controversy and some misinterpretations in the popular literature, such as the belief that "fertilizer-proof" cultivars can be developed and concerns about "mining" the soil of its available nutrients.

The purpose of this review is to bring together examples of low-input soil management technology adapted to well-drained, acid, inherently infertile soils of the American tropics classified mainly as Oxisols and Ultisols. These examples are components of overall production systems, but seldom have all the necessary components been developed for one specific farming system. Most of the examples are drawn from tropical America, reflecting the authors' experience, without resting importance to related work performed in other parts of the world. Soil taxonomy terminology (Soil Conservation Service, 1975), including soil moisture regimes, will be used.

A. Acid Soils of the Tropics

At the broadest possible level of generalization there are three main avenues for increasing food production in the tropics: increasing yields per unit area in presently cultivated regions, opening new lands to cultivation, and expanding irrigated land. The first two require the alleviation or elimination of soil constraints, while the third eliminates water stress as the main constraint. Bentley *et al.* (1980) have examined these three alternatives and concluded that all three are needed, although the irrigation alternative is limited to relatively small areas and is the most costly of the three. There is little question that increasing productivity in land already under cultivation is the principal avenue for increasing world food production. Recent FAO estimates quoted by Dudal (1980), however, show that in order for per capita food production to remain at the present but largely inadequate levels, food production must increase by 60% within the next 20 years. Dudal further estimated that increasing yields on lands already in use is not sufficient; an additional 200 million ha of land must be incorporated into agriculture during the next two decades in order to accomplish this goal. This amount is roughly equivalent to the present cropland area of the United States. Is this possible? The answer is largely dependent on the use made of the acid soils of the tropics.

1. Extension and Importance

The world is currently utilizing about 40% of its potentially arable land resources (Buringh *et al.*, 1975). The greatest potential for expanding the world's agricultural frontier lies in the tropical rain forest and savanna regions dominated by acid, infertile soils classified mainly as Oxisols and Ultisols (Kellogg and Orvedal, 1969; National Academy of Sciences 1977a). These vast regions have a large proportion of favorable topography for agriculture, adequate temperatures for plant growth throughout the year, sufficient moisture year-round in 70% of the region, and for 6–9 months in the remaining 30% (Sanchez, 1977). The paramount limiting factors preventing widespread agricultural development in these areas are low native soil fertility and the limited transportation and market infrastructure.

Table I shows the approximate extension of areas dominated by Oxisols and Ultisols in the tropics. As a whole, they account for about 1582 million ha or 43% of the tropical world. The almost equal proportion of Oxisols and Ultisols differ from previous estimates (Sanchez, 1976), as new information shows that there are less Oxisols than previously thought in Africa and Latin America. The sum of areas dominated by Oxisols and Ultisols, however, remains similar to previous estimates. The largest concentration of Oxisols occurs in the South American savannas, the eastern Amazon, and parts of Central Africa. These soils are generally located in old, stable land surfaces, which makes them attractive for mechanized agriculture. Ultisols are scattered over large areas of tropical America, Africa, and Southeast Asia. Many of these regions are being rapidly developed.

There are other acid soils with similar properties and potentials included in other rows of Table I: acid, well-drained Inceptisols (Dystropepts); acid volcanic ash soils (Dystrandepts); and acid, well-drained red sands (Oxic Quartzipsamments). Excluded from consideration in this article are acid soils that are poorly drained and have an aquic soil moisture regime.

Tropical America, at the broadest level of generalization, can be subdivided into two major regions in terms of farming systems and soil constraints (Sanchez and Cochrane, 1980). About 30% of tropical America (405 million ha) is dominated by relatively fertile, high-base status soils that support dense populations. The remaining 70% of the tropical portions of the Western Hemisphere is dominated by acid, infertile soils of the orders Oxisols and Ultisols with relatively low population densities and mostly under savanna and forest vegetation.

In spite of a widespread belief that Oxisols and Ultisols cannot support intensive and sustained agriculture in the tropics (McNeil, 1964; Goodland and Irwin, 1975), there is ample evidence that they can be continuously cultivated and intensively managed for growing annual crops (Sanchez, 1977; Marchetti and Machado, 1980), pastures (Vincente-Chandler *et al.*, 1974), and permanent

Table I
Generalized Areal Distribution of Soils in the Tropics[a]

Soil associations dominated by:	Tropical America[b] (10^6 ha)	Tropical Africa[c] (10^6 ha)	Tropical Asia[d] (10^6 ha)	Tropical Australia[e] (10^6 ha)	Total (10^6 ha)	Percentage of tropics
Oxisols	502	316	15	—	833	23
Ultisols	320	135	286	8	749	20
Entisols	124	282	75	93	574	16
Alfisols	183	198	123	55	559	15
Inceptisols	204	156	169	3	532	14
Vertisols	20	46	66	31	163	5
Aridisols	30	1	23	33	87	2
Mollisols	65	—	9	0	74	2
Andisols	31	1	11	0	43	1
Histosols	4	5	27	—	36	1
Spodosols	10	3	6	1	20	1
Total	1493	1143	810	224	3670	100

[a] Based on tabular data from FAO-UNESCO (1971–1979) with indicated modifications.
[b] From 23°–23°S, updated by senior author.
[c] Areas with more than 150 days of growing season. From Dudal (1980).
[d] Includes temperate portions of India, Bangladesh, and Indochina plus Papua New Guinea.
[e] North of the Tropic of Capricorn. From Sanchez and Isbell (1979).

crops (Alvim, 1976). This is also the case with Oxisols and Ultisols of Hawaii, and Ultisols of southeastern United States and southeastern China where they support large populations.

2. Major Constraints

The major soil-related constraints of tropical America and its acid, infertile soil region are shown in Table II, based on preliminary estimates. The most widespread ones in the Oxisol–Ultisol regions are chemical rather than physical, including deficiency of phosphorus, nitrogen, potassium, sulfur, calcium, magnesium, and zinc plus aluminum toxicity and high phosphorus fixation. The main soil physical constraints are low available water holding capacity of many Oxisols and the susceptibility to erosion and compaction of many Ultisols with sandy topsoil texture. Laterite hazards cover a minor areal extent and most of the soft plinthite occurs in subsoil layers in flat topography not prone to erosion. In contrast, the main soil constraints of the high-base status soil region of tropical America are drought stress, nitrogen deficiency, and erosion hazards (Sanchez and Cochrane, 1980).

When the chemical soil constraints are eliminated by liming and application of

Table II
Geographical Extent of Major Soil Constraints in Tropical America (23°N–23°S) and in Regions Dominated by Acid, Infertile Soils[a]

	Tropical America (1493 10^6 ha)		Acid, infertile soil region (1043 10^6 ha)	
Soil constraint	10^6	Percentage of total area	10^6 ha	Percentage of total area
N deficiency	1332	89	969	93
P deficiency	1217	82	1002	96
K deficiency	799	54	799	77
High P fixation	788	53	672	64
Al toxicity	756	51	756	72
S deficiency	756	51	745	71
Zn deficiency	741	50	645	62
Ca deficiency	732	49	732	70
Mg deficiency	731	49	739	70
H_2O stress > 3 months	634	42	299	29
Low H_2O holding capacity	626	42	583	56
Low ECEC[b]	620	41	577	55
High erosion hazard	543	36	304	29
Cu deficiency	310	21	310	30
Waterlogging	306	20	123	12
Compaction hazard	169	11	169	16
Laterite hazard	126	8	81	8
Fe deficiency	96	6	?	?
Acid sulfate soils	2	0	2	0
Mn toxicity	?	?	?	?
B deficiency	?	?	?	?
Mo deficiency	?	?	?	?

[a] Source: adapted from Sanchez and Cochrane (1980).
[b] ECEC = Exch. Al + Exch. Ca + Exch. Mg + Exch. K (Exch. = exchangeable).

the necessary amounts of fertilizers, the productivity of these Oxisols and Ultisols are among the highest in the world. For example, Fig. 1 shows the annual dry matter production of elephant grass (*Pennisetum purpureum*) under intensive nitrogen fertilization in Ultisols of Puerto Rico, where all other fertility constraints have been eliminated. This yield approximates the calculated maximum potential of tropical latitudes of 60 tons/ha/yr of dry matter according to DeWitt (1967). Another example is shown in Fig. 2, where excellent corn grain yields on the order of 6.3 tons/ha/crop were obtained on a sustained basis in clayey Oxisol from Brasília, Brazil, when its high phosphorus requirement was satisfied by one broadcast application of 563 kg P/ha and the other chemical soil constraints were corrected by liming and fertilization.

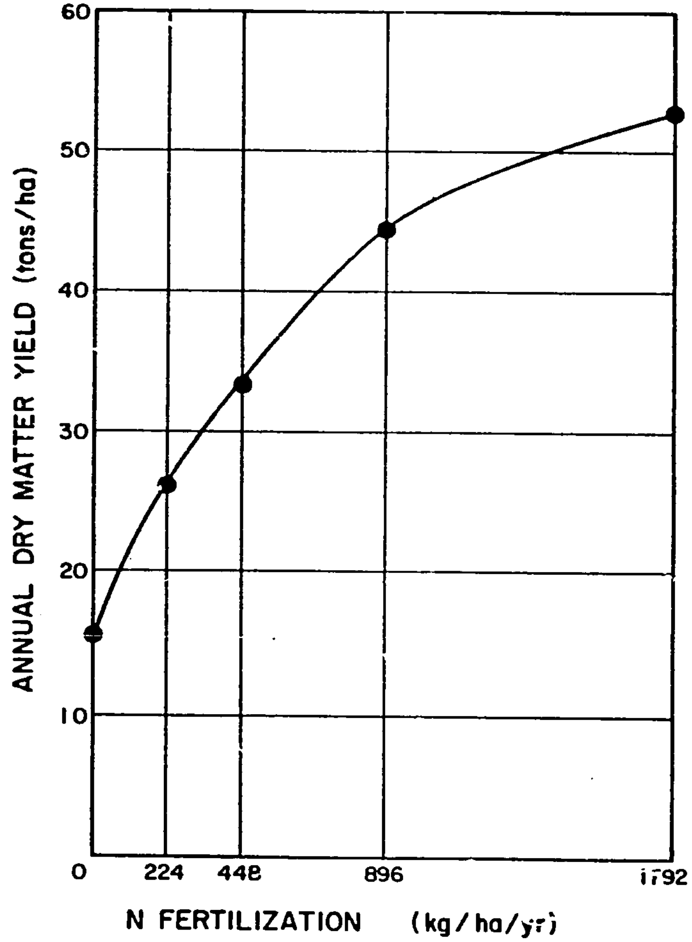

FIG. 1. Dry matter production of *Pennisetum purpureum* cv. Napier cut for forage in Ultisols of the udic mountains of Puerto Rico under intensive management. (Source: Vicente-Chandler *et al.*, 1974.)

These management strategies can be very profitable, even at present prices, when the market provides a favorable ratio of crop prices to fertilizer cost. Whenever economics and infrastructure considerations make these high-input strategies profitable, they should be vigorously pursued.

B. Conceptual Basis of Low-Input Technology

In the majority of acid soil regions in the tropics, favorable market conditions do not exist, either because fertilizers and lime are expensive or not available at

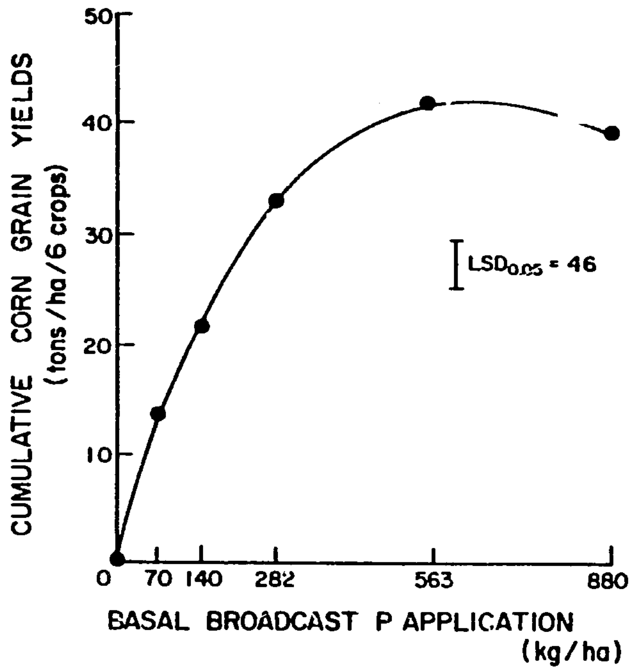

FIG. 2. Corn grain yield response to phosphorus applications on an Oxisol (Typic Haplustox) of the Cerrado of Brazil. Cumulative yield of six consecutive crops. (Adapted from NCSU, 1978.)

all, because transportation costs are excessive, or simply because the risks are too high. The first two situations are self-explanatory. The third one is illustrated in Fig. 3, showing the response to phosphorus by *Phaseolus vulgaris* in a Typic Dystrandept from Popayán, Colombia, with a high capacity to fix phosphorus. The optimum phosphorus application rate according to marginal analysis was 507 kg P/ha, taking into consideration the residual effects for two subsequent crops. When the costs were further analyzed, economists found that farmers needed to invest a total of U.S. $1500/ha/crop to approach these maximum yields and obtain a net profit of U.S. $375/ha (CIAT, 1979). Although this represents a 25% return on the investment, most farmers with limited resources are unwilling to make such an investment, considering the risk due to high variability in yields caused by drought, disease, insect attacks, and unpredictable price fluctuations.

Low-input soil management technology is based on three main principles: (1) adaptation of plants to the soil constraints, rather than elimination of all soil constraints to meet the plant's requirements; (2) maximization of the output per unit of added chemical input; and (3) advantageous use of favorable attributes of acid, infertile soils. It should be emphasized that the elimination of fertilization is not contemplated.

1. *Use of Plants Adapted to Soil Constraints*

The first basic concept of low-input soil management technology for acid soils is to alleviate or overcome certain soil constraints simply by using species or varieties that are tolerant to them. Among the soil constraints listed in Table II more knowledge is available on tolerance to aluminum toxicity, followed by tolerance to low levels of available soil phosphorus. Less information is available on tolerance to manganese toxicity and low levels of other nutrients.

Figures 4 and 5 illustrate the concept with two different yield response patterns to liming in two savanna Oxisols. Figure 4 shows the differential response of two upland rice cultivars grown on an Oxisol of Carimagua, Colombia with a pH value of 4.5 and 80% aluminum saturation prior to lime application. The tall variety Colombia 1 produced twice the yield without lime as the short-statured IR 5. Colombia 1 responded positively only to the first increment of lime (0.5 ton/ha) and negatively to higher increments. Spain *et al.* (1975) attributed this behavior to a nutritional response to the calcium and magnesium content of lime and to lodging at higher lime rates. In contrast, IR 5, bred under high fertility

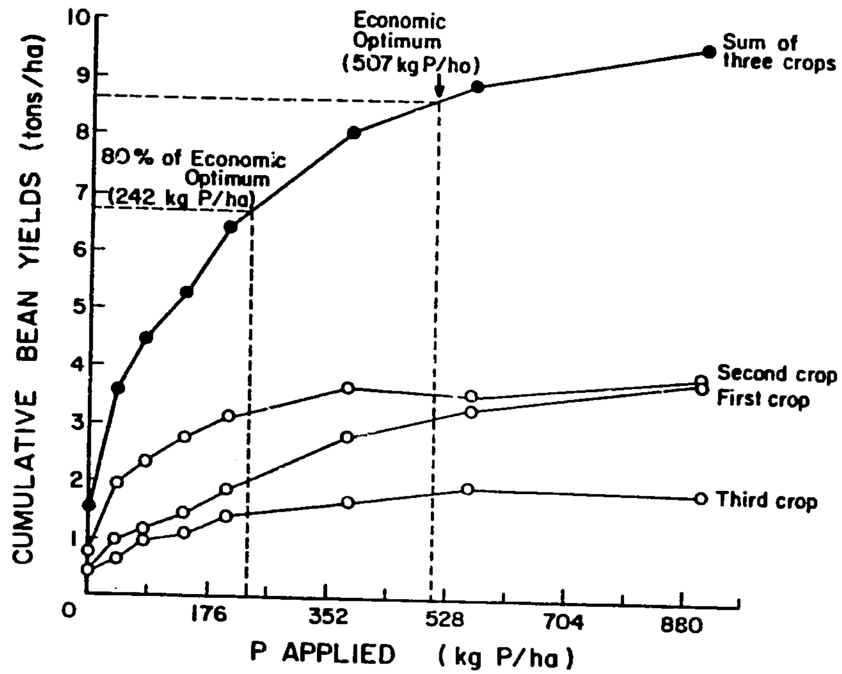

FIG. 3. Cumulative response of *Phaseolus vulgaris* grain yields to basal phosphorus applications and its residual effect to two consecutive crops on a Typic Dystrandept in Popayán, Colombia. (Source: CIAT, 1979.)

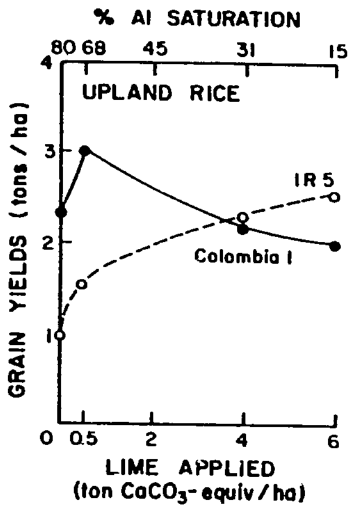

FIG. 4. Differential response to aluminum saturation and liming by two rice varieties grown on a Tropeptic Haplustox at Carimagua, Colombia. (Adapted from Spain *et al.*, 1975.)

conditions in the Philippines, produced a typical quadratic response to lime, attaining its maximum yield at the highest lime rate, which corresponded to pH 5.5 and 15% aluminum saturation. The maximum yield attained by the aluminum-sensitive IR 5 cultivar was lower than the maximum yield attained by the aluminum-tolerant Colombia I cultivar, which required less than one-tenth as much lime. The differential response shown in Fig. 4 shows an overwhelming advantage for the aluminum-tolerant cultivar.

Figure 5 illustrates a less dramatic but perhaps more common type of differential response to lime. Two grain sorghum hybrids were grown at different lime rates in a Typic Haplustox near Brasília, Brazil that had a topsoil pH value of 4.4 and 79% aluminum saturation at the time of planting (NCSU, 1976; Salinas, 1978). The Taylor Evans Y-101 hybrid produced about four times more grain without liming than RS-610. This difference decreased with increasing lime rate and disappeared at the highest lime rate, where both hybrids produced the same maximum yield of 6.8 tons/ha. The dotted lines of this figures indicate considerable savings in lime required to obtain 80 and 90% of maximum yields. For 80% maximum yields, the aluminum-tolerant hybrid required 1.3 tons lime/ha and the aluminum-sensitive hybrid required 2.9 tons/ha. For 90% maximum yield, the lime requirements were 2.0 tons/ha for the aluminum-tolerant hybrid and 5.2 tons/ha for the aluminum-sensitive one. The use of aluminum-tolerant cultivars therefore can significantly decrease lime input without a sacrifice in yields at 80 and 90% of the maximum.

These two examples illustrate the need for researchers to include more treat-

ments at lower input rates than used in the past in order to observe whether differential tolerance exists. If these experiments had not included rates of 0.5 or 1 ton lime/ha, the effects may not have been observed because cultivar differences tend to disappear at high input rates.

2. *Maximization of Output per Unit of Fertilizer Input*

Traditional methods used for determining optimum fertilizer rates are based on marginal analysis, where the optimum level is reached when the revenue of the last increment of fertilizer equals its added cost. This approach is designed to maximize yields and profit per unit area. A major disadvantage of this approach is that the optimum economic fertilizer rates frequently fall in the flatter portion of the response curve, where large increments in the fertilizer input cause small

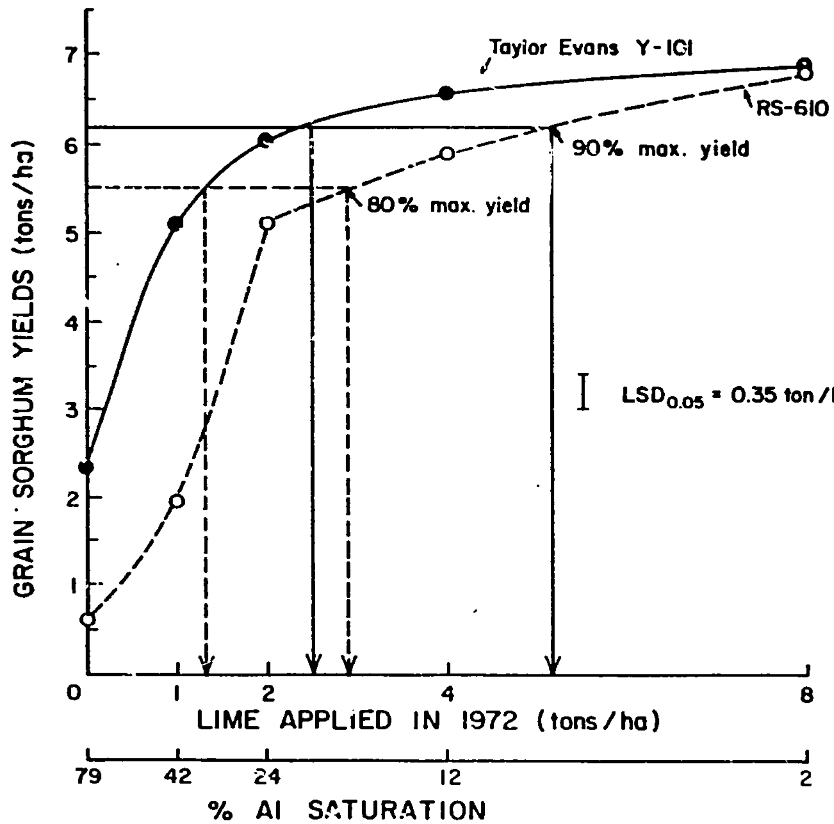

FIG. 5. Differential response of two grain sorghum hybrids to liming in Typic Haplustox of the Cerrado of Brazil. (Source: Salinas, 1978.)

increases in yields. Given the uncertainties associated in predicting yields under tropical conditions, these small yield increases are seldom realistic. A common feature of yield response curves in Oxisol–Ultisol regions is that the amount of fertilizer required to produce 80% of the maximum or optimum yield is considerably lower than the amount required to reach the maximum or optimum point. In Fig. 3 the optimum level of phosphorus application according to marginal analysis is 507 kg P/ha. If only 80% of that optimum yield is desired, this amount decreases to less than half, 242 kg P/ha. Other examples from Oxisol–Ultisol regions presented in Table III show that fertilizer or lime rates decrease by 33–76% when the target yield is lowered to 80% of the maximum. This table includes two examples of the effect of phosphorus and lime applications for a sufficiently long period of time to adequately evaluate their residual effects. The reduction in input is on the order of 50–75% in these cases. Consequently, by lowering yield expectations, the cost of input use can be reduced by a considerable amount.

Boyd (1970, 1974) in England and Bartholomew (1972) in the United States summarized large numbers of fertilizer response functions from all over the world and concluded that in most instances fertilizer response curves can be characterized by a sharp linear increase followed by a flat horizontal line. In essence, this approach follows Liebig's Law of the Minimum. Several techniques have been developed to put this principle to practice in interpreting fertilizer response curves (Cate and Nelson, 1971; Waugh *et al.*, 1975; Waggoner and Norvell, 1979). These methods are now widely used in tropical America.

A comparison of the linear approach versus the conventional marginal analysis with quadratic equations is shown in Fig. 6, using a wheat data set from Bolivia. This figure shows a lower recommended nitrogen application rate with the linear plateau model. This rate occurs at a point along the linear portion of the response curve where the efficiency of fertilization is highest, measured in terms of units of crop yield per unit of fertilizer input.

One of the authors of this review used previously published data from a series of nigrogen response studies of rice in Peru to compare the two ways of developing fertilizer recommendations (Sanchez *et al.*, 1973). The average nitrogen recommendation was 224 kg N/ha according to the quadratic model and 170 kg N/ha according to the linear response and plateau model. The differences in gross returns to fertilization were not significant, but the net return per dollar invested in fertilizer nitrogen was $8.80 in the linear plateau model versus $6.10 with the quadratic model (Sanchez, 1976). Although the applicability of the linear plateau model should be validated locally before using it as the basis for fertilizer recommendations, the concept of recommending rates that will produce the maximum output per unit of fertilizer input at an acceptable yield level is part of low-input technology.

Table III

Decreases in Recommended Fertilizer and Lime Application Rates When Only 80% of the Maximum Yield Is Desired[a]

Location	Crop	Input	MY (ton/ha/crop)	Rate to reach MY (kg/ha)	Rate to reach 80% MY (kg/ha)	Reduction of fertilizer rate 80% MY (%)	Source
Brasilia, Brazil	Corn (6)[b]	P_2O_5 (R)	7.0	563	282	50	NCSU (1978)
Brasilia, Brazil	Corn (5)	Lime (R)	5.6	8000	2000	75	NCSU (1978)
Brasilia, Brazil	Corn (1)	K	4.9	249	60	76	NCSU (1978)
Brasilia, Brazil	Soybeans (1)	P_2O_5	3.2	1200	300	75	CPAC (1976)
Brasilia, Brazil	Wheat (1)	P_2O_5	2.4	800	200	75	CPAC (1976)
Orocovis, Puerto Rico	Elephant grass	N	53.0	1792	746	58	Vicente-Chandler *et al.* (1964)
Carimagua, Colombia	Cassava (42)	Lime	8.0	6000	1700	72	CIAT (1978)
Carimagua, Colombia	Corn (20)	Lime	3.2	6000	2200	63	CIAT (1978)
Carimagua, Colombia	Rice (96)	Lime	2.8	6000	3500	42	CIAT (1978)
Carimagua, Colombia	Sorghum (240)	Lime	3.1	6000	1800	70	CIAT (1978)
Carimagua, Colombia	Beans (49)	Lime	1.0	6000	4000	33	CIAT (1978)

[a]Examples from Oxisol-Ultisol regions. R, residual effects; MY, maximum yield.
[b]Numbers in parentheses indicate number of crop harvests.

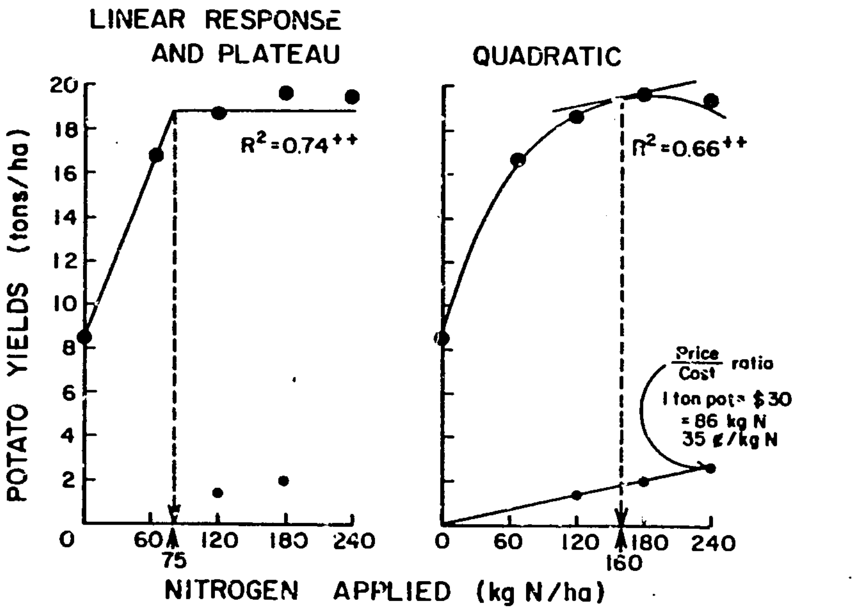

FIG. 6. Determination of nitrogen recommendations for potatoes in a set of field experiments from Bolivia according to the linear plateau response and the conventional curvilinear models. Each dot is the mean of several field experiments in a given crop-crop-soil category. (Source: Adapted from Waugh *et al.*, 1975.)

It should be emphasized that this approach differs from the simple fertilizer trials of the Food and Agriculture Organization (FAO), which also advocate the use of lower fertilizer rates than that suggested by marginal analysis (Hauser, 1974). The difference is that with the linear response and plateau model the yields at recommended fertilizer rates are at the maximum yield, while the FAO trials normally consist of low fertilizer rates that seldom approach maximum yields. Both methods emphasize working on the linear portion of the fertilizer response curve that produces maximum output per unit input, but they differ on the expected yield levels.

In addition to methods of determining fertilizer recommendations, there are a number of agronomic practices that also increase the efficiency of fertilizer use, such as better fertilizer sources, timing of application, and placement methods. These and other practices will be discussed in other sections of this review.

3. *Advantageous Use of Favorable Attributes of Acid, Infertile Soils*

Many Oxisols and Ultisols in thier acid state have several positive agronomic factors that can be used advantageously. By keeping the soil acid, the solubility

of slowly available rock phosphate is higher than if the soil is limed, and weed growth is decreased considerably as compared with a limed and fertilized soil. Also, the low effective cation-exchange capacity (ECEC) of these soils favors the downward movement of applied calcium and magnesium to the subsoil. Examples of these observations will be discussed in later sections of this review.

C. Main Components of Low-Input Technology

Several concepts or techniques are being developed as building blocks of low-input soil management technology for Oxisols and Ultisols of the tropics. The following is a partial list, some of which can be combined for certain farming systems:

1. Selection of most appropriate lands where, because of soil properties, landscape positions, and market accessibility, low-input technology has the comparative advantage over high-input technology.
2. Use of plant species and varieties that are more tolerant to the major acid soil constraints as well as being adapted to climatic, insect, and disease stresses.
3. Use of low-cost and efficient land clearing, plant establishment, cropping systems, and other practices to develop and maintain a plant canopy over the soil.
4. Manage soil acidity with minimum inputs, with emphasis on promoting deep root development into the subsoil.
5. Manage phosphorus fertilizers at the lowest possible cost with emphasis on increasing the efficiency of cheaper sources of phosphorus and prolonging the residual effects of application.
6. Maximize the use of biological nitrogen fixation with emphasis on acid-tolerant *Rhizobium* strains.
7. Identify and correct deficiencies of other essential plant nutrients.

II. SITE SELECTION

The first step is to select the soils and landscape positions most appropriate for low-input technology. This involves avoiding the best lands in terms of high native fertility, irrigation potential, or close proximity to the markets. Most of these favored lands could be managed more effectively with high-input technologies. In tropical America unfortunately, this is not always the case. It is common to find many valleys where the best bottomland soils are under extensive low-input management systems while attempts are made to intensively farm the adjacent acid steeplands. In many cases, this is due to land tenure patterns.

Efforts should be made to intensify production in the soils with less acute chemical constraints.

Large-scale evaluation schemes have improved our understanding of the areas suitable for low-input technologies in tropical America. Approximately 6% of the Amazon (30 million ha) is dominated by well-drained, high-base status soils classified as Alfisols, eutric Inceptisols, Vertisols, and Mollisols (Cochrane and Sanchez, 1981). Their higher native fertility gives the comparative advantage to intensive annual food crop production or to acid-sensitive export crops such as cocoa (*Theobroma cacao*). In addition, the same study indicates that the Amazon has about 116 million ha of poorly drained soils either in floodplains or swamps, accounting for 24% of the basin. Some of the alluvial floodplain areas are already under intense use, such as many "várzeas" in Brazil and many "restingas" in Peru and Ecuador. Flood hazards, however, limit the production potential of the lower topographic positions.

Also to be avoided, but for different reasons, are acid, infertile soils with severe physical limitations, such as shallow depth or steep slopes, and coarse sandy soils classified as Psamments or Spodosols and often called "tropical podzols." This latter group has extremely low native fertility and severe leaching and erosion hazards. These three groups cover about 41 million ha or 8.5% of the Amazon (Cochrane and Sanchez, 1981). The Psamments or Spodosols represent only 2.2% of the Amazon and combine the worst physical and chemical soil constraints.

The total area to which low-input technology may apply in the Amazon region is therefore on the order of 275 million ha or 57% of the basin—mainly Oxisols and Ultisols with less than 8% slope.

In the savanna regions of tropical America it is less difficult to identify the soils to be avoided, but the criteria remain the same. Many of the islands of high-fertility soils are already under intensive production, such as in the Eastern Llanos of Venezuela. Steep and shallow soils are readily recognized in the savanna landscapes. Large areas of seasonally flooded plains, such as parts of the Western Llanos of Venezuela and its extension into Colombia, and parts of the Beni of Bolivia and the Pantanal of Brazil, will require a different management strategy.

In the savanna regions of tropical America, the Land Resource Study of Tropical America of Centro Internacional de Agricultura Tropical (CIAT, 1978, 1979) indicates that there are 71 million ha of Oxisols and Ultisols with less than 8% slopes (T. T. Cochrane, personal communication). These lands correspond to approximately 24% of the savanna regions and are primarily where the low-input technology described in this article can be applied. These estimates are conservative since it is possible to produce beef from legume-based pastures on steeper slopes. There are an additional 19 million ha of savanna Oxisols and Ultisols with 8-30% slope that could be used for such a purpose.

Although the above generalizations provide an overall picture, actual land selection is site-specific. Soil parameters per se are not sufficient for appropriate site selection. Land classification therefore is a more useful tool because it also considers climate, landscape, native vegetation, and infrastructure. The land systems approach used in CIAT's Land Resource Study appears to be an appropriate method for evaluating the potential of these vast areas. Using a scale of 1 : 1 million, about 500 land systems have been identified so far, each representing a recurring pattern of climate, soil, landscape, and vegetation (Cochrane, 1979). Soils and climate are classified according to technical systems such as the moisture availability index (Hargreaves, 1977; Hancock *et al.*, 1979) and the Fertility Capability Soil Classification System (Buol *et al.*, 1975). The data are assembled on computer tapes (Cochrane *et al.*, 1979). Users of these tapes can examine computer-made maps of specific regions pinpointing one or several parameters, such as shallow soils or soils with more than 60% aluminum saturation at a specific depth.

A modification of the Land Use Capability Classification System of the U.S. Department of Agriculture (USDA) has been developed in Brazil to take into account the realities of the tropical environment. Ramalho *et al.* (1978) redefined land capability classes in terms of the high-, moderate-, or low-input use. High input levels mean intensive use of fertilizers, lime, mechanization, and other new technology. "Moderate" input use implies limited fertilizer use and limited use of mechanization. This corresponds to the low-input technology concept of this article. The "low" input use of Ramalho *et al.* implies primarily manual labor and few, if any, purchased inputs. This interpretive system has been applied to RADAM soil survey of the Brazilian Amazon (Ministério das Minas e Energia, 1973-1979).

Consequently, for low-input technology soil management systems it is appropriate to select Oxisols and Ultisols with less than 8% slopes, to avoid the high-base status soils that can be put to more intensive use, and to avoid acid soils with severe physical limitations such as steep slopes, shallow depth, the Spodosols, and poorly drained or seasonally flooded soils.

III. SELECTION OF ACID-TOLERANT GERMPLASM

A substantial number of plant species of economic importance are generally regarded as tolerant to acid soil conditions in the tropics. Many of them have their center of origin in acid soil regions, suggesting that adaptation to soil constraints is part of the evolutionary process. Also, some varieties of certain species possess acid soil tolerance although the species as a whole does not. These varieties have probably been selected involuntarily by farmers or plant reeders because of their superior behavior under acid soil conditions. Examples f such involuntary selection aic well documented in the literature (Foy *et al.*, 974; Silva, 1976; Martini *et al.*, 1977; Lafever *et al.*, 1977).

The term "acid soil tolerance" covers a variety of individual tolerances to dverse soil factors and the interactions that occur among them. When mentioned n this article, this term only conveys a qualitative assessment of plant adaptation o acid soil conditions under low fertilizer or lime levels. Quantitative assessments of plant tolerances to acid soil stresses include tolerances to high levels f aluminum or manganese, and to deficiencies of calcium, magnesium, phoshorus, and certain micronutrients, principally zinc and copper. One example of n interaction among this group is that the calcium level of the soil solution can artially attenuate aluminum toxicity in many plant species (Foy and Fleming, 1978; Rhue, 1979). Tolerance to aluminum and low phosphorus stresses occur ogether in cultivars of wheat, sorghum, rice, and common beans but not in corn (Foy and Brown, 1964; Salinas, 1978). The physiological mechani ms involved, however, are beyond the scope of this article. The reader is referred to review articles in books edited by Wright (1976), Jung (1978), Andrew and Kamprath (1978), and Mussell and Staples (1979) for detailed discussions.

Duke (1978) compiled a list of 1031 plant species of economic importance with known tolerances to adverse envi onmental conditions. Tolerance to "acid soils, "lateritic soils," and "aluminum toxicity" were included. The first two categories were qualitative assessments, and the last one identified only those species for which aluminum tolerance studies have been carried out. Duke's list, although preliminary and incomplete, illustrates the broad base of acid-tolerant germplasm. A total of 397 species were listed as tolerant either to acid soils, lateritic soils, or to aluminum toxicity. Of these, 143 species met two of these criteria and 29 met all three. This last number reflects the limited number of species for which aluminum tolerance studies have been conducted. Tables IV and VI–VIII list selected species from Duke's compilation that meet at least two of these criteria. These tables include modifications, additions, or deletions by the authors of this review, based on their own observations.

A. Annual Food Crops

Table IV lists several of the world's most important basic food crop species that have a considerable degree of acid soil tolerance. Seven of them—cassava, cowpea, peanut, pigeon pea, plantain, potato, and rice—can be considered acid-tolerant species, although there are some acid-sensitive cultivars. The degree of knowledge as to the nature and degree of acid soil tolerance varies with the species.

Cassava (*Manihot esculenta*) is more tolerant to high levels of aluminum and

Table IV
Some Important Food Crops Considered to Be Generally Tolerant of Acid Soil Conditions in the Tropics

Generally tolerant species:	Generally susceptible spec[illegible] with acid-tolerant cultivars:
Cassava (*Manihot esculenta*)	Common bean (*Phaseolus vulgaris*)
Cowpea (*Vigna unguiculata*)	Corn (*Zea mays*)
Peanut (*Arachis hypogaea*)	Sorghum (*Sorghum bicolor*)
Pigeon pea (*Cajanus cajan*)	Soybean (*Glycine max*)
Plantain (*Musa paradisiaca*)	Sweet potato (*Ipomoea batatas*)
Potato (*Solanum tuberosum*)	Wheat (*Triticum aestivum*)
Rice (*Oryza sativa*)	

manganese and to low levels of calcium, nitrogen, and potassium than many other species are (Gomes and Howeler, 1980; Cock, 1981). Although it has high phosphorus requirements for maximum growth, cassava apparently can utilize phosphorus sources that are relatively unavailable through mycorrhizal associations (Cock and Howeler, 1978; Edwards and Kang, 1978). Many cassava cultivars respond negatively to liming because of induced zinc deficiency at high soil pH levels (Spain *et al.*, 1975). The ability of cassava to tolerate acid soil stresses may be due to an interesting mechanism. Cock (1981) observed that cassava leaves maintain an adequate nutritional status in the presence of low nutrient availability (Table V). Rather than dilute its nutrient concentration as in other plants, cassava responds to nutritional stress by decreasing its leaf area index. This is one reason why it is difficult to assess visual symptoms of nutrient deficiency in cassava growing on acid soils.

Cowpea (*Vigna unguiculata*) is the major grain legume species considered to be most tolerant to acid soil stresses and specifically to aluminum toxicity (Spain *et al.*, 1975; Munns, 1978). Under field conditions in Oxisols, cowpea commonly outyields other grain legumes such as soybean and *Phaseolus vulgaris* beans at high levels of aluminum saturation (Spain *et al.*, 1975). As in other legumes, the acid soil tolerance of the associated rhizobia is an important as the acid soil tolerance of the cowpea plant (Keyser *et al.*, 1977; Munns, 1978).

Peanut (*Arachis hypogaea*) is also regarded as tolerant to soil acidity (Munns, 1978), although it has a relatively high calcium requirement. Fortunately, small quantities of lime can provide sufficient calcium without altering the soil pH for maximum yields in Oxisols and Ultisols of the Venezuelan Llanos (C. Sanchez, 1977).

Plantain (*Musa paradisiaca*) is one of the most important carbohydrate food sources in many areas of the humid tropics of America and Africa. Its tolerance to aluminum and general adaptability to acid soil stresses has been demonstrated in Ultisols of Puerto Rico (Vicente-Chandler and Figarella, 1962; Plucknett, 1978)

Table V

The Effect of Soil Fertility Level on Leaf Area Index and Leaf Nutrient Concentration of the Cassava Variety M Mex 59 6 Months after Planting[a]

Fertility level	Leaf area index	Nutrient concentration (%)			Nutrient content per unit of leaf area (mg/dm²)		
		N	P	K	N	P	K
High	5.39	3.69	0.25	2.00	18.9	1.28	10.3
Medium	3.54	3.68	0.19	1.40	20.2	1.04	7.7
Low	1.65	3.52	0.18	0.73	21.7	1.11	4.5

[a] Source: Cock (1981).

and Oxisols of the Llanos Orientales of Colombia (CIAT, 1975). This crop, however, has relatively high requirements for nitrogen and potassium. Strong positive responses to nitrogen, phosphorus, potassium, magnesium, and micronutrient applications have been recorded (Caro Costas *et al.*, 1964; Silva and Vicente-Chandler, 1974; Samuels *et al.*, 1975).

The potato (*Solanum tuberosum*) has long been considered an acid-tolerant crop. Potato growers keep pH values below 5.5 in order to control the common scab organism, *Streptomyces scabies*. Definite varietal differences in tolerance to aluminum have been established (Villagarcía, 1973). Disease problems in isohyperthermic temperature regimes are a greater limitation than acid soil constraints.

Acid soil tolerance of rice (*Oryza sativa*) under flooded conditions is normally not of significance. Except in some acid sulfate soils, the pH of most acid soils rises to 6 to 7 with flooding as a consequence of the chemical reduction of iron and manganese oxides and hydroxides (Ponnamperuma, 1972). Exchangeable aluminum is precipitated at these pH levels, thereby eliminating aluminum toxicity. In nonflooded systems, many rice varieties are quite tolerant to aluminum (as shown in Fig. 4) and/or low available levels of phosphorus (Spain *et al.*, 1975; Howeler and Cadavid, 1976; Salinas and Sanchez, 1976; Ponnamperuma, 1977; Salinas, 1978). Also, varietal differences in tolerance to manganese toxicity and iron deficiency in acid soils have been identified (Ponnamperuma, 1976). In the Oxisol/Ultisol regions of Latin America, upland rice is generally considered to be more tolerant to acid soil stresses than corn is (Salinas and Sanchez, 1976; Sanchez, 1977).

Other less common grain legume species are also considered to be tolerant to acid soil stresses in Oxisols and Ultisols of the tropics, although there is little quantitative information about their degree of tolerance. They are pigeon peas (*Cajanus cajan*), lima beans (*Phaseolus lunatus*), winged beans (*Psophocarpus tetragonolobus*), and mung beans (*Vigna radiata*), according to Munns (1978).

Table IV also lists five species for which certain cultivars have been identified as acid soil-tolerant, but the species as a whole is not. Great variability exists in *Phaseolus vulgaris* beans, some cultivars being tolerant to aluminum toxicity and/or low phosphorus levels and some highly sensitive to both stresses (Spain *et al.*, 1975; Whiteaker *et al.*, 1976; Salinas, 1978; CIAT, 1977, 1978, 1979, 1980). In this species, disease and insect stresses, particularly in isohyperthermic temperature regimes, are more yield-limiting than soil constraints.

Although corn (*Zea mays*) is considered by some investigators to be generally acid-tolerant (Rhue, 1979), lime response trials in the tropics tend to demonstrate the opposite. Nevertheless, several hybrids and composites possess a marked degree of aluminum tolerance and/or tolerance to phosphorus stress (Fox, 1978; Salinas, 1978).

As a species, grain sorghum (*Sorghum bicolor*) is poorly adapted to acid soil conditions. Most of the varietal improvement work on this crop has been conducted in neutral or calcareous soils. Fortunately, cultivar differences in terms of aluminum tolerance do exist (Brown and Jones, 1977a). An example is shown in Fig. 5 adapted from Salinas (1978). Brown and Jones (1977a) have also reported marked cultivar differences to copper stress but none to manganese toxicity. Cultivar differences in tolerance to phosphorus stress also exist (Brown *et al.*, 1977).

As a species, soybean (*Glycine max*) is probably less tolerant to overall acid soil conditions than most of the previously mentioned ones. Considerable varietal differences in tolerance to aluminum exist (Sartain and Kamprath, 1978; Muzilli *et al.*, 1978; Miranda and Lobato, 1978) as well as intolerance to manganese toxicity (Brown and Jones, 1977b). Unlike the other grain legumes, rhizobia strains associated with soybeans tend to be more aluminum-tolerant than the plant (Munns, 1980).

Aluminum tolerance in some sweet potato (*Ipomoea batatas*) cultivars has also been identified (Munn and McCollum, 1976; Toma, 1978). Some varieties grown in Puerto Rico are quite tolerant to aluminum and manganese toxicity (Perez-Escolar, 1977).

Wheat (*Triticum aestivum*) is probably the species most thoroughly studied in terms of acid soil tolerance. It is an important crop in Oxisol–Ultisol regions of Latin America with isothermic or thermic soil temperature regimes. Varietal differences appear to be related to the soil acidity status where they were developed (Silva, 1976; Foy *et al.*, 1974). For example, the well-known short-statured CIMMYT wheat varieties, which were selected on calcareous soils of northern Mexico, perform poorly in Oxisols of the Cerrado of Brazil in comparison with varieties that were developed in Brazil, in spite of the latter's inferior plant type (Salinas, 1978). Acid soil tolerance in such wheat cultivars is related to a joint tolerance to aluminum toxicity and low available soil phosphorus (Salinas, 1978; Miranda and Lobato, 1978). Other studies also show that aluminum-tolerant wheat varieties perform well at higher percent aluminum saturation levels than aluminum-tolerant soybean varieties in Oxisols (Muzilli *et al.*, 1978).

B. Perennial and Tree Crops

Table VI lists some of the tropical fruit crop species considered to be tolerant to acid soil stresses. Some species like pineapple and cashew are well known for their adaptation to acid soils. Like the annual food crops, some species are severely affected by other constraints. For example, bananas are hampered by diseases and high potassium requirements; the citrus species are less productive in isohyperthermic temperature regimes than in cooler climates; mango requires an ustic soil moisture regime for high productivity.

Some important perennial crops and forestry species adapted to acid soils in the tropics are listed in Table VII. Arabica coffee is very tolerant to aluminum but is sensitive to manganese toxicity (Abruña *et al.*, 1965). It prefers an isothermic soil temperature regime and an udic soil moisture regime. Robusta coffee is better adapted to isohyperthermic regimes but produces lower-quality coffee than arabica coffee.

Among other perennial crops, rubber and oil palm are very well adapted to Oxisol–Ultisol regions, particularly those with udic isohyperthermic regimes (Alvim, 1981; Santana *et al.*, 1977). Sugarcane is also generally tolerant to acid soil conditions (Abruña and Vicente-Chandler, 1967) but requires large quantities of nitrogen and potassium to support high production levels.

Table VI
Some Important Fruit Crops Considered to Be Generally Tolerant to Acid Soil Conditions in the Tropics

Name	Species	Source
Banana	*Musa sapiensis*	Authors
Carambola	*Averrhoa carambola*	Duke (1978)
Cashew	*Anacardium occidentale*	Duke (1978)
Coconut	*Cocos nucifera*	Duke (1978)
Granadilla	*Passiflora edulis*	Duke (1978)
Grapefruit	*Citrus paradisi*	Duke (1978)
Guava	*Psidium guajava*	Authors
Jackfruit	*Artocarpus heterophyllus*	Duke (1978)
Lime	*Citrus aurantiifolia*	Duke (1978)
Mango	*Manguifera indica*	Duke (1978)
Orange	*Citrus sinensis*	Duke (1978)
Pineapple	*Ananas comosus*	Duke (1978)
Pomegranate	*Punica granatum*	Duke (1978)

Table VII
Some Important Perennial and Forest Crops Considered to Be Tolerant to Acid Soil Conditions in the Tropics

Name	Species	Source
Brazil nut	*Bertholletia excelsa*	Duke (1978)
Coffee	*Coffea arabica*	Duke (1978)
Eucalyptus	*Eucalyptus grandiflora*	Alvim (1981)
Gmelina	*Gmelina arborea*	Alvim (1981)
Guaraná	*Paullinia cupana*	Alvim (1981)
Jacarandá	*Dalbergia nigra*	Alvim (1981)
Oil palm	*Elaeis guineensis*	Duke (1978)
Peach palm	*Guilielma gasipaes*[a]	Alvim (1981)
Pepper, black	*Piper nigrum*	Duke (1978)
Pine	*Pinus caribea*	Alvim (1981)
Rubber	*Hevea brasiliensis*	Duke (1978)
Sugarcane	*Saccharum officinarum*	Duke (1978)

[a] Known as "pejibaye," "chontaduro," "pijuayo," and "pupunha."

Although many native wood species of the Amazon are tolerant to acid soil conditions, some of the most promising forestry species are imported from other regions. *Gmelina arborea*, *Pinus caribea*, *Dalbergia nigra*, and certain species of *Eucalyptus* have proven to be well adapted to Oxisols and Ultisols of the Brazilian Amazon without liming (Alvim, 1981). Other species native to the Amazon, such as Brazil nut (*Bertholletia excelsa*), guaraná (*Paullinia cupana*), and peach palm (*Guilielma gasipaes*), also have significant commercial potential.

Several important tropical perennial crops are not included in the above list. Noteworthy among them are cocoa (*Theobroma cacao*) and *Leucaena leucocephala*, a legume species with potential for grazing, browse, and firewood (National Academy of Sciences, 1977b). Neither of these two species are aluminum-tolerant (Alvim, 1981; Hill, 1970). Therefore, they are not adapted to acid soils with low inputs. Breeding for aluminum tolerance, however, is proceeding in both species. In the case of legume, selection for acid-tolerant *Rhizobium* strains is considered to be equal in importance to plant selection (CIAT, 1979; Munns, 1978).

C. Grass and Legume Pastures

Extensive work on screening grass and legume pasture species for acid soil tolerance has been conducted in Australia and Latin America (Andrew and Hegarty, 1969; Andrew and Vanden Berg, 1973; Spain *et al.*, 1975; Andrew, 1976, 1978, Helyar, 1978; CIAT, 1978, 1979, 1980, 1981; Spain, 1979). A fundamental difference of the work in the two continents is that aluminum toxicity is infrequent in the tropical pasture regions of Australia, while the opposite is the case in tropical pasture regions of Latin America (Sanchez and Isbell, 1979). The predominant acid soil stresses in tropical Australia are low phosphorus, sulfur, molybdenum, and to a lesser extent manganese toxicity. Aluminum toxicity, low phosphorus availability, and high phosphorus fixation are more important in tropical America.

1. Aluminum Tolerance

A wide range of CIAT's forage germplasm bank is tolerant to high levels of exchangeable aluminum simply because much of it has been collected from acid, infertile soil regions of tropical America (Schultze-Kraft and Giacometti, 1979). An example of differential tolerance to aluminum of four common tropical grasses is shown in Fig. 7 from a solution culture study of Spain (1979). *Brachiaria decumbens* even shows a slight positive response to the first increment of aluminum. *Panicum maximum* exhibits strong tolerance up to one-half the aluminum concentration tolerated by *Brachiaria decumbens*. In contrast, *Cenchrus ciliaris*, one of the most widespread tropical grasses in ustic but not acid areas of Australia, is severely affected by aluminum. This excellent grass is well adapted to nonacid soils, but to grow well in Oxisol–Ultisol regions it is

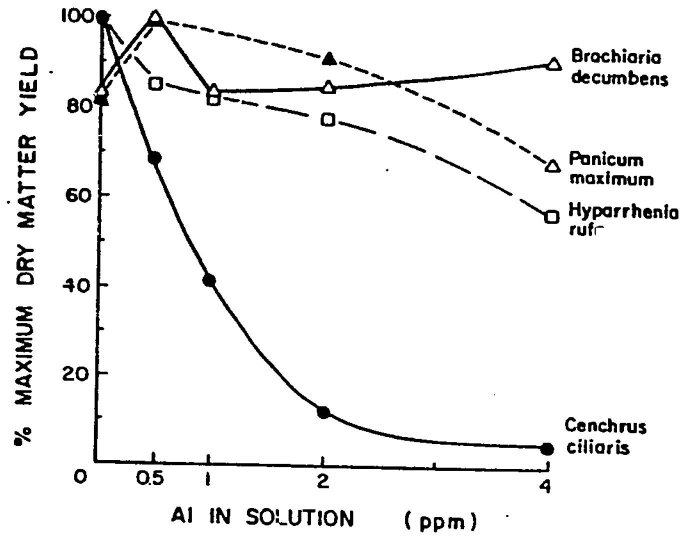

Fig. 7. Differential tolerance to aluminum in culture solution by four tropical grasses. (Source: Spain, 1979.)

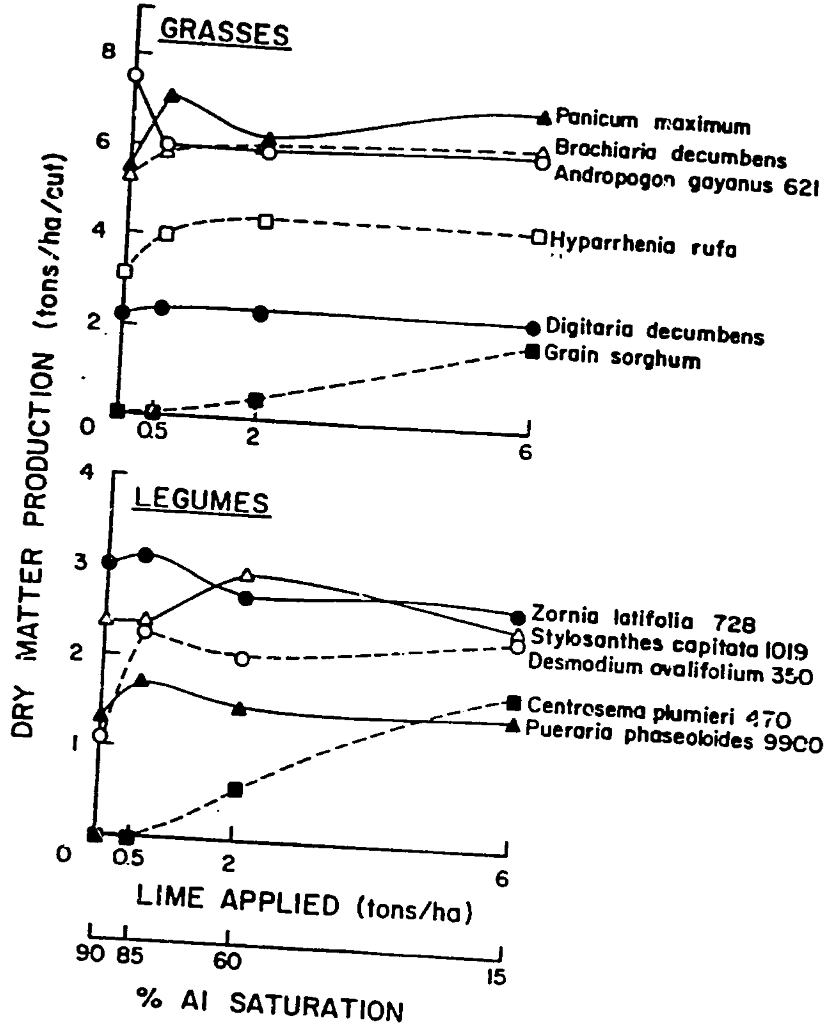

Fig. 8. Field response to lime applications by several grass and legume forage species in an Oxisol of Carimagua, Colombia. Mean of four to five cuts for the grasses and first cut for legumes. (Adapted from Spain, 1979.)

necessary to completely neutralize the exchangeable aluminum by liming to about pH 5.5. A list of tolerant species is shown in Table VIII.

Figure 8, also adapted from Spain (1979), shows responses to lime applications in an Oxisol of Carimagua, Colombia, with pH 4.5 and 90% aluminum saturation before liming. Acid-tolerant grasses such as *Andropogon gayanus*, *Brachiaria decumbens*, and *Panicum maximum* and the legumes *Stylosanthes capitata* and *Zornia latifolia* produced maximum growth either at 0 or 0.5 ton lime/ha. The 0.5 ton/ha rate did not alter soil pH or aluminum saturation but provided calcium and magnesium to the plants.

Their performance is clearly superior to aluminum-sensitive species such as grain sorghum and *Centrosema plumieri*, a legume clearly not adapted to acid soils. It is also relevant to point out that some aluminum-tolerant species do not grow vigorously in acid soils. This is the case of pangola grass (*Digitaria decumbens*), shown in Fig. 8.

2. *Low Levels of Available Soil Phosphorus*

Phosphorus is the single most expensive input needed for improved pastures in Oxisol–Ultisol savannas (CIAT, 1979). It is not, however, the only nutrient that is deficient in these soils, but its correction is usually the most expensive one. No improved pastures are likely to be established or maintained without phosphorus fertilization in these savannas. In order to increase the efficiency of phosphorus fertilization, it is possible to select plants that have a lower phosphorus requirement for maximum growth than those presently used. Fortunately, aluminum tolerance and "low phosphorus tolerance" often occur jointly because the latter seems associated with the plant's ability to absorb and translocate phosphorus from the root to the shoot in the presence of high levels of aluminum in the soil solution and/or root tissue (Salinas, 1978).

Several promising grass and legume species require a fraction of the available soil test phosphorus levels required by annual crops and much less than other pasture species. For example, the general soil test critical level used for crops in Colombia is 15 ppm P by the Bray II method (Marín, 1977). Promising aluminum-tolerant ecotypes of *Stylosanthes capitata*, *Zornia latifolia*, and *Andropogon gayanus* require 1/3–1/5 of that amount to attain maximum yields. This information is shown in Table XXXIII of Section VI,D.

It should be noted that adapted grasses such as *Andropogon gayanus* and *Brachiaria decumbens* require higher critical levels of Bray II available soil phosphorus (5–7 ppm P) than adapted legumes like *Stylosanthes capitata* and *Zornia latifolia* (3–4 ppm P) require for near maximum growth (CIAT, 1979). The commonly held view that fertilization of grass–legume mixtures should be based on the legume's higher nutritional requirement does not apply to these species. This has been proven in the field by Spain (1979), where, in addition to phosphorus, there was a higher need for potassium in the grasses than in the legumes.

Field responses during the establishment year show significant differences in the levels of phosphorus fertilization needed for near maximum growth on an Oxisol with about 1 ppm available P (Mehlich 2 method) prior to treatment applications (Fig. 9). *Andropogon gayanus* required 50 kg P_2O_5/ha to reach maximum yields, while *Panicum maximum* required 100 kg P_2O_5/ha and *Hyparrhenia rufa* required 200 or perhaps more. The latter species, very widespread in

Table VIII
Some Important Pasture Species Adapted to Oxisols and Ultisols of the Tropics[a]

Species	Observations
	Grasses
Andropogon gayanus	Well adapted; new release in tropical America
Brachiaria decumbens	Well adapted; spittlebug susceptible
Brachiaria humidicola	Very Al-tolerant, low palatability
Digitaria decumbens	Adapted, but requires high fertility
Hyparrhenia rufa	Adapted, high K requirement, low productivity
Melinis minutiflora	Adapted but low productivity
Panicum maximum	Adapted, somewhat higher nutritional requirement
Pennisetum purpureum	Adapted for cut forage, high nutrient requirement
Paspalum notatum	Low productivity
Paspalum plicatulum	Disease susceptibility in some areas
	Legumes
Desmodium heterophyllum	Prefers udic soil moisture regime
Desmodium gyroides	Shrub for browse
Desmodium ovalifolium	High tannin in ustic climates
Calopogonium mucunoides	Persistent but low palatability
Centrosema pubescens	Insect attack problems
Galactia striata	Productive in certain systems only
Pueraria phaseoloides	Not for long dry season
Stylosanthes capitata	Savannas only
Stylosanthes guianensis	Only few cultivars have anthracnose tolerance
Stylosanthes scabra	Promising for isothermic savannas
Stylosanthes viscosa	Promising for isothermic savannas
Zornia latifolia	Promising for isohyperthermic savannas

[a]Source: CIAT (1978, 1979, 1980) and authors' observations.

Latin America, performs poorly in Oxisol–Ultisol regions because of a generally higher requirement for phosphorus and potassium and a lower tolerance to aluminum than the other two (Spain, 1979). These differences are quite significant at the animal production level. At levels of inputs where other grasses produce good cattle liveweight gains, *Hyparrhenia rufa* produced serious liveweight losses at Carimagua, Colombia (Paladines and Leal, 1979).

It may be argued that the use of pastures requiring less phosphorus may provide insufficient phosphorus for animal nutrition. There is no evidence in the CIAT work that this is so (CIAT, 1978, 1979), but if it were, it is probably cheaper to apply only the phosphorus fertilizer required for maximum plant growth to the soil and supplement the rest directly to the animals via salt licks.

3. *Water Stress*

The ability to grow and survive the long dry seasons of ustic environments under grazing is a necessary requirement for acid-tolerant forage species because

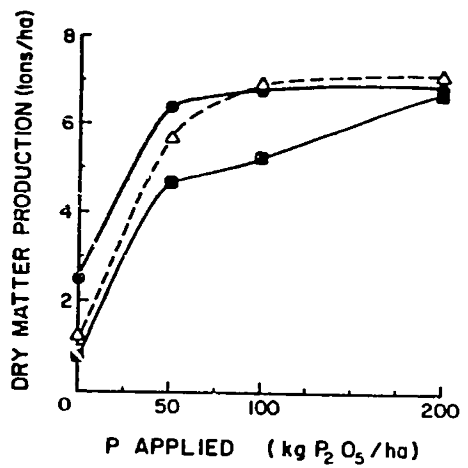

FIG. 9. Differential response to phosphorus fertilization of three grass species during the establishment year in an Oxisol of Carimagua, Colombia: (●) *Andropogon gayanus* 621, (△) *Panicum maximum* 622, (■) *Hyparrhenia rufa* 601. Sum of three wet season cuts. All treatments received 400 kg N/ha. (Source: CIAT, 1979.)

irrigating pastures is prohibitively expensive in most Oxisol–Ultisol regions. Because of their aluminum tolerance, roots of adapted forage species are able to penetrate deeply into acid subsoils and exploit the residual moisture that is available. This is in sharp contrast with aluminum-sensitive crops that suffer severely from water stress, even during short dry periods, because their roots are confined to the limed topsoil (Gonzalez *et al.*, 1979).

Adapted legume species are generally more tolerant to drought stress than the grass species. Also, legumes are able to maintain a higher nutritive value during the dry season than the grasses. For example, *Zornia latifolia* 728 contained 24% protein in its leaves at the height of the Carimagua dry season, while accompanying grasses contained about 5% protein (CIAT, 1979).

Among the adapted grasses, *Andropogon* is more tolerant to drought stress than *Brachiaria decumbens* or *Panicum maximum* (CIAT, 1979). Its pubescent leaves also permit dew drops to remain on the leaves longer than in *B. decumbens* or *P. maximum*. It is common to get one's pant legs wet while walking through an *Andropogon* pasture at about 10:00 A.M. in the Llanos or in the Amazon, when swards of the other two species are already dry.

4. *Insect and Disease Attacks*

Most of the adapted legume species have their center of origin in Latin America and therefore, have many natural enemies. Anthracnose caused by *Collectotrichum gloesporoides* is a most devastating disease of legumes (CIAT,

1977, 1978, 1979). Stem-borers of the genus *Caloptilia* also attack several *Stylosanthes* species (CIAT, 1979). Spittlebug attacks caused by *Deois incompleta* and other species have destroyed thousands of hectares of *Brachiaria decumbens* pastures in udic regions of tropical Brazil. The solution to these problems is varietal resistance since applications of insecticides or fungicides to these pastures are likely to be uneconomical. Screening for tolerance to these and other pathogens has provided ecotypes that combine the adaptation to adverse soil conditions with pathogen resistance. Examples of these to date are several ecotypes of *Andropogon gayanus*, *Stylanthes capitata*, and *Desmodium ovalifolium*. Several promising ecotypes of *Stylosanthes guianensis*, a legume extremely well adapted to acid soil constraints, unfortunately have succumbed to insect and disease attacks (CIAT, 1978, 1979). As in other plant improvement programs, the search for new ecotypes that combine tolerance to pathogens with other desirable characteristics is a continuing activity.

It is interesting to note that plant protection problems increase in importance after the soil constraints are alleviated by plant selection or fertilization in Oxisol–Ultisol regions. This may be a consequence of elimination of a previously limiting factor, or of a pathogen buildup as new plants are grown on many hectares for the first time in a new environment. This observation applies both to pastures and to annual food crops. Tolerance to disease and insect attacks, however, varies with ecological conditions and therefore the degree of tolerance of each promising cultivar must be validated locally.

5. *Tolerance to Burning*

Accidental burning is common in savanna regions and intentional burning may be a necessary management practice in cases where grasses approach maturity rapidly and lose their nutritive value. Consequently, the adapted pasture species must be able to regrow after burning. Studies in Quilichao, Colombia show that *Andropogon gayanus*, *Panicum maximum*, *Brachiaria decumbens*, and *Brachiaria humidicola* regrow rapidly after burning (CIAT, 1979). Later CIAT work shows that regrowth after burning depends very much on soil moisture conditions at the time of burning. The *Brachiarias*, for example, are very susceptible to burning when the surface soil is moist.

D. CONCLUSIONS

There is a broad germplasm base of acid-tolerant annual crops, permanent crops, tree crops, and pasture species adapted to tropical conditions in Latin America. In addition, selection of breeding programs can provide acid-tolerant varieties from generally sensitive species. The degree of quantification of these differences, however, is very limited. A more systematic classification of what are the critical tolerance levels of each important variety or species is needed. Such a plant classification system could be linked with present technical soil classification systems in order to better match plant characteristics with soil constraints.

IV. DEVELOPMENT AND MAINTENANCE OF GROUND COVER

The choice of farming systems is extremely varied and very dependent on market demands or opportunity, farming tradition, and government policies. The prevalent farming systems in Oxisol-Ultisol regions of tropical America can be grouped into four major categories: shifting cultivation (primarily in the forested areas), extensive cattle grazing in both forested and savanna regions, permanent crop production systems, and intensive annual crop production systems. The extent of the last two is very limited. These systems are described in a review by Sanchez and Cochrane (1980).

Regardless of the farming system or the plant species used, a basic principle of low-input technology is to develop and maintain a plant canopy over the soil for as long as possible in order to decrease erosion, compaction, and leaching hazards. The main technology components are land clearing methods, crop and pasture establishment techniques, mulching, the use of managed fallows, intercropping, and multiple cropping systems. Some of the advances in developing these technology components are discussed in this section.

A. Land Clearing Methods in Rain Forests

The choice of land clearing method is the first and probably the most crucial step affecting the future productivity of farming systems in rain forest areas. Several comparative studies conducted in the humid tropics of Latin America confirm that manual slash-and-burn methods are superior to different types of mechanical clearing because of the fertilizer value of the ash and because of less soil compaction and topsoil displacement compared to mechanized land clearing.

1. Nutrient Additions by the Ash

The nutrient content of ash has been directly determined upon burning a 17-year-old secondary forest on Typic Paleudult from Yurimaguas, Peru. The data of Seubert *et al.* (1977) in Table IX show significant beneficial effects of ash on soil chemical properties (Fig. 10), which resulted in higher yields of a

Table IX

Nutrient Contribution of Ash and Partially Burned Material Deposited on an Ultisol of Yurimaguas, Peru, after Burning a 17-Year-Old Forest[a]

Element	Composition	Total additions (kg/ha)
N	1.72%	67
P	0.14%	6
K	0.97%	38
Ca	1.92%	75
Mg	0.41%	16
Fe	0.19%	7.6
Mn	0.19%	7.3
Zn	132 ppm	0.3
Cu	79 ppm	0.3

[a] Source: Seubert *et al.* (1977).

wide variety of crops during the first 2 years after clearing (Table X). There is considerable variability among sites in the quantity of ash and its nutrient composition because of differences in soil properties, clearing techniques, and the proportion of the forest biomass actually burned. Silva (1978) estimated that only 20% of the felled forest biomass was actually converted to ash after burning a virgin forest on an Oxic Paleudult of southern Bahia, Brazil. Silva also analyzed the ash composition of the burned parts of individual tree species and observed wide ranges (0.8–3.4% N; 0–14 ppm P; 0.06–4.4 meq Ca/100 g; 0.11–21.03

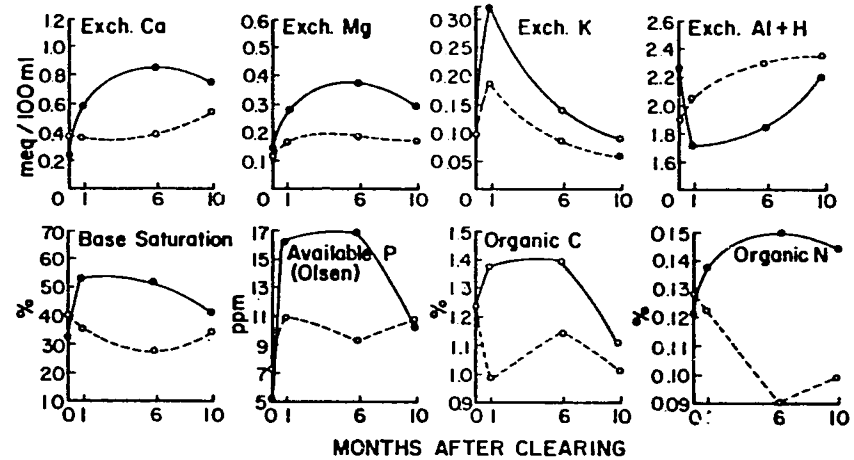

Fig. 10. Effects of two land clearing methods on changes in topsoil (0–10 cm) properties in a Typic Paleudult of Yurimaguas, Peru: (●) slash-and-burn method; (○) bulldozer clearing. (Source: Seubert *et al.*, 1977.)

Table X
Effects of Land-Clearing Methods on Crop Yields at Yurimaguas[a,b]

Crop	Fertility level[c]	Slash and burn (tons/ha)[d]	Bulldozed (tons/ha)[d]	Bulldozed / Burned (%)
Upland rice (3)	0	1.3	0.7	53
	NPK	3.0	1.5	49
	NPKL	2.9	2.3	80
Corn (1)	0	0.1	0.0	0
	NPK	0.4	0.04	10
	NPKL	3.1	2.4	76
Soybeans (2)	0	0.7	0.2	24
	NPK	1.0	0.3	34
	NPKL	2.7	1.8	67
Cassava (2)	0	15.4	6.4	42
	NPK	18.9	14.9	78
	NPKL	25.6	24.9	97
Panicum maximum (6 cuts/yr)	0	12.3	8.3	68
	NPK	25.2	17.2	68
	NPKL	32.2	24.2	75
Mean relative yields	0			37
	NPK			47
	NPKL			48

[a]Source: Seubert *et al.* (1977).
[b]Yield is the average of the number of harvests indicated in parentheses.
[c]50 kg N/ha, 172 kg P/ha, 40 kg K/ha, 4 tons lime/ha (L).
[d]Grain yields of upland rice, corn, and soybeans; fresh root yields of cassava; annual dry matter production of *Panicum maximum*.

meq Mg/100 g, and 34–345 meq K/100 g). This information suggests the presence of certain species that can be considered accumulators of specific nutrients.

The fertilizer value of the ash is likely to be of less importance in high-base status soils. Cordero (1964) observed that increases in phosphorus and potassium availability caused by burning the biomass on an Entisol of pH 7 in Santa Cruz, Bolivia, did not increase crop yields. The soil was already high in these elements. Information on ash composition from different soils and clearing methods therefore will contribute significantly to our understanding of soil dynamics and its subsequent management.

2. *Soil Compaction*

Conventional bulldozing has the clearly detrimental effect of compacting the soil, particularly coarse-textured Ultisols. Significant decreases in infiltration

rates, increases in bulk density, and decreases in porosity have been recorded on such soils in Surinam (Van der Weert, 1974), Peru (Seubert *et al.*, 1977), and Brazil (Silva, 1978) after mechanized land clearing. Table XI shows the decreases in infiltration at three sites. The slash-and-burn method had a moderate effect on infiltration rates, but bulldozing decreased them by one order of magnitude. Comparisons between sites are difficult because of differences in the time span used in measuring. The Manaus example illustrates the compaction observed in degraded pastures in parts of the Brazilian Amazon.

3. *Topsoil Displacement*

The third major consideration is the degree of topsoil carryover, not by the bulldozer blade, which is normally kept above the soil, but by dragging uprooted trees and logs. Although no quantitative data are available, topsoil removal from high spots and accumulation in low spots are commonly observed. The better forest regrowth near windrows of felled vegetation suggests that topsoil displacement can result in major yield reductions (Sanchez, 1976). For example, Lal *et al.* (1975) in Nigeria observed that corn yields decreased by 50% when the top 2.5 cm of an Alfisol was removed. No comparable data, however, is available from acid soils of tropical America. Nevertheless, the yield decreases shown in Table X are undoubtedly associated with topsoil displacement.

4. *Alternative Land Clearing Methods*

The detrimental effects of bulldozer land clearing are generally well known to farmers and development organizations in parts of the Amazon. Government credits for large-scale mechanized land clearing operations have been sharply reduced in the Brazilian Amazon since 1978. Also, the practice of completely

Table XI
Effects of Clearing Methods on Water Infiltration Rates in Ultisols from Yurimaguas, Peru; Manaus and Barrolândia (Bahia), Brazil[a]

Clearing method	Yurimaguas Peru (cm/hr)	Manaus, AM Brazil (cm/hr)	Barrolândia, BA Brazil (cm/hr)
Undisturbed forest	26	15	24
Slash and burn (1 year)	10	—	20
Bulldozed (1 year)	0.5	—	3
Slash and burn and 5 years in pasture	—	0.4	—

[a]Sources: NCSU (1972), Seubert *et al.* (1977), Schubart (1977), and Silva (1978).

destroying the forest versus its partial harvest before burning is being considered. Silva (1978) provided the first quantitative estimate of the possible benefits of such a practice. He compared the two extremes, the slash-and-burn method and bulldozing, with treatments that include the removal of marketable trees first, followed by cutting and burning the remaining ones. All the advantages of burning on soil fertility were observed in this latter treatment, with no significant differences from the conventional slash-and-burn method (Silva, 1978), but with a valuable increase in income. The lack of difference is probably due to the small proportion of the total biomass that is actually burned. Indeed many farmers in the Amazon harvest wood first, some of them developing profitable lumber mills in the process of clearing land for pasture establishment.

The pressures for opening new lands in some areas of the Amazon are so intense that it is now necessary to develop technology that minimizes the detrimental effects of mechanized land clearing on soil properties. Research comparing presently available mechanized land clearing technologies has not been conducted in this region on a systematic fashion. Bulldozers equipped with a "KG" blade that cuts tree trunks at ground level by shearing action could cause less topsoil displacement since the root systems remain in place. "Tree pusher" attachments on tractors reduce energy requirements for felling and may decrease compaction by machinery. A heavy chain dragged by two bulldozers should also minimize compaction. With these three techniques the felled vegetation could be burned and the remaining material could be removed by bulldozers equipped with a root rake at a later time.

A large-scale unreplicated study on Typic Acrorthox near Manaus showed little difference in chemical or physical soil properties when some of the above combinations were compared with conventional bulldozing (UEPAE de Manaus, 1979). The slash-and-burn treatment provided superior chemical properties and better pasture growth than the mechanized land clearing treatments. Work on Alfisols of Nigeria with totally different physical and chemical properties shows that the clearing of land with bulldozers equipped with a shear blade, followed by burning and removal of residues with a root rake, was the least damaging mechanized system (IITA, 1980).

One type of low-input technology that has produced few satisfactory results is the partial clearing of tropical rain forests. Strips are cleared by the slash-and-burn method in order to plant shade-tolerant crops such as cocoa or certain pastures, or to enrich the forest with valuable timber species. Experiments have been conducted in Manaus, Brazil, by various organizations, but the results have been disappointing. No data are available as such experiments have not been published. Apparently, it is difficult to provide sufficient sunlight for vigorous plant establishment without eliminating the forest canopy. Leaving a few trees untouched, however, is often done, particularly when they are of value or to provide shade for pasture. Hecht (1979) has identified several legume tree and

shrub species that should be allowed to regrow after clearing for pastures because of their capacity to provide browse forage for cattle.

Many of the failures of large-scale farming operations observed by the authors in the humid tropics can be directly attributed to improper land clearing methods. Research on alternative mechanized land clearing methods that involve burning is needed.

B. Soil Dynamics after Clearing Tropical Rain Forests

When a tropical forest is cleared and burned several changes in soil properties generally occur within the first year: Large losses of biomass nitrogen and sulfur occur upon burning by volatilization, soil organic matter decreases with time until a new equilibrium is reached; the pH of acid soils increases, aluminum saturation levels decrease, exchangeable bases and available phosphorus increase; and topsoil temperatures increase (Sanchez, 1973). The following discussion is based on a recent review of the subject by the senior author (Sanchez, 1979).

Most of the available data is based on sampling nearby sites of known age after clearing at the same time. This technique confounds time and space dimensions and increases the already considerable variability between sites. Fortunately, there are five studies in which changes in soil properties were followed with time in humid tropical America; Yurimaguas, Peru; Manaus, Belém, and Barrolândia, Brazil; and Carare-Opón, Colombia. Most of them, however, are limited to what happens during the first year, but one covers an 8-year period. Nevertheless, they illustrate the differences that take place within sites as a function of time.

1. *Soil Organic Matter*

Salas and Folster (1976) estimated that 25 tons C/ha and 673 kg N/ha were lost to the atmosphere when a virgin forest growing on an Aeric Ochraquox in the middle Magdalena Valley of Colombia was cut and burned. These figures were derived by measuring the biomass changes before and after burning, but before the first rains. These losses accounted for only 11–16% of the total carbon and about 20% of the total nitrogen in the ecosystem (Salas, 1978). Consequently, assertions that *most* of the carbon and nitrogen in the vegetation is volatilized upon burning deserve scrutiny. Another unknown factor is whether or not a proportion of the volatilized elements is returned back to nearby areas via rainwash.

The influence of burning on the thin organic-rich layer consisting of litter-topsoil interphase was also determined by Salas (1978). The C/N ratio of this material increased from 8 to 46 within 5 months, suggesting that the volatile losses were rich in nitrogen.

The literature has conflicting information about the losses of soil organic matter when the cropping phase begins. Larger losses will occur in soils with higher initial organic matter contents (Sanchez, 1976). This effect, however, is attenuated by the topsoil clay content. Turenne (1969, 1977) found an inverse relationship between organic carbon losses and clay contents in Oxisols of French Guiana.

Another supposedly detrimental effect of burning is a decrease in soil microbiological activity. Silva's (1978) southern Bahia study reports no significant differences caused by various degrees of burning on fungal flora, but decreases in the bacterial and actinomycetal population during the first 30 days after the conventional burn. Figure 11 shows the time trend in cellulose decomposition activity. Burning actually had a stimulating effect on the decomposing microflora, probably because of the increase in phosphorus and other nutrients, plus the higher soil temperatures incurred upon exposing the soil surface to direct sunlight. No such effect was observed in the bulldozer clearing, probably because of topsoil displacement and soil compaction. The partial sterilization effect in the conventional burn may account for the lower microbiological acitvity observed during the first 25 days after burning.

The dynamics of organic carbon during the first 4 years of continuous upland, rice-corn-soybean cropping on an Ultisol from Yurimaguas, Peru, without fertilization or liming, are shown in Fig. 12. There was an actual increase in organic carbon contents 1 month after burning, probably a result of ash contami-

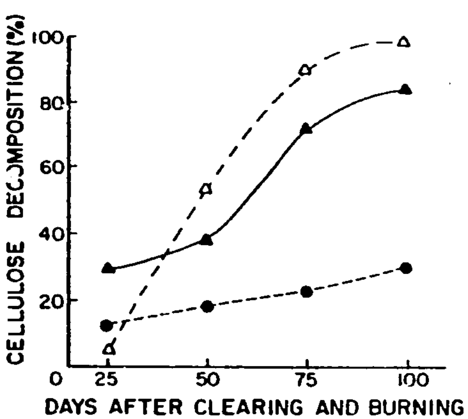

FIG. 11. Effects of degrees of burning intensity on microbial activity as measured by cellulose decomposition rates as a function of time after burning a rain forest on an Ultisol of southern Bahia, Brazil. △—·—△, conventional slash-and-burn method; ▲- - - ▲, harvest-valuable trees plus slash-and-burn method; ●---●, bulldozer clearing (no burning). (Adapted from Silva, 1978.)

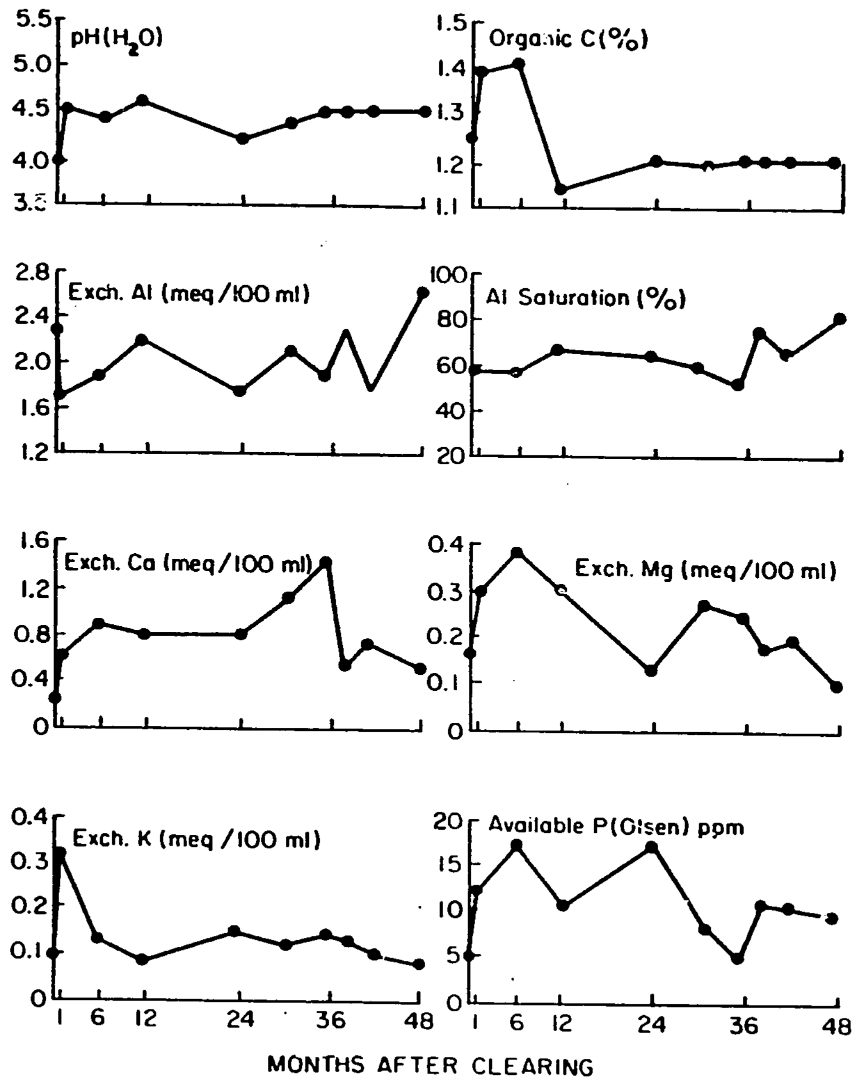

FIG. 12. Changes in chemical properties of an Ultisol (0-10 cm) continuously cropped to upland rice, corn, and soybeans (8 crops), without fertilization at Yurimaguas (1972-1976). (Compiled from data by Seubert *et al.*, 1977; Villachica, 1978; and Sanchez, 1979.)

nation. This increase was followed by a plateau for the first 6 months, then a sharp decrease was observed after the first rice crop was harvested, and finally an equilibrium was reached at the end of the first year. The annual decomposition rate during the first year was on the order of 30%, but a new equilibrium was attained the second year of cropping (Villachica, 1978). This high decomand potassium became deficient with 6 months after clearing. Aluminum reached toxic levels for corn at 10 months after clearing. At that time phosphorus, magnesium, copper, and boron became deficient and crop yields without fertilization approached zero. When potassium fertilizers were added, a K/Mg imbalance resulted; this necessitated further magnesium additions. Zinc approached deficiency levels at the end of the second year and sulfur and molybdenum deficiencies were observed sporadically (Villachica, 1978; Sanchez, 1979). The Yurimaguas results indicate that most of the rapid changes occur during the first 2 years after clearing, after which equilibria are established.

C. Land Preparation and Plant Establishment in Rain Forests

In traditional slash-and-burn clearings, land preparation is usually limited to removal of some logs for firewood or charcoal. The first plantings consist of poking holes in the ground with a pointed stick called "espeque" or "tacarpo," followed by dropping seeds or simply inserting cassava stakes or plantain rhizomes. This zero-tillage system protects the soil against erosion by a tangled mass of logs and branches, numerous tree stumps, and a mulch of ash and unburned plant material. Since fertilizers are seldom needed for the first planting, there is little need for tillage. Trials in Yurimaguas, Peru, showed no significant differences in upland rice yields between the "tacarpo" no-till plantings and rototilling followed by row seeding after clearing a rain forest by the slash-and-burn method (Sanchez and Nureña, 1972). Plant spacing, however, had a marked effect on yields. Table XIII shows that decreasing spacing between the "tacarpo" holes from the conventional pattern of 50 × 50 cm to 25 × 25 cm increased rice yields. The incidence of weeds decreased dramatically.

Closer spacing plus a change from the traditional tall-statured Carolino variety to the short-statured blast-tolerant IR4-2 variety has resulted in a 76% yield increase (0.95 to 1.67 tons/ha) on farmer field trials in the Yurimaguas region (Donovan, 1973). This simple low-input technology has improved the traditional shifting cultivation system. To change from shifting to continuous cultivation in this region, however, fertilization is definitely needed (Sanchez, 1977).

Oversowing pasture species on land cleared by the slash-and-burn method is a common practice in the Amazon. The high initial fertility favors rapid pasture establishment and ground cover development. Toledo and Morales (1979) reported successful pasture establishment in Ultisols of Pucallpa, Peru, with *Brachiaria decumbens* and *Panicum maximum*. They also reported that grass-legume associations may be difficult to establish because the most aggressive species may tend to dominate. To avoid this difficulty it is recommended to plant each species in single or double rows.

Table XIII
Effect of Planting Method, Spacing, and Seed Density on IR8 Upland Rice Yields on Aeric Tropaqualf in Yurimaguas, Peru[a]

Planting method and spacing	Seed density (kg/ha)	Grain yields (tons/ha)
Rototilled, row seeding (25-cm rows)	50	5.93
No till, "tacarpo" holes 25 × 25 cm	35	5.68
No till, "tacarpo" holes 50 × 50 cm	18	4.25
LSD.05		0.31

[a] Source: Sanchez and Nureña (1972).

For many of the pasture species adapted to acid soil conditions, better establishment is obtained when the seeds encounter a corrugated soil instead of a highly pulverized one (Spain, 1979). This is attributed to the need of small pasture seeds to be sheltered and to avoid desiccation during germination. Planting deeper than 1 or 2 cm is likely to retard establishment or prevent it altogether.

Because of the initial high fertility level of the topsoil after burning, the development of a plant canopy after slash-and-burn land clearing is seldom a problem in the humid tropics. The critical issue is the nature of such a cover. With good management it consists of vigorous crops or fast-growing pastures; with poor management or adverse weather conditions, weeds and jungle regrowth may constitute the principal components of the canopy. In either case, the soil is likely to be protected from erosion hazards.

With mechanized land clearing, however, the situation is totally different. The absence of burning keeps the soil in its original acid, infertile state (Fig. 10) and some degree of compaction can be expected. Tillage is usually necessary to correct compaction and to incorporate moderate quantities of fertilizer and lime that the first crop or pasture may need. Although weed competition is likely to be less than with slash-and-burn clearing, jungle regrowth does take place in bulldozed areas.

D. Land Clearing Methods in the Savannas

The absence of a closed tree canopy in savanna regions poses a wide variety of alternatives for transforming the native savanna into agricultural production systems. Unlike in rain forests, a significant production system—extensive cattle grazing with essentially zero soil management—exists in native savanna. Native low-density pasture establishment methods, and crop–pasture relay intercropping.

1. Improving the Native Savanna

Unlike in the rain forests, where partial clearing is not promising, gradual improvement of the native savanna appears promising. Oversowing pasture species on undisturbed native savanna, however, is usually unsuccessful (Spain, 1979). Some degree of soil disturbance is necessary for the small pasture seeds to have contact with sufficient moisture for germination. Light disking or sod seeding in rows 50 cm apart has successfully established acid-tolerant legumes in *campo limpo* savannas of the Brazilian Cerrado and improved the nutritional quality of the sward considerably (CIAT, 1980). After 1 year of disking and sod seeding, improved legume species with 14% protein content were well established in the native savanna, which contained only 4% protein (CIAT, 1980).

2. Gradual Displacement of Native Savanna with Improved Pastures

A second low-cost alternative is to plant improved pasture species in strips without disturbing the native savanna between the strips. A trial conducted by J. M. Spain and colleagues in Carimagua, Colombia, is showing promising results (CIAT, 1980). Grass–legume pastures were established in 60-cm-wide strips prepared with spring tines or with a field cultivator to a 12-cm depth, followed by phosphorus and potassium applications. The area between strips, about 2.5 m wide, received four levels of native savanna vegetation control. Several grass and legume species were able to invade and gradually displace the native savanna strips. The most successful species were the legumes *Desmodium ovalifolium* and *Pueraria phaseoloides* and the creeping grasses *Brachiaria humidicola* and *B. decumbens*. Table XIV summarizes the results. Spain's work shows that the native savanna can be gradually replaced by such strip plantings, at a much lower cost, while limiting erosion hazards to a fraction of the land.

3. Low-Density Seedings

In Oxisol savannas, weed growth after land preparation is normally slow due to the extremely low native soil fertility, as long as the soil is not limed or fertilized. Taking advantage of this situation, Spain (1979) developed a low-density planting system with considerable savings in seed costs and initial fertilizer applications. After the land is prepared with one or two passes of an offset disk harrow, grass and/or legume seeds are planted in holes spaced about 3 m, giving a population of 1000 plants/ha during the rainy season. The plants

Table XIV

Ability of Different Forage Species to Invade and Displace Fertilized Native Savanna with Different Degrees of Control and Tillage in Oxisols of Carimagua, Colombia[a]

Treatment of native savanna	Species capable of: Invading	Species capable of: Displacing
Burn only	*D. ovalifolium* *P. phaseoloides* *B. radicans*	*D. ovalifolium* *P. phaseoloides*
Chemical control	*D. ovalifolium* *P. phaseoloides* *B. humidicola* *B. radicans*	*D. ovalifolium* *P. phaseoloides* *B. humidicola*
Tine tillage to 12 cm	*D. ovalifolium* *P. phaseoloides* *B. humidicola* *B. decumbens* *A. gayanus* *B. radicans*	*D. ovalifolium* *P. phaseoloides* *B. humidicola* *B. decumbens* *A. gayanus*
Complete seedbed preparation	*D. ovalifolium* *P. phaseoloides* *B. humidicola* *B. decumbens* *A. gayanus* *B. radicans*	*D. ovalifolium* *P. phaseoloides* *B. humidicola* *B. decumbens* *A. gayanus* *B. radicans*

[a]Source: CIAT (1980).

received a localized high rate of phosphorus and potassium, but on a per hectare basis the highest rates used were 9 kg P_2O_5/ha and 1.5 kg K_2O/ha. One man ~d with a shovel can plant and fertilize 1 ha in 1 day (Spain, 1979). lants grow vigorously during the rainy season due to their high soil us and the absence of competition from weeds or plants of their own oniferous species cover the ground within 8 months, at the beginning . xt rainy season (CIAT, 1979). Tussock-type grasses such as *Andropc ... nus* and *Panicum maximum* produce seed at the end of the rainy season. At Carimagua, the seeds aligned themselves in the furrows left by the disk harrow and germinated with the first rainy season showers, starting ahead of the weeds. The new seedlings had to be fertilized shortly after emergence, otherwise they would have died because of acute phosphorus and potassium deficiencies. With such a system, pastures in Carimagua were ready for grazing within 9 months after planting, which is about 3 months later than with conventional land preparation. The details are explained more thoroughly in reports by Spain (1979) and C..T (1978, 1979, 1980). Although this system does not reduce the fertilizer requirements relative to conventional plantings, the seed costs are greatly reduced (from U.S. $34 to $3/ha; CIAT, 1979). Since seed of improved pasture species is generally scarce, the use of vegetative propagation is an additional advantage.

4. *Use of Crops as Precursors of Pasture Establishment*

The previously described low-density planting system is not likely to be successful in savanna areas that have been previously utilized or in recently cleared rain forest areas where vigorous weed and jungle regrowth takes place. In many of these areas a feasible alternative is to grow crops as precursors of pasture establishment, using the land preparation and fertilization practices required by the crops, but interplanting pasture species so that when crops are harvested, the pasture is established (Kornelius *et al.*, 1979; Toledo and Morales, 1979). In effect, pasture establishment costs are largely paid for by the cash crop.

Results with an Orthoxic Palehumult in Quilichao, Colombia, shown in Table XV, describe some of the relationships involved. When cassava and *Stylosanthes guianensis* were planted simultaneously, cassava yields were slightly decreased and stylo production was halved, but a stylo pasture was ready for grazing after the cassava harvest. When cassava was interplanted with a mixture of *Brachiaria decumbens* and *S. guianensis*, crop yields were adversely affected by the vigorous grass growth. Although the relative yield totals were identical to the previous

Table XV
Crop and Pasture Production in Monoculture and Row-Intercropped Systems Planted Simultaneously on an Ultisol from Quilichao, Colombia, Fertilized with 0.5 ton/ha of Dolomitic Lime and 150 kg P_2O_5/ha of Triple Superphosphate[a]

Species		Crop yields (tons/ha)			Pasture (dry matter, tons/ha)			
Crop	Pasture[b] (No. of cuts)	Monoculture	Intercropped	RY[c] (%)	Monoculture	Intercropped	RY (%)	Sum of RY (%)
Cassava (roots)	*S.g.* (3)	45.6	38.2	84	2.1	1.0	48	132
Cassava (roots)	*B.d.* + *S.g.* (3)	42.4	17.0	40	7.0	6.4	92	130
Beans (grain)	*S.g.* (1)	1.08	1.08	100	0.80	0.37	46	146
Beans (grain)	*B.d.* + *S.g.* (1)	1.22	1.24	102	1.70	0.93	55	157

[a] Adapted from CIAT (1979).
[b] S.g., *Stylosanthes guianensis* 136; B.d., *Brachiaria decumbens*.
[c] RY, relative yields; RY = (Intercropped/Monoculture) × 100.

case, this combination seriously decreased cassava yields and is therefore not promising.

When a crop with short growth duration is used, the results are different. Table XV also shows the same two pasture species planted at the same time with *Phaseolus vulgaris*. Bean yields were not affected by the presence of either the legume alone or the grass–legume mixture, although pasture growth was retarded by the presence of the bean crop. Nevertheless, a pasture was already established after the bean harvest.

Intercropping between pastures and crops is extremely site-specific and weather-dependent. The actual systems to be used must be validated locally, particularly in terms of relative planting rates, row spacing, crop varieties, and fertility levels. On the same location in Colombia, the first upland rice–pasture experiment failed because rice growth was so vigorous that pastures could not compete with it. A second trial with different relative planting dates and spacings produced excellent association of short-statured upland rice with *Brachiaria decumbens* and *Desmodium ovalifolium* (CIAT, 1979).

It is likely that pastures established in such a manner will enjoy a higher initial and residual soil fertility level than pastures established in the conventional manner. If managed in conjunction with other conventionally established pastures, they could serve as a source of protein or energy for cattle herds.

F. Maintenance of Established Pastures

After the pasture is established, management is aimed at maintaining its initial productivity and botanical composition by manipulating stocking rates, grazing pressure, fertilization, and weed control. Unfortunately, most of the existing information in Oxisol–Ultisol regions is limited to stocking rates and grazing pressure, with little experience of maintenance fertilization rates and weed control. It is generally believed that maintenance fertilization rates should be less than half of the establishment rates of all nutrients applied. Soil tests and field trails can identify the most economical rates and what their frequency of application should be, either every year or every 2 years. Also, these techniques would identify nutritional deficiencies or imbalances that arise with time. Unfortunately, soil testing services for maintenance pasture fertilization are very scarce in tropical America.

Pasture degradation in the Amazon has received considerable attention. According to Hecht (1979) most of the *Panicum maximum* pastures in the Brazilian Amazon are in some stage of degradation. In the Paragominas area of the State of Pará, Hecht (1981) reports that about 70% of the cattle ranches went out of business because of degraded pastures. The main causes of degradation are the use of a grass species with relatively high nutritional requirements, no fertilization, no legumes, and often excessively high stocking rates. The costs of controlling jungle regrowth becomes too high when the *Panicum maximum* population decreases; then the fields are gradually transformed into a secondary forest.

Serrão and co-workers (1979) have found that phosphorus deficiency is the limiting factor that sets this process in motion. Phosphorus availability was high immediately after burning the forest, remained above the critical level for up to 4 years, and then declined. The correction of this problem is relatively simple. Serrão *et al.* (1979) recommended cutting the jungle regrowth with machetes and burning in the field, then broadcasting 50 kg P_2O_5/ha, half as simple superphosphate and half as phosphate rock. Under these conditions, the *Panicum maximum* population increased from abour 25% to 90%. Broadcasting legume seeds is being incorporated into the system.

It is likely that potassium, sulfur, and other nutrients may also become limiting with time. Frequent monitoring of soil properties is essential to identify these constraints and correct them quickly. The use of better adapted species that are more tolerant to aluminum toxicity and low levels of available phosphorus could also improve this particular system. The grasses *Brachiaria humidicola* and *Andropogon gayanus* and the legume *Desmodium ovalifolium* appear more promising for these areas than *Panicum maximum*.

Hutton (1979) asserted that the main reason for pasture degradation in Ultisol-Oxisol regions in Latin America is lack of soil fertility maintenance. This is a correct statement, and it underscores the need to establish critical levels of soil test or tissue analysis for the main species grown in this region, particularly for phosphorus, potassium, calcium, magnesium, sulfur, zinc, boron, copper, and molybdenum. The present lack of such information is a major limiting factor preventing the maintenance of productive pastures in the region.

G. Mulching, Green Manures, and Managed Fallows

In crop production systems, better soil cover protection can be obtained by the use of mulches and green manures. The possibility of using managed fallows as opposed to the typical secondary forest fallow may also improve soil protection.

1. *Mulching*

A major component of low-input technology in the subhumid (ustic) forest region of West Africa is the use of crop residues as mulches to maintain soil physical properties (Lal, 1975). Impressive results have been obtained by the International Institute for Tropical Agriculture in Nigeria showing the advantages of mulching for sustained crop production. Most of this work, however, has been

conducting on Plinthic or Oxic Haplustalfs characterized by a sandy, gravelly topsoil underlain by clayey, gravelly subsoils, often with soft plinthite. Unlike most Oxisols and Ultisols of tropical America, the dominant soils of West Africa's forest region have more acute physical constraints than chemical ones.

Limited research on mulching conducted in Oxisol-Ultisol regions of tropical America has provided less positive results than those reported in West Africa. The effect of a 10-cm-thick *Melinis minutiflora* grass mulch on corn growth on Oxisols of the Cerrado of Brazil provided only slight yield increases (Bandy, 1976; NCSU, 1976). Table XVI shows the results during the rainy season, which included a considerable period of drought stress at about tasseling. Mulching decreased topsoil temperatures by 2-3°C, decreased evaporation losses by 4-7 mm daily during the water stress period, and reduced water stress in the plant as evidenced by a lower leaf water potential (Bandy, 1976). The resulting average yields, however, were only 6% higher with mulch than without. The experiment also continued during the dry season with an irrigation pattern that simulated the water stress periods encountered during the previous rainy season. A black plastic mulch treatment was also included. Corn yields were the same without mulch as with the *Melinis minutiflora* mulch, but a significantly higher yield was obtained with the black plastic mulch (Table XVI). This was attributed to vigorous and deeper root development associated with higher soil temperatures caused by the black plastic mulch during the cool dry season in Brasília (Bandy, 1976; NCSU, 1976). Consequently, the benefits of a grass mulch were not sufficiently attractive to recommend it as a practice. The black plastic mulch is probably too expensive to justify its use.

Mulching with *Panicum maximum* has been extensively evaluated on Typic Paleudults at Yurimaguas, Peru. The overall effect on crop yields, summarized in Table XVII, is not clear. Valverde and Bandy (1981) indicate that mulching is

Table XVI
Effects of Mulching on Corn Yields on a Typic Haplustox near Brasília, Brazil[a,b]

Treatment	Grain yields (tons/ha): Rainy season	Grain yields (tons/ha): Dry season (irrigated)
No mulching	6.16	5.93
Melinis minutiflora mulch	6.54	5.99
Black plastic mulch		6.75

[a] Sources: Bandy (1976) and NCSU (1976).
[b] Means of varieties and other management treatments per season.

almost always detrimental to upland rice, since the plants remain greener into maturity and are subject to more fungal attacks. Mulching is especially advantageous to corn when severe drought stress occurs. Since corn is planted during the drier part of the year, it is subjected to more drought stress than rice. Therefore the differences encountered are also related to the amount of rainfall during the cropping season. There were no overall trends on the effect of mulching on the three grain legumes included in this study.

Most of the comparisons summarized in Table XVII as well as the Brasília results shown in Table XVI were conducted at a generally high level of fertilizer inputs. A study conducted at lower input levels by Wade (1978) in Yurimaguas showed a definitely positive effect of mulching on crop yields. Table XVIII shows the relative yields of five consecutive crops that were either left bare or were covered with a *Panicum maximum* grass mulch or a *Pueraria phaseoloides* legume mulch. These treatments did not receive fertilizers or lime. The results are compared with a bare plot that received sufficient fertilizer and lime applications to overcome most fertility constraints (120 kg N/ha/crop and 70 kg K_2O/ha/crop, 4 tons lime/ha/yr, and 45 kg P_2O_5/ha/yr). The yields obtained with this treatment were considered maximum. Crops mulched with *Panicum maximum* produced an average of 54% of the maximum yields without chemical inputs. The beneficial effect of the *Pueraria phaseoloides* mulch was even greater, producing 80% of the maximum yield, again without inorganic inputs. The *Panicum maximum* mulch decreased maximum topsoil temperatures by an average 2°C on dry, hot afternoons. It also increased available soil moisture, prevented surface crusting, and reduced weed growth. Both mulch materials had no effect on soil chemical properties, but because of higher yields than in the bare unfertilized plots, they promoted greater nutrient uptake by the crops.

Table XVII
Overall Effect of Mulching with *Panicum maximum* on Crop Grain Yields in Typic Paleudults of Yurimaguas, Peru[a]

Crop	Number of harvests	With mulching (tons/ha)	Without mulching (tons/ha)
Upland rice	7	2.10	2.71
Corn	4	3.94	3.56
Soybeans	6	2.34	2.29
Peanut	4	2.96	2.88
Cowpea	1	0.64	0.74
Mean yields	20	2.56	2.49

[a]Source: Valverde and Bandy (1981).

Table XVIII
Overall Effect of Mulching and Green Manure Incorporations in Unfertilized Treatments Relative to the Yields Attained in the Bare, Fertilized Treatments in Five Consecutive Crops[a,b]

Treatments (all unfertilized)	First crop, soybeans (1.10)	Second crop, cowpeas (0.74)	Third crop, corn (4.17)	Fourth crop, peanuts (2.88)	Fifth crop, rice (2.74)	Mean effect
Bare soil	9	59	33	55	64	44
Grass mulch	14	103	57	52	94	64
Grass incorporated	33	90	70	69	94	71
Kudzu mulch	—	97	72	63	90	80
Kudzu incorporated	109	77	88	79	99	90

[a]Sources: NCSU (1976) and Wade (1978).
[b]Numbers in parentheses are the actual yields in tons per hectare, which were made equal to 100. Values in table are percent of yields in bare, high-NPKL treatments. Yurimaguas, 1974-1975.

2. *Green Manuring*

Table XVIII also includes treatments in which *Panicum maximum* and *Pueraria phaseoloides* were incorporated as green manures after every crop harvest. The yields obtained average 71 and 90% of the maximum, respectively. This suggests an almost equivalent substitution of legume green manure for inorganic fertilization and liming. The incorporation of these green manures also increased soil moisture retention, and reduced bulk density and soil compaction. The kudzu green manure supplied considerable quantities of nitrogen, potassium, calcium, and magnesium to the soil. The addition of bases decreased aluminum saturation and provided a more favorable environment for plant growth. As a result, nitrogen, phosphorus, potassium, calcium, and magnesium uptake of the four crops increased (Wade, 1978).

It appears that kudzu green manure can be substituted for fertilizers in Yurimaguas to obtain moderate yields of continuous crops. This is essentially a trade-off between nutrients supplied as fertilizers and the use of green manures. Taking account of the labor involved in incorporating kudzu, the cost of adding 1 kg N/ha as urea is approximately equal to the cost of adding the same amount of nitrogen as kudzu. The trade-off of labor for purchased input appears attractive, but has the disadvantage of the hard work involved in incorporating the green manure: labor shortage at peak periods. Farmers in Yurimaguas seem more interested in obtaining credit to purchase fertilizers and machinery than in carrying and incorporating kudzu with a hand hoe. It should be pointed out that the aforementioned green manure treatments were not grown *in situ* but were collected from adjacent areas. If grown *in situ*, green manures would compete with growing an additional crop at the same time. Experience from West Africa indicates that farmers would rather grow an additional crop and use fertilizers if available than grow a green manure crop (Sanchez, 1976). Intercropping green manures with cereal crops could be a better alternative because no time is wasted in growing the green manure crop. Agboola and Fayemi (1972) have shown the beneficial effects of such practice in Western Nigeria.

3. *Managed Fallows*

A further extension of the green manuring concept would be to substitute the conventional secondary forest fallow with one that could improve soil physical and chemical properties in a shorter period of time. Promising results have already been produced in Alfisols of Nigeria (Jaijebo and Moore, 1964; Juo and Lal, 1977), and the potential of planted kudzu fallow is presently being studied at Yurimaguas with promising results.

H. Intercropping and Multiple Cropping Systems

Various forms of intercropping are widely used by farmers in the Oxisol–Ultisol regions of tropical America. They range from intercropping annual food crops to combining annual crops with pastures, permanent crops, or both. These patterns are generally more complex in the udic than in the ustic soil moisture regime. Intercropped systems other than the use of crops as precursors of pasture establishment are not widespread in the savannas. In udic rain forest areas, intercropping is practiced both by shifting cultivators and by large-scale plantations. Unlike other sections of this review, most of the technology described is based on farming rather than research experience.

1. *Intercropping Food Crops*

Traditional shifting cultivators almost invariably intercrop. In the Amazon, a marketable cash crop is planted right after clearing, usually upland rice or corn. Shortly afterward, cassava and plantains are interplanted either in rows or at random with an average spacing of about 2 × 2 m for cassava and 3 × 5 m for the plantains. When the grain crop is ready for harvest the cassava canopy takes over; with time it is gradually replaced by a plantain canopy that can last as long as 2 years depending on the rate of soil fertility depletion and the presence of nematode attacks. Finally the degrading plantain canopy is gradually replaced by a secondary forest fallow, from which occasional plantain bunches may be harvested.

There are many variations of the above theme, some of which have been described by Pinchinat *et al.* (1976) in a review of multiple cropping systems in tropical America. Variations include other annual food crops such as cowpeas, pigeon peas (*Cajanus cajan*), yams (*Dioscorea* sp.), malanga (*Xanthosoma* sp.), yautía (*Colocasia esculenta*), and a wide variety of vegetable crops.

The traditional intercropping pattern has the advantage of keeping a continuous crop canopy over the soil, imitating the regrowth of a forest fallow eventually becoming one. Soil exposure to erosion and compaction hazards is limited, and the use of acid-tolerant species such as rice, cassava, and plantain permits a better utilization of the available soil nutrient supplies. The more nutrient-demanding crops, such as corn, or the most valuable, such as rice, are normally grown first to capitalize on the fertilizer value of the ash.

Research has shown that intensifying intercropped systems can produce higher annual yields than when individual crops are grown in monocultures. In an Ultisol of Yurimaguas, Peru, Wade (1978) also developed a row-intercropped system that produced nine consecutive crops in 21 months. A virgin rain forest was cleared by the slash-and-burn method and the first upland rice crop was grown without fertilization. Following the rice harvest, corn was planted in rows 2 m apart and soybeans in three rows 50 cm apart between the corn rows. Forty-five days later, cassava cuttings were inserted in the corn rows as 1-m spacing. Soybeans were harvested at 91 days and corn at 105 days. Cassava grew vigorously in the former corn rows and cowpeas were planted where the soybeans had been. The four crops were harvested in 266 days. A second cycle started 1 month afterward. Corn was planted the same way, but upland rice replaced soybeans as the companion crop. Cassava was planted again in the corn rows, this time 67 days after the corn seeding. Corn was harvested at 105 days and rice after 140 days. Five days after the rice harvest, peanuts were planted where the rice had been and matured 96 days later. There was enough time to grow a crop of cowpeas where the peanuts had been before the cassava canopy closed in.

The crop yields shown in Table XIX, include a comparison of monocultures grown in separate stands at the same time. Although the yields of individual crops were always lower under intercropping than as monocultures, the total market value of 1 ha of intercropping was 20–28% higher than if the same hectare were split among the four or five crops grown as monocultures. Intercropping produced more protein and energy per hectare than the monocultures. Also, intercropping increased nutrient uptake and the efficiency of nitrogen fertilizer used (Wade, 1978). The annual fertilizer application was moderate for the very acid soil conditions: 1 ton lime/ha, 45 kg N/ha, 100 kg P_2O_5/ha, 45 kg K/ha, 10 kg S/ha, 0.5 kg B/ha, and 0.5 kg Mo/ha.

Although this intensive intercropping system does not require high levels of purchased inputs, it requires intensive hand labor. Therefore its value may be limited to small areas near the farmhouse, while less labor-demanding systems could be used on a larger scale.

Table IX
Intensive Intercropping Systems Producing 4-5 Crops/Yr as Compared with Growing the Same Crops under Monoculture in a Typic Paleudult at Yurimaguas, Peru[a,b]

	Grain or tuber yields (tons/ha)					Total market value (U.S. $/ha)	Percentage over monoculture
Year 1:	Corn	Soybeans	Cassava	Cowpeas			
Intercropped	1.54	0.83	11.7	0.54		1055	20
Monoculture	3.35	1.15	16.8	1.05		879	—
	Grain or tuber yields (tons/ha)						
Year 2:	Rice	Soybeans	Cassava	Peanuts	Cowpeas		
Intercropped	2.01	0.52	8.0	2.62	0.24	1996	28
Monoculture	2.38	1.19	22.9	3.05	0.47	1558	—

[a]Source: adapted from NCSU (1975, 1976) and Wade (1978).
[b]Tall crops spaced in 2-m rows.

Other intercropping systems can be even more efficient. Leihner (1979; CIAT, 1980) reported that when cassava was interplanted with cowpeas or peanuts in an Orthoxic Palehumult of Quilichao, Colombia, at their normal planting densities, neither crop suffered significant yield declines. This was apparently due to less interspecific competition between the early-maturing grain legumes and the later-maturing cassava. Planting cassava in double rows spaced at 2-3 m with 50 cm between rows has increased yields significantly and enhanced the advantages of intercropping throughout Brazil (Oliveira, 1979). These and other refinements may further increase the value of intercropping acid-tolerant annual crops in Oxisol-Ultisol regions.

2. *Intercropping Annual with Perennial Crops*

Planting of acid-tolerant perennial crops such as rubber, oil palm, guaraná, and timber species requires an alternative soil cover until the trees produce a closed canopy. Several variations of the "taungya" agroforestry system are presently being practiced in the Amazon. Corn, cowpeas, and sweet potatoes are grown between rows of rubber, oil palm, and guaraná for 2-5 years until the tree canopy fully develops (UEPAE de Manaus, 1978; Andrade, 1979). Although no data on the relative yields of annual and perennial crops are available, there seems to be little interspecific competition for the first 2-3 years. In addition to producing food while a plantation is being established, the soil between the tree rows is protected from erosion during most of the year, except for intervals between harvesting of annual crops and the planting of the subsequent one.

3. *Intercropping Pastures with Tree Crops*

When a legume or legume-grass pasture is grown under young tree crops, the soil is better protected than with annual crops. Many combinations exist in tropical America (Thomas, 1978). *Pueraria phaseoloides* is used as understory for rubber, *Gmelina arborea* or *Dalbergia nigra* plantations in Brazil presumably supplying nitrogen to the tree crops. In some cases, cattle graze the *Pueraria* with little apparent detriment to rubber production under careful management. When the trees are planted at less than optimal density, certain grass-legume pastures persist and produce beef and milk. This is the case for *Brachiaria humidicola-Desmodium ovalifolium* pastures under a planted stand of laurel (*Cordia aleodora*), a fast-growing fuelwood species in nonacid alluvial soils of the Ecuadorian Amazon (Bishop, 1981).

The value of agroforestry as a low-input soil management component is now widely acknowledged (Mongi and Huxley, 1979). Research data on agroforestry, however, are difficult to find. The lack of data to accompany these most interesting combinations underscores the need of systematic research aimed at understanding soil dynamics and improving soil management in agroforestry systems.

The potential of some annual crop-pasture-permanent crop successions in acid soils of the humid tropics of tropical America is indeed tremendous. There is little doubt that the most stable production system in this environment is the one that produces essentially another tree canopy. It is also the one that require the least chemical inputs because a nutrient cycle between the soil and the trees is reestablished. Acid-tolerant food crops like rice, cassava, soybeans, peanuts, cowpeas, plantains, and others must be grown in order to provide food, but they can gradually be replaced by pastures or better by perennial crops. Oil palm, for example, can produce 5 tons/ha/yr of oil without lime and with modest fertilizer applications in Oxisols and Ultisols (Alvim, 1981). This is three to five times the oil production potential per hectare of other oil crops, including soybeans. Palm oil can be directly used as fuel in diesel engines with minor modifications. Mass production of totally renewable bioenergy could accompany increased food crop and livestock production in Oxisol-Ultisol regions.

I. Conclusions

The desirable goal of keeping the soil covered by a plant canopy during most of the year can be accomplished by various low-input technology components in

Oxisol–Ultisol regions. Some, like low-density pasture seedings, take advantage of acid soil infertility in suppressing weed growth. An understanding of changes in chemical and physical soil properties with time is helpful for designing or improving continuous farming systems in acid, infertile soil regions.

It would be ideal from the ecological point of view if this review could stop at this point. Unfortunately, few of the above systems would remain productive unless fertilizers and lime were added to partially overcome critical acid soil constraints. The remaining sections of this review address this issue.

V. MANAGEMENT OF SOIL ACIDITY

Soil acidity constraints are largely eliminated in the northern temperate regions of the world by liming to increase the soil pH to near neutrality. This strategy does not work in most Oxisol–Ultisol regions because of the different chemistry of low-activity clay minerals, which often results in yield reductions if such soils are limed to near neutrality (Kamprath, 1971). In addition, lime transportation costs are often very high in many savanna and rain forest areas. Nevertheless, the main soil acidity constraints (aluminum and manganese toxicities, calcium and magnesium deficiencies) need to be alleviated in order to have successful agriculture in these regions. The importance of these constraints has been indicated in Table II. Aluminum toxicity and calcium and magnesium deficiencies occur in about 70% of the acid, infertile soil region of tropical America, and on approximately half the territorial extension of tropical America as a whole. Three main strategies are used to attenuate acid soil stresses without massive lime applications: (1) lime to reduce aluminum saturation below toxic levels for specific farming systems; (2) lime to supply calcium and magnesium and to promote their movement into the subsoil; and (3) use of plant species and varieties tolerant to aluminum and manganese toxicities.

A. Lime to Decrease Aluminum Saturation

There are three major considerations when adding lime to decrease aluminum saturation: determination of how much, if any, lime should be added, consideration of the quality of lime used, and promotion of the longest residual effect.

1. Lime Rate Determination

The diagnosis of aluminum toxicity in acid soils of tropical America has been based on exchangeable (Exch.) aluminum extracted by 1 *N* KCl since the

1960s (Mohr, 1960; Cate, 1965; Kamprath, 1970; Salinas, 1978). Liming recommendations are commonly derived from the following formulas, where the lime requirement is expressed in either milliequivalents of calcium or tons of $CaCO_3$ equivalent per hectare:

$$\text{meq Ca/100 g soil} = 1.5 \times \text{meq Exch. Al/100 g} \quad (1)$$

$$\text{tons } CaCO_3\text{-eq/ha} = 1.65 \times \text{meq Exch. Al/100 g} \quad (2)$$

Lime applications based on these formulas usually neutralize most of the exchangeable aluminum and raise the soil pH to the range 5.2–5.5. Figure 13 shows the relationship between pH and exchangeable aluminum levels in acid soils of Panama (Méndez, 1973).

The very low levels of exchangeable bases common to these soils must be taken into consideration, along with the amounts of exchangeable aluminum present (Olmos and Camargo, 1976; Freitas and Silveira, 1977). Percent aluminum saturation [Exch. Al/(Exch. Ca + Mg + K + Al) × 100] expresses these relationships well. Lopes and Cox (1977a) suggested that in most cases the

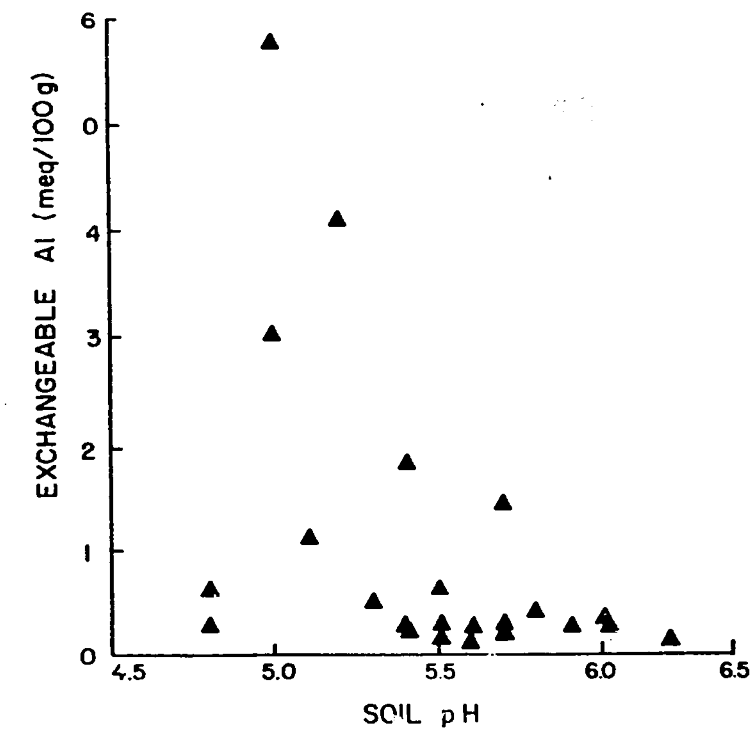

Fig. 13. Exchangeable Al at different pH values in nine Oxisols and Andepts from Panama. (Source: Méndez, 1973.)

percentage aluminum saturation should be considered first, since soils having the same level of exchangeable aluminum but different degrees of aluminum saturation would have different crop responses to liming at the same lime rates. Moreover, Evans and Kamprath (1970), Kamprath (1971), and subsequent workers, including Spain (1976), have indicated that for many crops the liming requirements based only on exchangeable aluminum may overestimate the lime rates because of varying degrees of plant tolerance to aluminum.

From the pioneer work of liming an acid soil of tropical America by Menezes and Araújo in Brazil 30 years ago (Coimbra, 1963) until a recent experiment established 8 years ago also in Brazil (Gonzalez *et al.*, 1979), the common approach has been to lime the soil for optimum crop response. This criterion can be interpreted as changing the soil to satisfy the plant's demands. This approach is difficult to apply in many areas of tropical America due to economic constraints. It may also be noted that Kamprath (1971) has reported that excessive liming may have a detrimental effect on plant growth, for example, lime-induced zinc deficiency in cassava (Spain, 1976). Therefore, it is important to determine the most appropriate formula to convert exchangeable Al into the amount of lime for specific soil-crop systems. Cochrane *et al.* (1980) developed a formula for determining the amount of lime needed to decrease the aluminum saturation level of the topsoil to the desired range:

$$\text{Lime required (tons } CaCO_3\text{-eq/ha)} = 1.8[\text{Al} - \text{RAS}(\text{Al} + \text{Ca} + \text{Mg})]/100, \quad (3)$$

where RAS is the critical percent aluminum saturation required by a particular crop, variety, or farming system to overcome aluminum toxicity, and Al, Ca, and Mg are the exchangeable levels of these cations expressed in meq/100 g. When compared with actual field data, the predictability of this equation is excellent (Cochrane *et al.*, 1980). An additional advantage is that it requires no soil analysis beyond the 1 *N* KCl extraction of aluminum, calcium, and magnesium as well as the information about crop tolerance to aluminum in terms of percent aluminum saturation. The adoption of such a formula could lead to the more effective use of lime and considerable savings in the quantities applied as well as in cost.

2. *Use of Quality Liming Materials*

In addition to how the amounts of lime to be applied are determined, the quality of the liming material deserves consideration. Unfortunately, usually little attention is given in Oxisol–Ultisol regions of tropical America to particle size and chemical composition of lime, other than whether the lime is calcitic or dolomitic (Lopes, 1975). Characterization studies of local lime deposits such as that conducted by Guimarães and Santos (1968) for the State of Pará in the

Brazilian Amazon should be encouraged. The ideal liming material should be in the carbonate form with all of it passing a 10-mesh sieve and 50% passing a 100-mesh sieve. Coarse $CaCO_3$ sources seldom produce the desired yield responses for the first crop because they are slow to react. In order to compensate, farmers often apply higher than recommended rates, which may cause overliming problems for later crops (Camargo *et al.*, 1962; Jones and Freitas, 1970).

In parts of the Amazon, most of the lime sources are exploited for construction purposes and hydrated lime, $Ca(OH)_2$, is produced. This liming material is extremely reactive and produces short-lived residual effects (NCSU, 1975, 1976). The alternative for better utilization of $Ca(OH)_2$ as a lime source is smaller and more frequent application rates (Wade, 1978). A better alternative is to request the lime producers to grind the limestone to the appropriate size and thus keep it in the carbonate form.

Since magnesium is frequently limiting in Oxisols and Ultisols, dolomitic lime sources are preferred. A Ca:Mg ratio of 10:1 in the liming material is generally considered adequate, although there is very little data to support this assertion.

3. *Residual Effects of Lime*

The beneficial effects of liming acid soils are usually expected to last for several years. However, the residual effects are often shorter in tropical than in temperate regions because of higher rainfall and higher temperatures (Lathwell, 1979). The estimation of the residual effects of liming acid soils becomes a main soil management concern for udic tropical rain forests and ustic savanna regions. The length of the residual effect will also depend on the ecosystem. In general, acid soils in tropical rain forests will have shorter residual effects of lime than in savanna regions because of faster release of aluminum from organic matter complexes and higher base removal by plants in year-round crop production systems, and perhaps higher leaching losses in the rain forests (Villachica, 1978).

Figure 14 shows the changes in topsoil exchangeable aluminum, calcium, and magnesium within 4½ years after applying lime on an Oxisol from Carimagua, Colombia, on which seven annual crops were grown consecutively. There was an increase in exchangeable aluminum with time at all but the high lime rate, probably caused by leaching of bases, release of H^+ ions from organic matter, and residual acidity of nitrogen fertilization. The losses were on the order of 1–2 tons lime/ha for the 4½-year period. Howeler (1975) considered an annual application of 200–500 kg lime/ha/yr to be sufficient to maintain an adequate level of calcium and magnesium in this soil under continuous cropping and reverse the above increases in exchangeable aluminum.

Table XX summarizes the residual effect of a Brazilian long-term liming

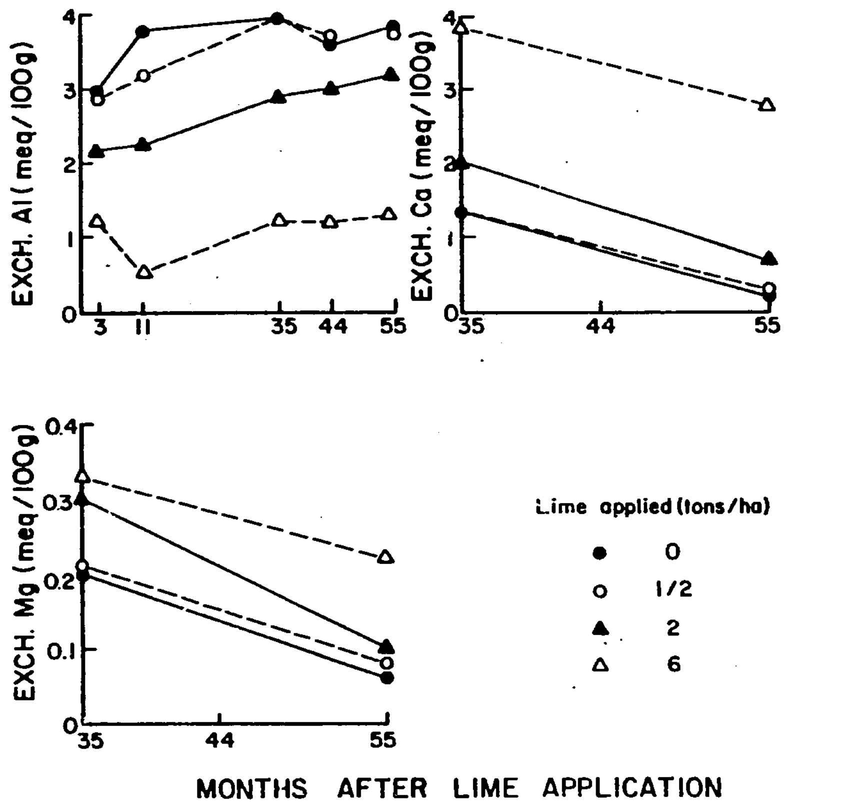

FIG. 14. Residual effect of lime (Ca/Mg = 10 : 1) in an Oxisol of Carimagua, Colombia, from January 1972 to August 1976. (Source: Gualdrón and Spain, 1980.)

experiment after seven consecutive crops (five of corn, one of sorghum, and one of soybean). After 6½ years, soil pH decreased at all lime rates, probably because of the residual acidity of nitrogen fertilizers. Exchangeable aluminum increased with time and exchangeable calcium and magnesium decreased. Aluminum saturation levels increased by about 20% from initial values for the 0, 1, and 2 ton/ha rate. The grain yields indicate an excellent residual effect, with the 1 ton/ha rate still providing over 80% of the maximum yield of soybean in the seventh successive crop. This is probably associated with the relatively high aluminum tolerance of the soybean variety used (UFV-1).

B. Lime as Calcium and Magnesium Fertilizer

The traditional emphasis on NPK fertilization in tropical America (with the welcome addition of sulfur in recent years) has distracted attention from the

widespread calcium and magnesium deficiencies found in Oxisol–Ultisol regions. In high-input systems, traditional fertilizer sources such as ordinary superphosphate and dolomitic lime often satisfy the plant's nutritional requirements for the three secondary elements. In low-input systems with plants tolerant to high levels of aluminum saturation and low available phosphorus growing on low-effective cation exchange-capacity (ECEC) soils, the correction of calcium and magnesium deficiencies requires direct attention.

1. Availability of Calcium and Magnesium

The principal factors affecting the availability of calcium and magnesium in Oxisols and Ultisols are the level of these nutrients in exchangeable form, ECEC, exchangeable aluminum levels, texture, and clay mineralogy (Kamprath and Foy, 1971).

Exchangeable calcium and magnesium levels in Oxisols and Ultisols are usually very low. The range encountered in savannas of Brazil, Colombia, and Venezuela is on the order of 0.1–0.7 meq Ca/100 g and 0.06–0.4 meq Mg/100 g for the topsoil (Lopes and Cox, 1977a; Salinas, 1980; C. Sanchez, 1977). Calcium and magnesium levels in the subsoil are usually lower and sometimes are undetectable in Oxisol subsoils (Ritchey *et al.*, 1980).

Exchangeable calcium and magnesium levels in rain forest Oxisols and Ultisols are somewhat higher, particularly in the topsoil. The examples previously shown in Table XII indicate a range of 0.4–1.46 meq Ca/100 g in the topsoil prior to clearing and burning. The same data set indicates a range of 0.07–0.33

Table XX
Residual Effects of Lime Applications on an Oxisol of Brasilia in Terms of Changes in Topsoil Properties and Relative Grain Yields at 6 and 66 Months after Application[a]

Lime applied in 1972 (tons/ha)	pH (1:1 H_2O)		Exch.[b] Al (meq/100 g)		Exch. Ca + Mg (meq/100 g)		Al saturation (%)		Relative grain yields (%)	
	6[c]	66[c]	6	66	6	66	6	66	6	66
0	4.7	3.9	1.1	1.5	0.6	0.3	63	80	53	50
1	5.0	4.2	0.9	1.1	1.1	0.6	45	61	85	93
2	5.1	4.3	0.5	1.0	1.5	1.0	25	46	88	88
4	5.6	4.8	0.2	0.4	3.1	2.1	6	15	100	89
8	6.3	5.2	0.0	0.1	4.4	4.0	2	2	93	100

[a]Compiled from NCSU (1974), Gonzalez (1976), Gonzalez *et al.* (1979), CPAC (1979), and Miranda *et al.* (1980).
[b]Exch., exchangeable.
[c]Months after lime incorporation. Yields refer to the first crop (corn) and the seventh consecutive crop (soybeans). Maximum yields were 4.0 and 2.1 tons/ha, respectively.

meq Mg/100 g. Consequently, topsoil exchangeable calcium levels seem higher in the rain forest than in savanna regions, but exchangeable magnesium levels show no differences. Decreases with depth of these two elements is sharper in the rain forest than in the savannas, but the levels remain within the detectable range. The dynamics of these two nutrients as a result of burning rain forests has been described in Section IV,B.

The low ECECs of most Oxisols and Ultisols pose some advantages and disadvantages to the supply of calcium and magnesium. The first disadvantage is the rapid leaching during periods of intense rainfall. During such periods temporary anaerobic conditions may actually occur and inhibit calcium and magnesium uptake by roots. During the dry season, drought stress may accentuate calcium and magnesium deficiencies. The concentration of these elements in tissue samples of *Melinis multiflora* and native savanna species decreased significantly during the dry season at Carimagua (Lebdosoekojo, 1977). Plants are therefore faced with a difficult situation: probably adequate calcium and magnesium supplies during part of the rainy season, rapid leaching losses during periods of intense rainfall, and low availability of both nutrients during the dry season because of water stress (Gualdrón and Spain, 1980). Nevertheless, both native and introduced plants in Oxisol savannas appear to do better in terms of calcium and magnesium than the low soil levels and the adverse moisture-dependent relationships would infer. Rodriguez (1975) indicated that some species may have more efficient calcium and magnesium uptake mechanisms than those presently understood.

Aluminum competes with calcium in the soil solution for exchange sites. Aluminum toxicity therefore can be decreased by calcium additions (Millaway, 1979). In cocoa, the presence of aluminum decreases calcium uptake but not its translocation to the aereal plant parts (Garcia, 1977). Reduction in root development under high aluminum concentrations could be due to calcium deficiency, which hinders the development of tap roots (Zandstra, 1971).

In general, soils dominated by 1:1 clays require a lower level of base saturation for adequate availability of calcium and magnesium to plants than soils dominated by 2:1 clays (Kirkby, 1979). This is an advantage of Oxisols and Ultisols because of the predominance of 1:1 clays.

2. *Fertilizer Requirements*

Information about the rates of lime application to satisfy calcium and magnesiuh fertilization requirements is scanty. Table XXI summarizes the experience in Oxisols of the Llanos Orientales of Colombia, with levels in a range on the order of 0.1–0.4 meq/100 g for both elements.

In some cases the response of 0.5 ton/ha of dolomitic lime is due to magnesium. Spain (1979) reported this situation for the establishment and maintenance phase of two pasture legumes, *Desmodium ovalifolium* and *Pueraria phaseoloides*, in Carimagua, Colombia. A straightforward magnesium response also accounted for most of the lime response by the first crop of corn in a long-term experiment at Brasília (NCSU, 1974). In rain forest Ultisols of Yurimaguas, Peru, where dolomitic lime is not available, Villachica (1978) recommended magnesium application rates on the order of 30 kg Mg/ha/crop to overcome magnesium deficiencies and prevent K/Mg imbalances.

Recent studies sh- that tropical grasses also differ in their calcium requirements (CIAT, 198.). Figure 15 shows the field response of seven grass species grown in an Oxisol of Carimagua as a function of calcium concentration in plant tissue. The critical internal calcium requirements ranged from 0.32 to 0.60%. Figure 15 also shows the corresponding levels of aluminum saturation, calcium saturation, and lime requirement, according to the formula of Cochrane *et al.* (1980). This information suggests that these species should be classified not only

Table XXI
Estimated Lime Requirements for Main Crops and Pasture Species in the Well-Drained Savanna Oxisols of the Colombian Llanos Orientales

Species	Lime rate (tons/ha)	Source
Crops		
Rice (tall-statured)	0.25–0.5	Calvo *et al.* (1977)
Cassava	0.25–0.5	Spain *et al.* (1975)
Mango	0.25–0.5	Spain *et al.* (1975)
Cashew	0.25–0.5	Spain *et al.* (1975)
Citrus	0.25–0.5	Spain *et al.* (1975)
Pineapple	0.25–0.5	Spain *et al.* (1975)
Cowpea	0.5 –1.0	Spain *et al.* (1975)
Plantain	0.5 –1.0	Spain *et al.* (1975)
Corn	1.0 –2.0	Spain *et al.* (1975)
Black beans	1.0 –2.0	Spain *et al.* (1975)
Tobacco	1.5 –2.0	Spain *et al.* (1975)
Peanuts	1.5 –2.0	Alvarado (undated)
Rice (short-statured)	2.0 +	Alvarado (undated)
Pastures		
Andropogon gayanus	0.4	Salinas and Delgadillo (1980)
Panicum maximum	1.5	Salinas and Delgadillo (1980)
Brachiaria decumbens	1.1	Salinas and Delgadillo (1980)
Stylosanthes capitata	0.5	Salinas and Delgadillo (1980)
Zornia latifolia	0.5	Spain (1979)
Desmodium ovalifolium	0.5	Spain (1979)
Pueraria phaseoloides	1.0	Salinas and Delgadillo (1980)
Pennisetum purpureum	2.6	Salinas and Delgadillo (1980)

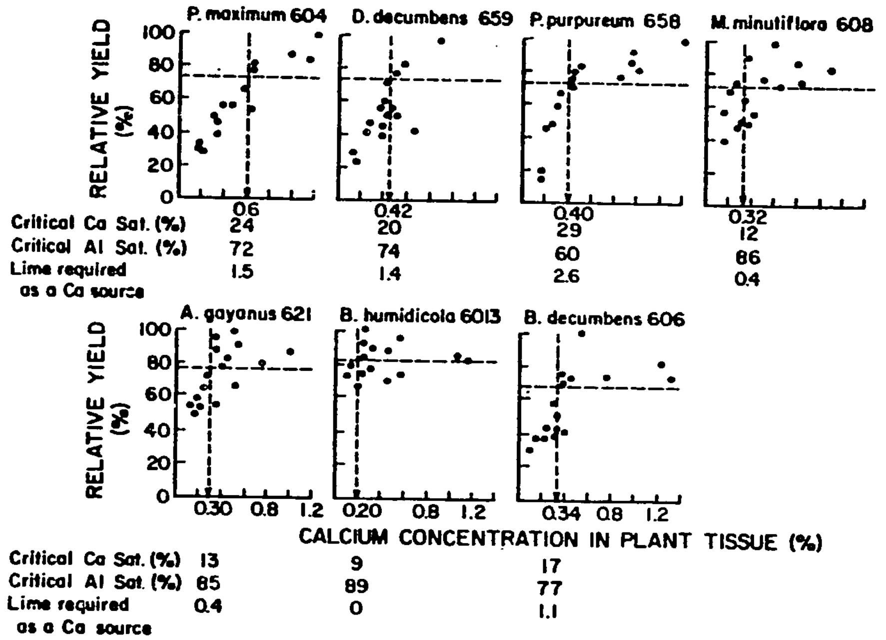

FIG. 15. Critical calcium concentrations in the tissue of seven tropical grasses grown on a Carimagua Oxisol under field conditions. Lime requirement calculated from formula by Cochrane *et al.* (1980). (Source: Salinas, unpublished results.)

according to their tolerance to aluminum but also according to their different calcium requirements.

3. Downward Movement of Calcium and Magnesium

Regardless of whether liming is practiced to decrease aluminum saturation and/or to supply calcium and magnesium, its beneficial effects occur mainly at the depth to which it is incorporated, because lime does not move appreciably in soils. The subsoil of most Oxisols and Ultisols is usually quite acid and often presents a chemical barrier to root development, either because of aluminum toxicity, extreme calcium deficiency, or both. It is common to observe roots of annual crops almost exclusively confined to the limed topsoil, with little penetration into the acid subsoil in savanna Oxisols (Gonzalez, 1976; Bandy, 1976) and rain forest Ultisols (Bandy, 1977; Valverde and Bandy, 1981). Such plants suffer from water stress when drought periods occur in spite of having ample soil moisture stored in the subsoil. Large yield losses occur when temporary droughts occur at critical growth stages during the rainy season in Oxisol regions (Wolf, 1977).

A major objective of low-input technology is to promote root development into these acid subsoils as an alternative to the more expensive supplemental irrigation systems. Three strategies have been devised to overcome this problem: (1) deep lime applications in Oxisols, (2) promotion of the downward movement of calcium and magnesium, and (3) the use of aluminum-tolerant cultivars and species.

Although incorporating the same rates of lime application into the top 30 cm rather than the top 15 cm does not appear to be a low-input technology, it has increased corn yields through various seasons in an Oxisol near Brasilía (NCSU, 1974; Salinas, 1978; Gonzalez *et al.*, 1979). This practice is feasible in well-granulated Oxisols that can be tilled to a depth of 30 cm without major increases in tractor fuel consumption. In Ultisols with a marked textural change within the top 30 cm, this practice is not recommended because it may create severe soil physical problems (Sanchez, 1977). This suggests that not only chemical but also physical soil parameters should be considered when defining the most appropriate liming practice.

Olmos (1971) presented experimental results that demonstrate significant differences among various kinds of acid soils because of subsoil aluminum. Figure 16 shows the changes in pH, calcium, magnesium, potassium, and aluminum saturation throughout the profile of a Tropeptic Haplustox. Aluminum toxicity levels that inhibit root penetration are found within the first 80 cm. Below this depth aluminum saturation decreases to values less than 60% (Salinas and Delgadillo, 1980).

A major advantage of many acid, infertile soils is that their chemical and

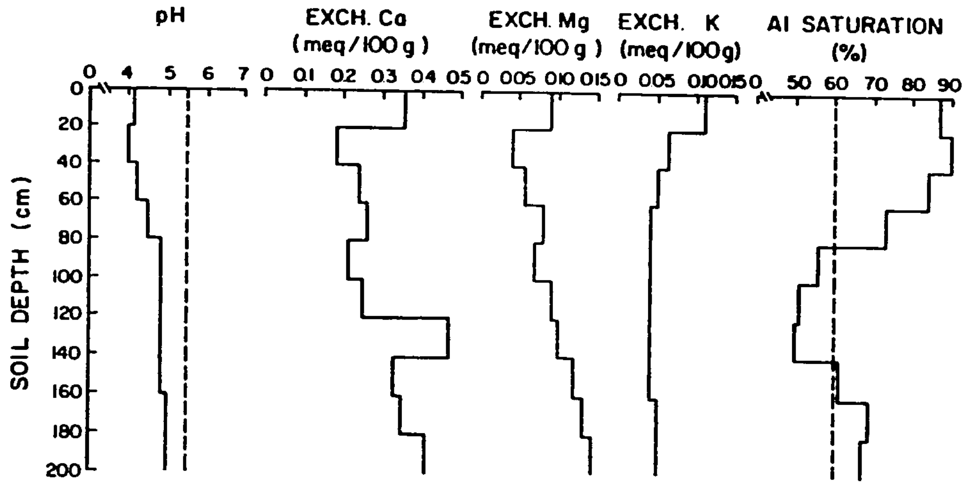

FIG. 16. Acidity profile of an Oxisol of Carimagua, Colombia. (Source: Salinas and Delgadillo, 1980.)

physical properties permit the downward movement of calcium and magnesium into subsoil layers, thereby decreasing acid soil stresses at depth and increasing root development. Downward movement of calcium and magnesium applied as lime is of little or no practical significance in other soils dominated by high-acitivity clays.

As mentioned before, lime does not move appreciably in soils, but exchangeable calcium and magnesium do so in low-ECEC Oxisols and Ultisols accompanied by anions such as sulfates or nitrates (Pearson, 1975; Ritchey *et al.*, 1980). The first evidence of this phenomenon in tropical Latin America was reported by Pearson *et al.* (1962) after applying about 800 kg N/ha/yr as ammonium sulfate to intensively fertilized grass pastures in Puerto Rico. The prob-

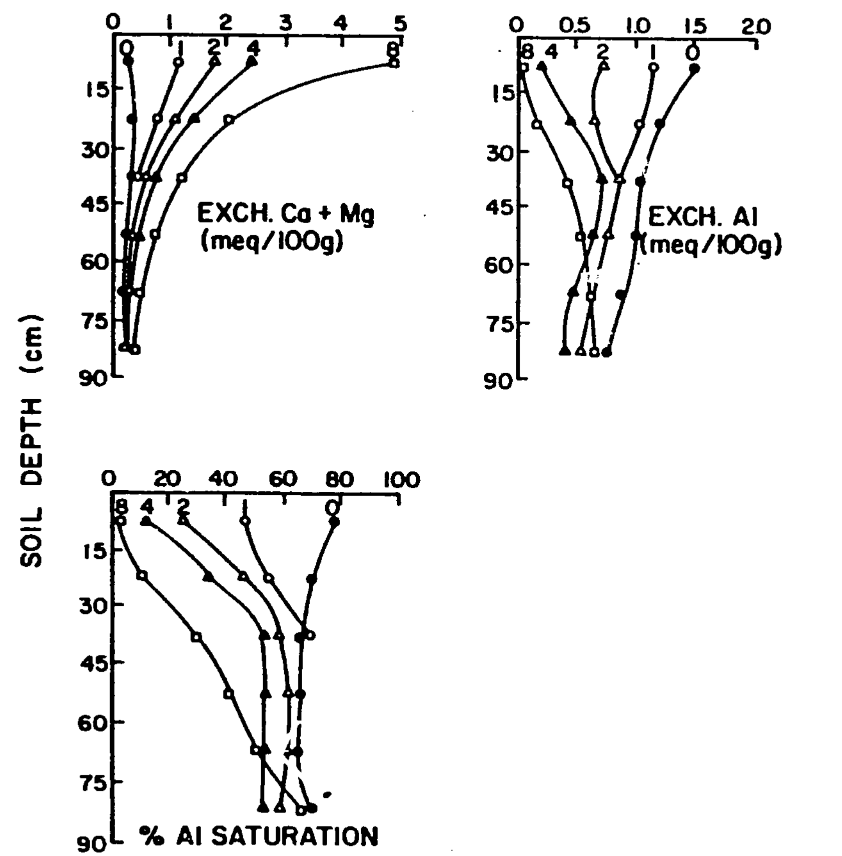

FIG. 17. Residual effects of lime incorporation on changes in soil properties with depth 40 months after lime application to the top 15 cm in a Typic Haplustox from Brasilia, Brazil. Numbers on top of curves are lime rates in tons/ha. (Source: NCSU, 1976.)

able presence of large concentrations of accompanying anions promoted rapid movement of basic cations into the subsoil.

Within the last 3 years similar observations have been reported for Oxisols of the Brazilian and Colombian savannas and for Ultisols of the Peruvian Amazon, but at much lower levels of lime and fertilizer inputs (Salinas, 1978; NCSU, 1978; Villachica, 1978; Ritchey *et al.*, 1980; Gualdrón and Spain, 1980). Figure 17 shows the changes in soil properties with depth 40 months after applying lime to the top 15 cm of a Brazilian Oxisol and cropping it continuously for 5 years. Subsoil acidity was gradually ameliorated, particularly when high rates of lime were used. With rates of 2 and 4 tons/ha, the critical level of 60% aluminum saturation for corn was reached at a depth of about 30 cm. With 8 tons lime/ha, this level was reached at a depth of about 80 cm. Crop rooting volume did increase as the aluminum toxicity barrier was gradually pushed down (Bandy, 1976).

Laboratory column experiments and field observations with the same soil have confirmed the previous results. Ritchey *et al.* (1980) showed significant calcium movement down to depths of 180, 75, and 25 cm when $CaCl_2$, $CaSO_4$, and $CaCO_3$, respectively, were mixed with the top 15 cm of an Oxisol column and the equivalent annual rainfall leached through (Fig. 18). Under field conditions, gypsum included in simple superphosphate increased subsoil pH and calcium plus magnesium levels, while aluminum saturation decreased at depths of 75–90 cm 3–4 years after application (Fig. 19). Corn roots growing in the improved subsoil environment were able to take up water and withstand droughts (Ritchey *et al.*, 1980).

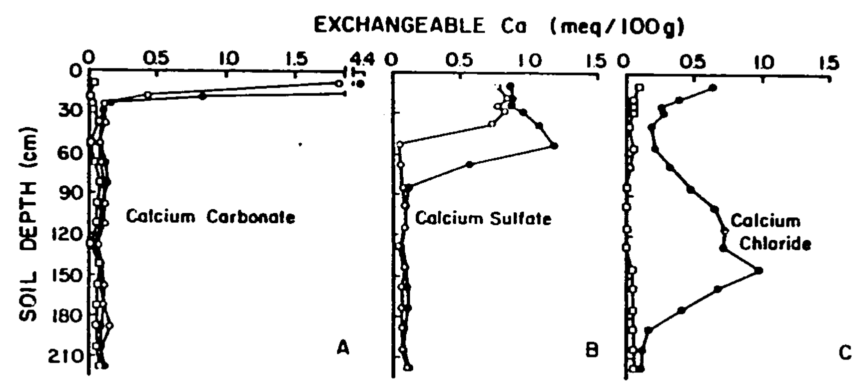

FIG. 18. The effects of various anions on the distribution of calcium after leaching with the equivalent of 1200 mm rainfall in a reconstructed virgin Oxisol profile 0–135 cm. Calcium as carbonate (A), sulfate (B), or chloride (C) was added to the 0–15 cm layer and incubated 3 weeks before leaching began. Ca (kg/ha): ○, 800; ●, 2000; □, ○ (A) and initial value (C). (Source: Ritchey *et al.*, 1980.)

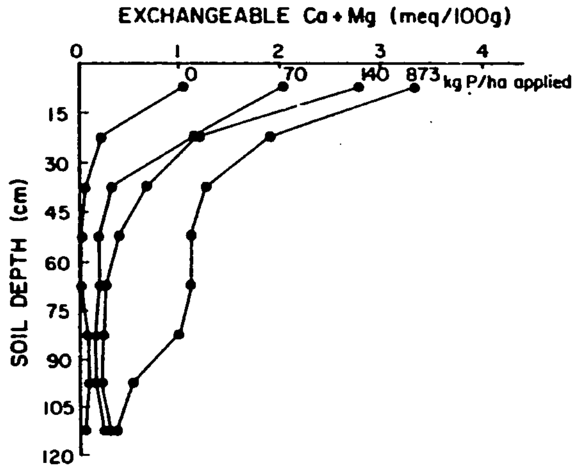

FIG. 19. Effect of varying rates of simple superphosphate (as kg P-ha) on Ca + Mg in the soil profile as sampled 4 years after application. (Source: Ritchey *et al.*, 1980.)

It is interesting to observe that considerable increases in subsoil calcium and magnesium can be attained with moderate applications of lime (1–2 tons/ha) and simple superphosphate (70 kg P/ha).

C. Selection of Aluminum-Tolerant Varieties

The main component of managing soil acidity is the selection of productive varieties that are tolerant to aluminum toxicity. Screening a large number of ecotypes either in culture solution, in the greenhouse, in the field, or a combination of the three is the preferred procedure. This requires close cooperation between soil scientists and plant breeders. Among the nutrient culture solution screening techniques, the hematoxylin test proposed by Polle *et al.* (1978) appears to be very useful. Results of culture selection or greenhouse screening, however, must be validated in the field with a representative range of the cultivars screened. Examples of such correlations are given by Spain *et al.* (1975), Howeler and Cadavid (1976), Salinas (1978), and Salinas and Delgadillo (1980). The latter two studies include the joint tolerance to aluminum and phosphorus stresses, because they tend to occur together (Salinas, 1978). Cultivars can then be classified by the critical aluminum saturation level required for attaining 80% of the maximum yield. For a specific site, this parameter can be reported in terms of lime requirement using the formula of Cochrane *et al.* (1980), incorporating the required percent aluminum saturation (RAS).

1. *Screening of Annual Crops*

Figure 20 shows an example of 10 wheat varieties screened in this fashion on a Typic Haplustox from Brasília, Brazil. The results are presented in a modified Cate–Nelson diagram (Cate and Nelson, 1971) plotting percent maximum yield against aluminum saturation, with the critical aluminum saturation level indicated by a vertical arrow. Critical levels ranged from 22 to 60% aluminum saturation, which for that soil represents a lime requirement of 0.5–1.6 tons $CaCO_3$-eq/ha. Figure 21 shows similarly obtained data on five upland rice varieties. Critical aluminum saturation levels ranged from 22 to over 70%, and lime requirements from 0.2 to 1.4 tons $CaCO_3$-eq/ha. These results confirm the existence of wide differential tolerance to aluminum in both rice and wheat. The rice variety Pratão Precoce was not affected by aluminum within the range tested, while the sensitive varieties Flotante and Batatais showed a decreasing linear yield response to increasing aluminum saturation.

The general trend shows that wheat varieties bred in Brazil exhibit greater tolerance to both stress factors than do varieties bred in Mexico, such as Sonora 63, INIA 66, and CIANO. Brazilian varieties were selected under acid soil conditions, while the Mexican ones were selected in calcareous soils. Among Brazilian varieties, the two developed closest to the Cerrado, (IAC-5 in Campinas and BH 1146 in Belo Horizonte, were more tolerant to the aluminum and low

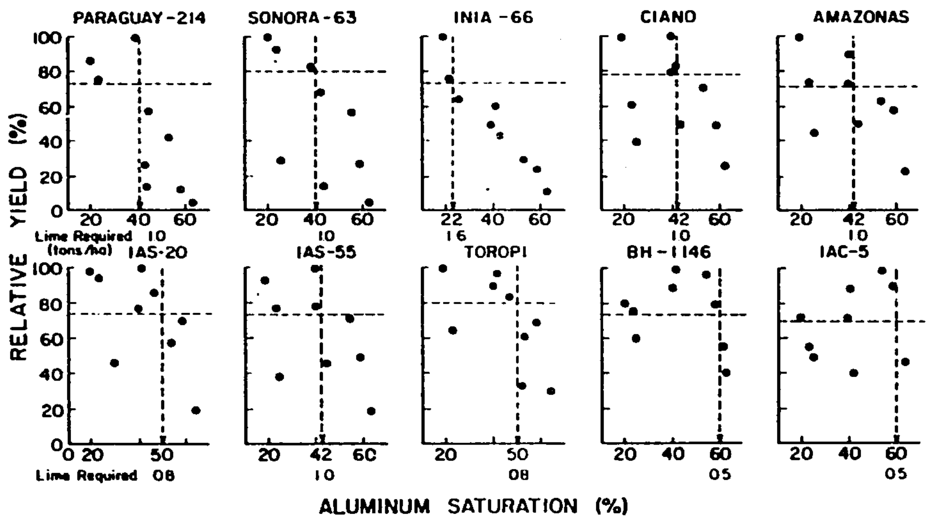

FIG. 20. Critical aluminum saturation levels of 10 wheat varieties grown on a Brazilian Oxisol. "Lime required" refers to the formula of Cochrane *et al.* (1980). (Source: Adapted from Salinas, 1978.)

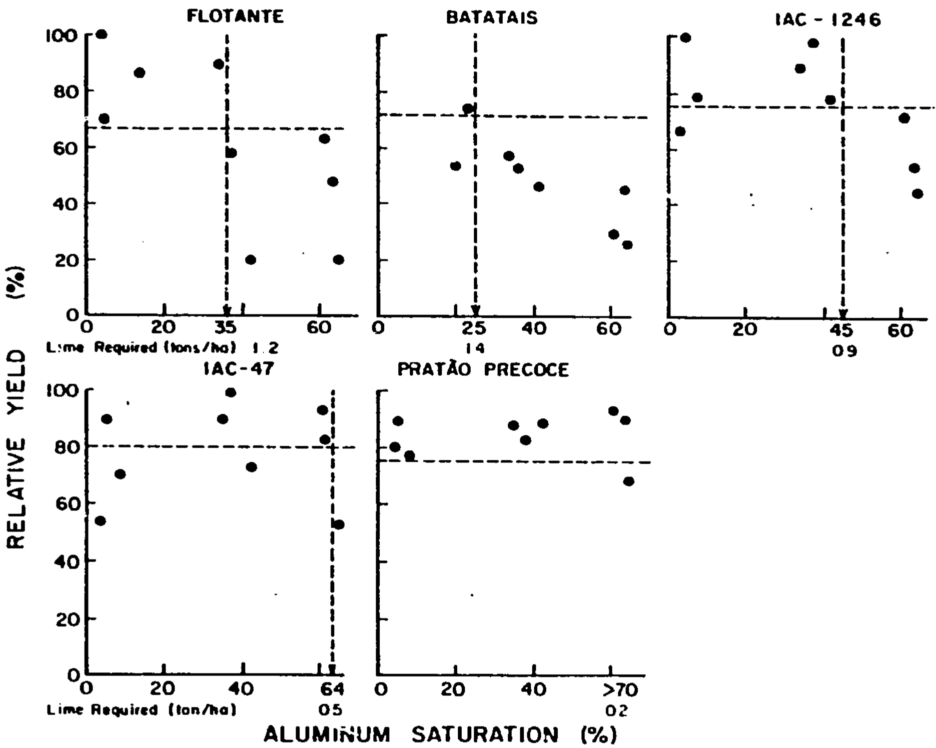

FIG. 21. Critical aluminum saturation levels of five rice varieties grown on a Brazilian Oxisol. "Lime required" from Cochrane *et al.* (1980). (Adapted from Salinas, 1978.)

phosphorus than those developed in Rio Grande do Sul (IAS-20 and IAS-55), where the soils, although acid, are generally more fertile than in the Cerrado. Some variability is also observed among the Mexican varieties. These results suggest good possibilities of combining the aluminum tolerance of the Brazilian varieties with the short-statured, lodging-resistant plant type of the Mexican varieties.

A third field study conducted in Oxisols in the State of Paraná, Brazil, compared the differential aluminum tolerance of 10 soybean cultivars. Muzilli *et al.* (1978) defined the critical aluminum saturation level as that required to obtain 80% of the maximum yield. This procedure is quite similar to that reported by Salinas (1978) in Figs. 20 and 21 since the modified Cate-Nelson plot diagrams show that yields at critical aluminum saturation levels were on the order of 70-80% of the maximum. Table XXII shows the classification of Muzilli *et al.* None were classified as tolerant, which Muzilli *et al.* defined as having a critical level of more than 25% aluminum saturation.

These critical levels may vary with location and management, and particularly

Table XXII
Classification of Soybean Cultivars according to Critical Aluminum Saturation Levels (Required for 80% Maximum Yields) in Oxisols of Paraná, Brazil[a]

Category	Cultivar	Critical Al saturation level (%)
Very susceptible	Andrews	9
	Cobb	10
Moderately susceptible	Florida	13
	Bragg	15
	Sant'ana	17
	Hutton	18
	Santa Rosa	18
	UFV-1	21
	Viçoja	22
	Bossler	22

[a] Source: Muzilli *et al.* (1978).

with the availability of calcium, magnesium, and phosphorus in the soil during the experiment. For example, one soybean variety, Improved Pelican, was tested in Yurimaguas, Peru (NCSU, 1976), using the same procedure as in the Brazilian experiment. Improved Pelican showed a critical aluminum saturation level of 40%, which was not approached by soybean cultivar in Paraná. Nevertheless, such studies clearly show which cultivars are more tolerant. The Paraná study suggests that the cultivars Bossier, Viçoja, and UFV-1 should be used instead of Andrews, Cobb, or Florida, as far as aluminum tolerance is concerned.

2. *Screening of Pasture Species*

A somewhat different approach has been followed by Salinas and Delgadillo (1980) in their systematic screening of grass and legume ecotypes for adaptation to aluminum and phosphorus stress. Both absolute and relative yields are considered since growth vigor during the establishment phase is an important consideration in the selection of superior pasture ecotypes. Salinas and Delgadillo considered a 50% maximum yield level as an index of survival, 50-79% maximum yield as moderate tolerance, and 80% of the maximum yield or more as high tolerance under conditions of high aluminum and phosphorus stresses. The 50% limit is consistent with biologic toxicology (Matsumura, 1976; Liener, 1969; Lal, 1980), while the 80% limit was set as the point beyond which the response curve is nearly flat.

Table XXIII, adapted from Salinas and Delgadillo (1980), summarizes the behavior of six grass and nine legume ecotypes at different levels of aluminum

Table XXIII
Differential Tolerance Rating of Pasture Grass and Legume Species under Field Conditions in an Oxisol of the Colombian Llanos Orientales[a]

Species and CIAT No.	Tolerance categories[b]							Maximum dry matter yield (tons/ha)
	No lime			0.5 ton lime/ha		5 tons lime/ha		
	0 kg P/ha	17 kg P/ha	227 kg P/ha	17 kg P/ha	227 kg P/ha	17 kg P/ha	227 kg P/ha	
Grasses/soil test levels (ppm Bray II):	92% Al 1.7 P	90% Al 2.1 P	89% Al 11.7 P	86% Al 2.3 P	81% Al 14.8 P	26% Al 1.5 P	22% Al 18.3 P	
Brachiaria humidicola 692	M	H	H	H	M	M	S	3.33
Andropogon gayanus 621	M	M	M	M	H	M	M	7.35
Melinis minutiflora 608	S	M	H	H	H	M	M	3.09
Brachiaria decumbens 606	S	S	S	S	S	M	M	3.58
Panicum maximum 604	S	S	S	S	M	M	H	5.86
Penisetum purpureum	S	S	S	S	M	M	H	6.98
Legumes/soil test levels:	92% Al 1.6 P	92% Al 2.6 P	92% Al 24.1 P	86% Al 2.6 P	86% Al 24.1 P	27% Al 1.6 P	27% Al 24.1 P	
Stylosanthes capitata 1078	M	M	H	M	M	M	H	4.04
Stylosanthes guianensis 184	S	M	M	H	H	M	H	2.66
Centrosema hybrid 438	S	M	H	M	H	S	M	2.04
Stylosanthes capitata 1405	S	M	H	M	H	M	M	2.88
Stylosanthes capitata 1019	S	M	M	M	M	M	M	2.67
Desmodium ovalifolium 350	S	S	M	M	H	M	M	3.68
Desmodium heterophyllum 349	X	X	S	S	S	M	H	2.41
Macroptilium sp. 506	X	X	M	S	M	S	M	2.96
Leucaena leucocephala 734	X	X	S	S	S	H	M	1.56

[a] Adapted from Salinas and Delgadillo (1980) and CIAT (1980).
[b] X, dead; S, surviving (<50% maximum yield); M, moderate (50-80% maximum yield); H, highly (>80% maximum yield).

and phosphorus stress at Carimagua, Colombia. The unamended Oxisol topsoil had 93% aluminum saturation and 1.7 ppm available P (extracted by the Bray II method). Treatments included lime rates of 0.5 ton/ha to supply calcium and magnesium and 5 tons/ha to neutralize most of the exchangeable aluminum. This latter rate decreased aluminum saturation to about 25%. Two phosphorus rates were included: 17 kg P/ha as minimal and 227 kg P/ha to attenuate and overcome most of the high phosphorus fixation capacity of the soil. The field design was a factorial of four lime rates × three phosphorus levels. Plant tolerance was classified as high (H) when the relative yield exceeded 80%, moderate (M)

between 50 and 79%, surviving (S) between 1 and 49%, and dead (X) for those that did not survive.

Table XXIII shows a marked differential response among grass and legume ecotypes. The tolerance rating varied with different levels of aluminum and phosphorus stresses. In the case of the grasses there was an overall positive growth response as the stresses were gradually eliminated, except for a decrease in yields by *Brachiaria humidicola* and *Andropogon gayanus* at high lime and phosphorus levels. *Brachiaria humidicola* and *Andropogon gayanus* showed the greatest overall tolerance, *Pennisetum purpureum* the least. The absolute yields show that *Andropogon gayanus* was the most productive overall. Also this species attained over 80% of the maximum yield with 86% aluminum saturation and 2.3 ppm P, a result of adding 0.5 ton lime/ha to supply calcium and magnesium and 17 kg P/ha. *Panicum maximum* showed less overall tolerance but relatively high absolute yield. Under Carimagua conditions this species required relatively high levels of lime and phosphorus to reach 80% of its maximum yield.

As a group, the legumes listed in Table XXIII are generally more tolerant to acidity and low phosphorus than the grasses, except for *Desmodium heterophyllum*, *Macroptilium* sp., and *Leucaena leucocephala*. These ecotypes died unless 0.5 ton lime/ha and some phosphorus were added. *Stylosanthes* showed generally better performance than other genera.

Such ratings do not guarantee the success of a tolerant ecotype under grazing conditions. Persistence and productivity of the pasture also depends on many other plant attributes, including regrowth capacity, tolerance to defoliation, trampling, drought, insect, and disease stresses. Nevertheless, the tolerance ratings give a clear estimate on the inputs needed to overcome acid soil constraints.

D. Selection of Manganese-Tolerant Varieties

Manganese toxicity is another constraint present in certain Oxisols and Ultisols. Although its geographical extent is not known (Table II), it is believed to be less common than aluminum toxicity. Manganese toxicity occurs in soils high in easily reducible manganese, usually with fairly high organic contents than can cause temporary anaerobic conditions. Manganese is very soluble at pH values lower than 5.5, particularly under anaerobic conditions where Mn^{4+} is reduced to Mn^{2+}. Temporary anaerobic conditions may occur in well-drained Oxisols and Ultisols due to rapid decompositions of organic matter and/or temporary waterlogging during periods of heavy rainfall. Examples of such soils are Coto clay, a Tropeptic Eutrorthox from Puerto Rico (Pearson, 1975), and some Orthoxic Palehumult soils at CIAT's Quilichao station in Colombia. Unlike aluminum toxicity, manganese toxicity can occur at pH levels as high as 6.0

(Simar *et al.*, 1974). The lime levels commonly needed to raise the pH of manganese-toxic Oxisols and Ultisols to about 6 is usually very high. For example, to raise the pH from 4.6 to 6.0 in the Ultisol at CIAT's Quilichao station it is necessary to apply pure $CaCO_3$ at a rate of 20 tons/ha. (CIAT, 1978). Consequently, the main strategy is to select tolerant varieties.

Unlike aluminum toxicity, symptoms of manganese toxicity occur in the leaves because this element tends to accumulate in the aerial parts, while excess aluminum accumulates in the roots (Foy, 1976b). Manganese toxicity symptoms include marginal chlorosis, induced iron deficiency, distortion of young leaves, and localized spots where manganese accumulates (Vlamis and Williams, 1973; Foy, 1976b). In general it seems that legumes are more susceptible to manganese toxicity than grasses (Lohnis, 1951; Hewitt, 1963). Australian scientists have found important differences in tolerance to manganese excess among the main pasture legume species. Table XXIV shows Andrew and Hegarty's ranking of manganese tolerance of major Australian tropical legumes. Souto and Dobereiner (1969) also found similar differences in manganese-toxic Oxisols of the State of Rio de Janeiro, Brazil. Their results shown in Table XXV suggest that *Centrosema pubescens* is relatively tolerant, while *Pueraria phaseoloides* is sensitive. Ongoing work by Salinas (unpublished) shows the opposite results, according to visual observation in Ultisols of Quilichao, Colombia. Australian scientists are breeding specifically to incorporate manganese tolerance into *Macroptilium atropurpureum* because the widespread variety Siratro is quite sensitive to manganese toxicity (Hutton *et al.*, 1978).

Table XXIV
Differential Response of Nine Forage Legumes to Manganese Toxicity in Australia[a]

Species	Regression coefficient[b]	Tolerance rating	Internal critical level (ppm Mn)
Centrosema pubescens	−0.0023	1 Tolerant	1600
Stylosanthes humilis	−0.0038	2	1140
Lotononis bainesii	−0.0039	3	1320
Macroptilium lathyroides	−0.0066	4	840
Leucaena leucocephala	−0.0077	5	550
Desmodium uncinatum	−0.0080	6	1160
Medicago sativa	−0.0102	7	380
Glycine wightii	−0.0128	8	560
Macroptilium atropurpureum	−0.0159	9 Susceptible	810

[a]Source: Andrew and Hegarty (1969).
[b]Indicates magnitude of dry matter production decreases with increasing manganese levels.

Table XXV
Differential Response of Five Tropical Forage Legumes to Manganese Toxicity in Rio de Janeiro State, Brazil[a]

Species	Regression coefficient	Tolerance rating
Stylosanthes guianensis	−0.014	1 Tolerant
Glycine wightii	−0.091	2
Centrosema pubescens	−0.162	3
Macroptilium atropurpureum	−0.197	4
Pueraria phaseoloides	−0.210	5 Sensitive

[a]Source: Souto and Döbereiner (1969).

Very little has been accomplished in establishing external (soil) or internal (foliar) critical levels of manganese toxicity. Andrew and Hegarty (1969) have developed internal critical levels shown in Table XXIV but they do not follow their tolerance rankings. Based on preliminary work at CIAT, more than 100 ppm 1 *N* KCl-extractable Mn within the top 50 cm of the soil could be considered as a tentative indication of manganese toxicity (Sanchez and Cochrane, 1980). This figure needs local validation before it can be considered as an external critical level for manganese toxicity.

E. Conclusions

Although about 70% of the land area of the Oxisol–Ultisol regions of tropical America posses severe acid soil constraints, it is not necessary to lime these soils to neutrality or even to pH 5.5 in order to obtain sustained crop and pasture production. Estimates of long-term world food production need should not include heavy rates of lime applications for the 750 million ha of tropical America with serious aluminum toxicity, calcium deficiency, and magnesium deficiency constraints. At the same time, statements that sustained agricultural production is possible without liming in most Oxisols and Ultisols are misleading. The existence of very aluminum-tolerant varieties of forage species and crops may eliminate the need to decrease the aluminum saturation level of the soil by liming, but in most cases the plants require fertilization with calcium and magnesium. This can be accomplished by small lime applications or by fertilizers containing sufficient amounts of these two essential nutrients. Small lime applications are probably less expensive per unit of nutrient than calcium and magnesium fertilizers.

A very positive attribute of many Oxisols and Ultisols of tropical America is the relative ease of movement of calcium and magnesium into the subsoil. It is possible to take advantage of what is normally considered a soil constraint—low ECEC. Together with a favorable soil structure and plenty of rainfall, low ECEC favors the gradual amelioration of the chemical properties of the subsoil. This, in turn, favors deeper root development and less chance of drought stress.

VI. PHOSPHORUS MANAGEMENT

Phosphorus deficiency is one of the most widespread soil constraints in tropical America. Approximately 82% of the land area of the American tropics is deficient in phosphorus in its natural state (Table II). In the Oxisol-Ultisol savannas and rain forests the estimate increases to 96% of the area (Sanchez and Cochrane, 1980). Phosphorus deficiency problems are compounded by widespread high phosphorus fixation capacity. Soils with high phosphorus fixation capacity can be defined as those that require additions of at least 200 kg P/ha in order to provide an equilibrium concentration of 0.2 ppm P in the soil solution (Sanchez and Uehara, 1980). Acid soils that fix such amounts of phosphorus can be identified as those with loamy or clayey topsoil textures with a sesquioxide/clay ratio of 0.2 or greater, or by the dominance of allophane in the clay fraction of the topsoil (Buol *et al.*, 1975). About 53% of tropical America's land surface is dominated by soils with such high capacity to fix phosphorus. In the Oxisol-Ultisol regions this figure increases to 72%, but high-fixing soils are less extensive in the Amazon jungle than in the savannas (Cochrane and Sanchez, 1981).

Figure 22 shows some examples of phosphorus sorption isotherms according to the Fox and Kamprath (1970) procedure. Among Oxisols and Ultisols phosphorus fixation generally increases with clay content because of its direct relationship with surface area, where the iron and aluminum oxides and hydroxides largely responsible for phosphorus fixation are located (Pope, 1976; Lopes and Cox, 1979; Sanchez and Uehara, 1980). High phosphorus fixation is considered one major reason why vast areas of arable lands in tropical American savannas are largely underutilized (León and Fenster, 1980).

The relatively high unit cost of phosphorus fertilizers coupled with the widespread deficiency and fixation constraints require the development of low-input technologies that can make most efficient use of applied phosphorus in these soils. Salinas and Sanchez (1976), Fenster and León (1979a,b), León and Fenster (1979a,b, 1980), and Sanchez and Uehara (1980) have suggested similar strategies in order to develop sound phosphorus management for crops and pastures on the acid, infertile soils of tropical America. The strategy now consists of six major components, five of which are relatively well established: (1) determination of the most appropriate combination of rates and placement methods to enhance initial and residual effects; (2) improvement of soil fertility evaluation

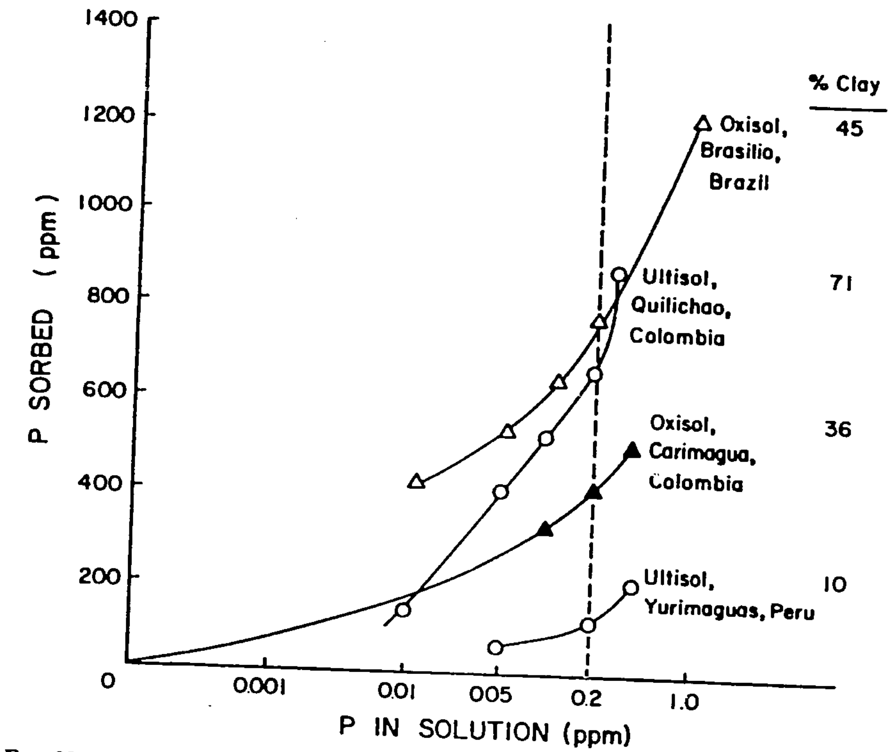

Fig. 22. Examples of phosphorus sorption isotherms of Oxisols and Ultisols in some research centers in tropical America. (Sources: Sanchez, 1976; CIAT, 1978; Sanchez and Isbell, 1979.)

procedures for making phosphorus recommendations; (3) use of less costly sources of phosphorus such as phosphate rocks, either alone or combined with superphosphate; (4) use of moderate amounts of lime to increase the availability of soluble phosphorus sources; (5) selection of species and varieties that can grow well at lower levels of available soil phosphorus; and (6) exploration of the practical possibilities of mycorrhizal associations to increase phosphorus uptake by plants. These strategies are discussed in the following sections.

A. Rates and Placement Methods of Phosphorus Applications

Extensive research has been conducted in tropical America to determine the optimum crop responses to phosphorus fertilization in Oxisols and Ultisols (Kamprath, 1973). Most of it, however, is limited to broadcast applications of superphosphates and their incorporation into the topsoil. Although this application method usually produces large yield responses, such as the one shown in Fig. 2 (Section 1,B), the high rates required and the placement method are not necessarily the most efficient way to apply phosphorus.

1. *Annual Crops*

A long-term experiment conducted on a high-fixing Typic Haplustox of the Brazilian Cerrado provides a comparison of banded versus broadcast superphosphate applications for a sufficient period of time to adequately evaluate the residual effects. Figure 23 (drawn from data by NCSU, 1974, 1975, 1976, 1978; CPAC, 1978, 1979, 1980; Yost *et al.*, 1979; and Miranda *et al.*, 1980) shows the results of different rates and placement of triple superphosphate on nine consecutive corn harvests during a 7-year period. Contrary to conventional opinion, banding was inferior to broadcast applications for the first crop. This soil was so deficient in phosphorus that root development was restricted to topsoil areas that had received phosphorus fertilization. With subsequent crops this effect disappeared as the banded applications were mixed with the rest of the topsoil by tillage operations.

Considering the long-term effects, the highest average grain yield of 6.3 tons/ha was obtained by broadcasting a massive application of 1280 kg P_2O_5/ha and incorporating it into the topsoil prior to the first planting. The residual effect was sufficient to keep the available soil phosphorus level above the critical level of 10 ppm P for corn (by the Mehlich 2 extraction) for 7 years. Economic calculations by Miranda *et al.* (1980) also indicate that this high-input strategy is the most profitable among the ones studied in this experiment, assuming an annual interest rate of 25% on credit to buy the fertilizer and an average price:cost ratio where 6.7 kg of corn are needed to pay for 1 kg of P_2O_5 as triple superphosphate.

The high capital investment and the implications on world fertilizer supplies suggest that other alternatives be pursued. Splitting the 1280 kg P_2O_5/ha rate into four 320 kg P_2O_5/ha banded applications to the first four crops produced 97% of the maximum yield; therefore the efficiency of fertilizer use was not affected. This alternative, however, has the disadvantage of initially low yields, but has the advantage of spreading the purchase of phosphorus over 4 years. A similar gradual buildup by banded applications for 4 years to reach a total of 640 and 320 kg P_2O_5/ha produced 74 and 51% of the maximum yield, respectively. These treatments performed similarly to initial broadcast applications of 640 and 320 kg P_2O_5/ha (Fig. 23B). The trade-offs are higher initial crop yields with broadcast applications instead of gradual yield increase and a more effective residual effect with the banded applications.

Combinations of broadcast and banded applications, shown in Fig. 23C, show more promise. An initial broadcast application of 320 kg P_2O_5/ha followed by

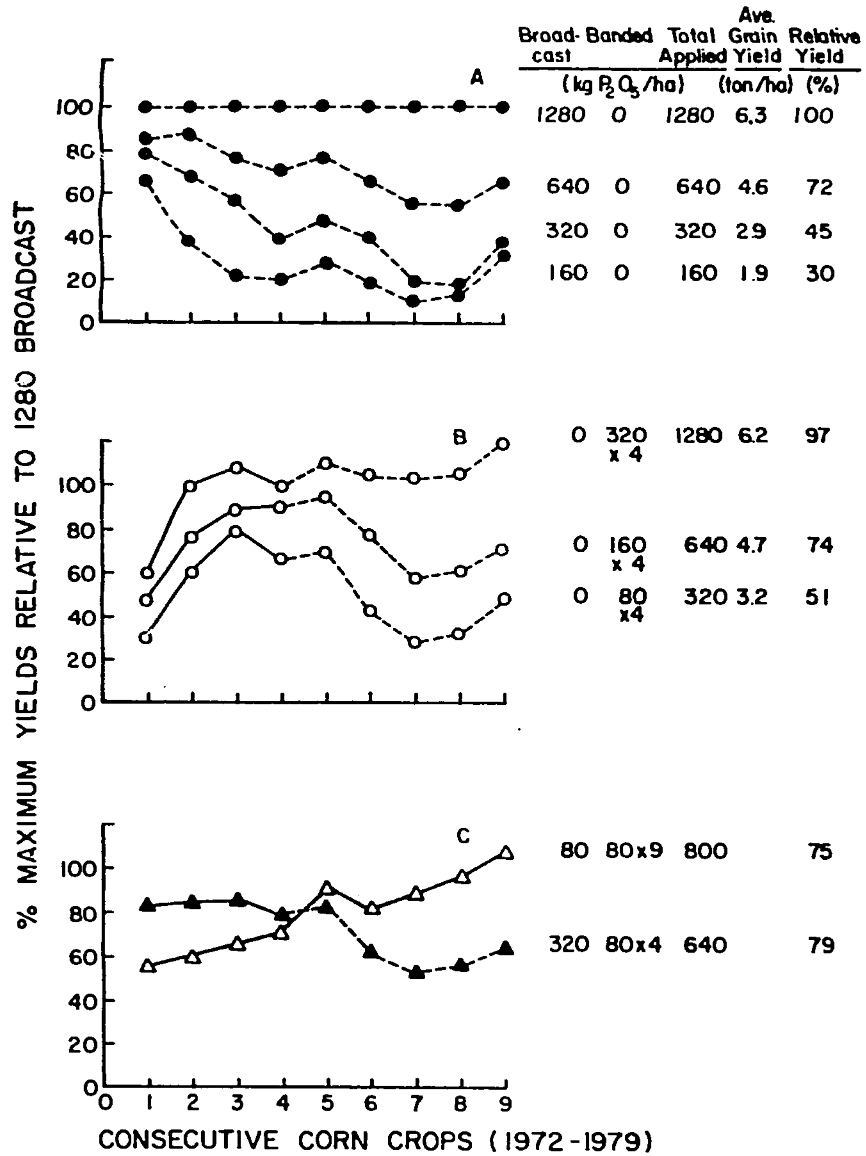

FIG. 23. Residual effects of different rates and placement methods of superphosphate applications on nine consecutive corn crops on a Typic Haplustox from Brasília, Brazil. (A) Broadcast in 1972; (B) banded crops 1-4; (C) broadcast plus banded. Solid lines, successive applications; dashed lines, no additional P applications. (Compiled from NCSU, 1975, 1976, 1978; CPAC, 1979, 1980; and Yost *et al.*, 1979.)

four banded applications of 80 kg P_2O_5/ha produced 79% of the maximum yield as an average of the nine crops. Miránda *et al.* (1980) reported that the economic return to this strategy was similar to broadcasting 1280 kg P_2O_5/ha once, but the total amount of phosphorus added was reduced to one-half. Another possibility is to broadcast a minimum amount of 80 kg P_2O_5/ha and apply the same quantity in bands to every crop, including the first one. This strategy produced 75% of the maximum yields, but the total investment in phosphorus during the nine crops increased to 800 kg P_2O_5/ha.

Both broadcast and banded combinations have the additional advantage of higher yield stability than either all broadcast or all banded applications. In retrospect, a more effective treatment may have been an initial broadcast application of 160 kg P_2O_5/ha followed by banding 80 kg P_2O_5/ha to all crops. This would have reduced the total investment to 640 kg P/ha for the nine crops, produced 75–80% of the maximum yield, and avoided large initial capital investments. Considering the high phosphorus fixation capacity of this soil (780 ppm P or 3545 kg P_2O_5/ha to reach 0.2 ppm in soil solution, shown in Fig. 22 as the Oxisol from Brazil), the broadcast-banded application strategies are examples of how to decrease fertilizer phosphorus inputs by a more judicious combination of rates and placement methods, with sufficient time to evaluate the residual effects.

2. *Pastures*

Phosphorus fertilizer rates and placement considerations are fundamentally different in the case of pastures in these high-fixing soils. The main reasons are the lower phosphorus rates required by acid-tolerant pastures, the lack of subsequent tillage operations that mix applied phosphorus within the topsoil, and a nutrient recycling mechanism via animal excreta under grazing. Figure 24 shows a completely different response pattern of adapted pasture species to broadcast superphosphate applications in an Ultisol from Quilichao, Colombia with a phosphorus fixation capacity similar to that of the Oxisol from Brasília mentioned in the previous example. Figure 22 indicates that the amount of phosphorus added to maintain 0.2 ppm P in the soil solution is similar in both soils (650 ppm P for the Quilichao Ultisol and 760 ppm P for the Brasília Oxisol). Annual crops grown on the Quilichao Ultisol require about 400 kg P_2O_5/ha to approach maximum yields. Pasture species like *Panicum maximum*, *Andropogon gayanus*, and *Centrosema pubescens* require about 80 kg P_2O_5/ha as one broadcast incorporated application to approach maximum dry matter production for the first 2 years (Fig. 24). In the Carimagua Oxisol with considerably lower phosphorus fixation capacity (400 ppm P to reach 0.2 ppm P in solution as shown in Fig. 22), adapted pasture species such as *Brachiaria decumbens* require only 50 kg P_2O_5/ha as triple superphosphate to achieve maximum production (Fig. 25).

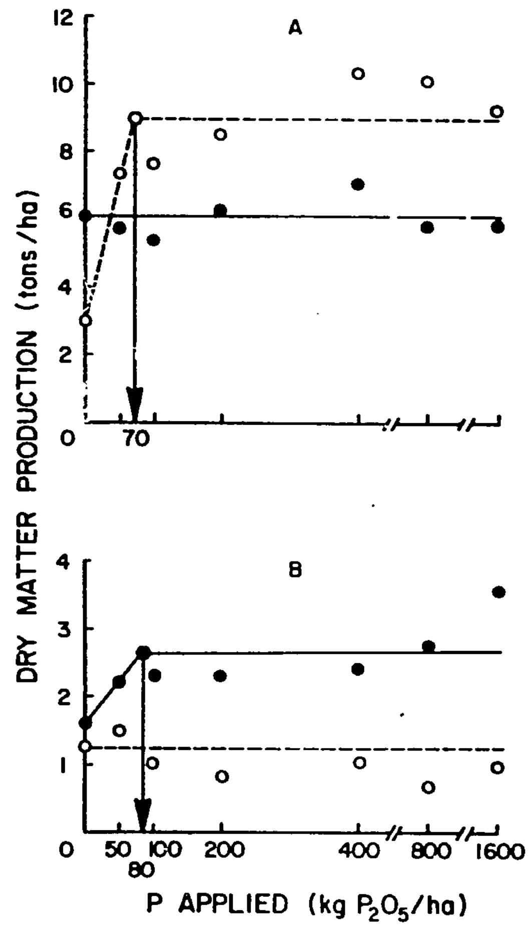

FIG. 24. Phosphorus response by *Panicum maximum* and *Centrosema* hybrid mixtures in an Ultisol from Quilichao during the establishment year. (A) O, *Panicum maximum*; ●, *Andropogon gayanus*. (B) *Centrosema*: O, *Panicum maximum*; ● *Andropogon gayanus*. (Source: CIAT, 1979.)

At such low levels of application, banding is definitely superior to broadcast incorporated application for pasture establishment, particularly if seeding is also done in bands (CIAT, 1978; Fenster and León, 1979b). Pasture species have their maximum phosphorus requirements a few weeks after germination, before a deep root system develops (Salinas, 1980). Consequently, it is important to assure that the seedlings have a nearby supply of phosphorus. Band placement also decreases weed growth between rows in these Oxisols (Spain, 1979).

After a pasture is well established, maintenance phosphorus applications can be broadcast on the soil surface without incorporation (NCSU, 1976). This

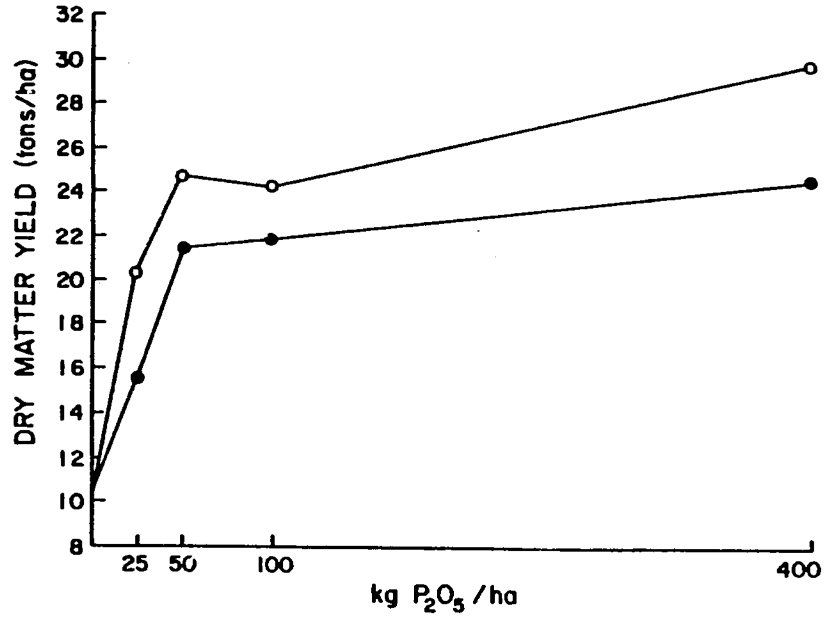

FIG. 25. Phosphorus response of *Brachiaria decumbens* grown on a Carimagua Oxisol (sum of eight harvests). In the annual treatment P was reapplied 1 year after planting. ●, TSP residual; ○, TSP annual. (Source: CIAT, 1978.)

permits the use of lower rates as the contact with the high phosphorus fixing soil is minimized. Although the means by which pasture species utilize surface-placed phosphorus is not well understood, apparently the superficial roots are able to absorb and utilize it efficiently.

B. THE NEED TO IMPROVE SOIL FERTILITY EVALUATION PROCEDURES

Another way to increase the efficiency of phosphorus fertilization is to use better methods for determining fertilizer recommendations. The purpose is to identify the initial phosphorus requirement for a particular species or variety either in terms of available soil phosphorus (external critical level) or foliar phosphorus content (internal critical level). These critical levels are those necessary to provide an adequate level of dry matter defined in this review as 80% of the maximum. The use of the Cate-Nelson (1972) diagrams and the linear response and plateau model, described in Section I,B,2, are quite useful for phosphorus, while the use of quadratic response models tend to exaggerate the optimum rates of fertilizer application (Anderson and Nelson, 1975).

Given the phosphorus fixation constraints in these soils, it is tempting to use estimates of phosphorus fixation as guides for the rates of phosphorus to apply. The most common approach is to extrapolate from the phosphorus sorption isotherms the amount of phosphorus that needs to be added in order to achieve a desired level in the soil solution (Fox *et al.*, 1971, 1974). The soil solution level extrapolated to the field that produced 95% of the maximum yield was defined by Fox and co-workers as the "external critical phosphorus requirement." The range of this critical level among species is 0.05–0.6 ppm P (Fox *et al.*, 1974). Table XXVI shows the amounts of broadcast superphosphate required to maintain specific soil solution levels in the field and their equivalence in terms of three common soil test methods. The soil on which the data on Table XXVI were obtained is a clayey Tropeptic Eutrorthox with a high capacity to fix phosphorus (350 ppm P applied to reach 0.2 ppm in solution).

When applied to Oxisols and Ultisols of tropical America this approach has been found to exaggerate the phosphorus rate recommendations by a significant amount (Novais and Kamprath, 1979; Smyth and Sanchez, 1980b; Sanchez and Uehara, 1980; Fenster and León, 1979a,b). The main reason is found in Table XXVI. The critical soil test levels for grain crops in Latin America, based on the Cate-Nelson approach, is on the order of 8–15 ppm P by the extractions shown in table (Cano, 1973; Kamprath, 1973; Miranda *et al.*, 1980). Soil solution levels as low as 0.025 ppm P produce soil test values way above the critical soil test levels that have been developed with proper calibration.

In addition, it is extremely difficult to establish critical levels of a few *parts*

Table XXVI
Solution Phosphorus Levels in Sorption Isotherms Equivalent Soil Test Levels and Amounts of Broadcast Triple Superphosphate Added After 7 Years and 13 Continuous Crops to a Tropeptic Eutrorthox from Hawaii[a]

P maintained in soil solution (ppm P)	Soil test P values (ppm P)			P added to soil (kg P_2O_5/ha)		
	Bray I	N.C.	Olsen	Initial	Maintenance in 7 yr	Total
0.003	3	6	12	80	114	194
0.006	5	9	15	200	204	404
0.012	14	20	30	432	714	1146
0.025	28	35	44	682	1445	2127
0.05	55	57	72	1000	2050	3050
0.1	72	86	93	1363	2614	3977
0.2	144	158	164	1591	3691	5282
0.4	156	209	160	1591	4634	6225
1.6	339	337	295	3273	7566	10,839

[a] Adapted from Yost and Fox (1979).

per billion that often correspond to the agronomically relevant range in such soils. The Langmuir and Freundlich isotherms are difficult to extrapolate at this range. Also, the low concentrations approach the detection limits of conventional spectrophotometers.

When considering low levels of phosphorus fertilizer additions (50–150 kg P_2O_5/ha), the sorption isotherms are of little value (Fenster and León, 1979a,b). For example, Fig. 22 shows that the Carimagua Oxisol fixes high amounts of applied phosphorus (400 ppm P or 1818 kg P_2O_5/ha to reach 0.2 ppm P in solution). After 4 years continuous cropping with *Brachiaria decumbens*, however, an initial application of 50 kg P_2O_5/ha as triple superphosphate produced 79% of the maximum yield obtained with the 400 kg P_2O_5/ha rate (Table XXVII). At such low rates, the conventional soil test extraction procedures often do not reflect the amount of fertilizer phosphorus added. Table XXVIII shows the very small increases in Bray II available phosphorus when an Oxisol received 0–100 kg P_2O_5/ha in 20-kg increments. This causes difficulties in making fertilizer phosphorus recommendations based only on soil tests. Some studies have been started to improve the sensitivity of the existing soil tests (CIAT, 1980) Figure 26 shows that increasing the NH_4F concentrations in the Bray extractant, which increases the available phosphorus values, reflects the sorbed phosphorus that is available to the plant (CIAT, 1981). Since NH_4F is

Table XXVII
Relative Agronomic Effectiveness of Several Phosphate Rocks as Determined by Yield of *Brachiaria decumbens* Grown in the Field at Carimagua[a,b]

Phosphorus source	Percent relative yield[c]			
	25[d]	50[d]	100[d]	400[d]
TSP Annual	(32.2)[e]	(34.5)	(35.9)	(43.6)
TSP Residual[c]	100 (21.1)[e]	100 (29.4)	100 (31.2)	100 (36.8)
Florida (U.S.)	122	93	101	104
Bayóvar (Peru)	120	80	105	109
Gafsa (Tunisia)	108	104	104	104
Huila (Colombia)	95	113	98	110
Pesca (Colombia)	110	82	111	116
Tennessee (U.S.)	104	76	96	108
Check: 13.6%				

[a] Source: León and Fenster (1980).
[b] Sum of 13 cuts taken over a 44-month period.
[c] Assumed at 100% for each level of application.
[d] P applied in kg P_2O_5/ha.
[e] Dry matter yields in tons/ha.

Table XXVIII
Phosphorus Fractions in the Carimagua Oxisol as a Function of Applied Phosphorus Rates[a]

Applied phosphorus (kg/ha)		Available Bray II (ppm)	Ca-P (ppm)	Al-P (ppm)	Fe-P (ppm)	Inorganic P (ppm)	Organic P (ppm)	Total P (ppm)
P_2O_5	P							
0	0	1.8	0.9	0.5	26	29.2	101	130.2
10	4.4	1.8	0.8	0.6	29	32.2	97	129.2
20	8.7	1.9	1.0	0.6	32	35.5	97	132.5
40	17.5	2.1	1.1	0.6	35	38.8	108	146.8
80	34.9	2.2	1.7	0.9	40	44.8	102	146.8
100	43.7	3.5	1.7	1.0	42	48.2	92	140.2
150	65.5	5.5	1.9	1.3	43	51.7	101	152.7
200	87.3	6.6	2.2	1.5	45	55.3	101	156.3

[a] Source: CIAT (1981).

able to extract some of the aluminum- and iron-bonded phosphorus, these fractions might play an important role in releasing phosphorus to the plants, perhaps through root excretion or microbial activity.

Table XXVIII shows the phosphorus fractions of the Carimagua Oxisol as a function of phosphorus rates. Increases in calcium- and aluminum-bonded phosphorus contribute to an increase in available phosphorus, but part of the large quantities of iron-bonded phosphorus may be having some influence on the availability of phosphorus. Therefore plants at low rates of applied phosphorus appear to extract phosphorus from these fractions in a way that conventional soil tests are not able to detect.

When phosphorus applications are banded, the interpretation of soil tests becomes even more difficult. One possibility is to use tissue analysis as the plant is the ultimate evaluator of soil fertility. Where internal critical levels are available and properly standardized in terms of plant part and age, tissue analysis can be used.

Another approach might be to interpret soil test data of samples between the bands in the form outlined in Fig. 27, where soybean yield responses are plotted as a function of soil test values in experiments that involve different broadcast and banding combinations.

Where field response data are available, making fertilizer recommendations based on soil tests has the benefit of calibration with known field responses. Table XXIX shows the initial broadcast and annual banding recommendations for clayey Oxisols near Brasília based on the data shown in Fig. 23. This table shows a decreasing rate of broadcast applications with increasing soil test level.

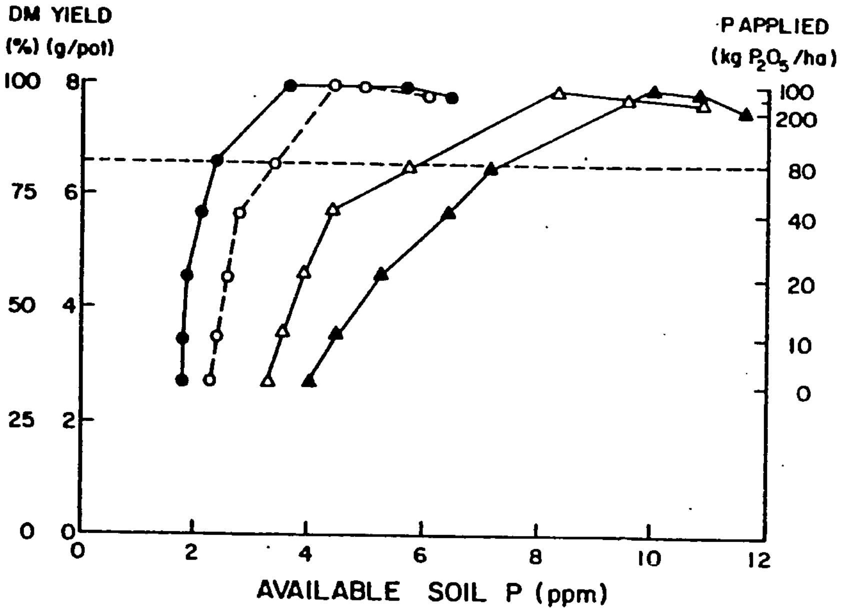

FIG. 26. Dry matter production of *Brachiaria decumbens* grown in a Carimagua Oxisol as a function of available soil test P levels obtained by different extractant solutions: 0.1 *N* HCl plus 0.03 (●), 0.05 (O), 0.10 (Δ), and 0.20 (▲) *N* NH_4F. (Source: CIAT, 1981.)

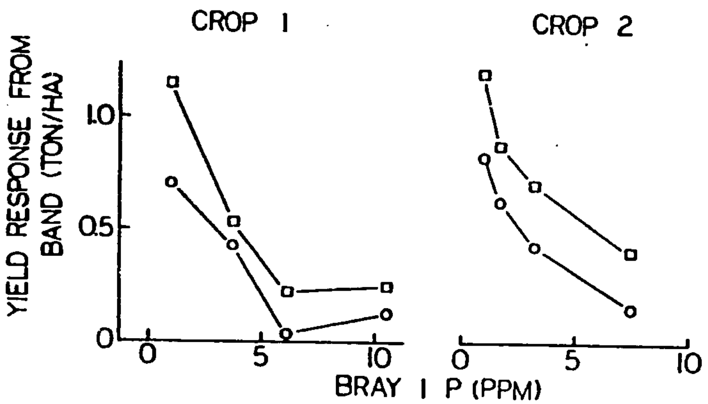

FIG. 27. Relationship between yield response to banding superphosphate applications and available soil test level of a Typic Acrustox from Brasília, Brazil, grown to two consecutive soybean crops. Band rate (kg P/ha): O, 22; □, 44. (Source: Smyth, 1981.)

Table XXIX
Phosphorus Rate Recommendations for Clayey Typic Haplustox near Brasília, Brazil, for Continuous Corn Production according to Soil Test Interpretations[a]

Available P (ppm) (N.C. method)	Soil test interpretation	Relative corn yields (% max.)	Basal broadcast application (kg P_2O_5/ha)	Banded application per crop (kg P_2O_5/ha)	Total for 9 crops (kg P_2O_5/ha)
0.0- 2.0	Extremely low	0-25	320	80	1040
2.1- 6.0	Very low	26-50	200	80	920
6.1-10.0	Low	51-75	80	80	800
10.1-16.0	Medium	76-90	0	70	630
>16.0	High	91-100	0	60	540

[a]Adapted from Miranda *et al.* (1980).

C. USE OF LESS SOLUBLE PHOSPHORUS SOURCES

A third component of the low-input phosphorus management strategy is to utilize the abundant rock phosphate deposits present in tropical South America, shown in Fig. 28. All these deposits, except two, are classified as low-reactivity materials that are considered unsuitable for direct application (Lehr and McClellan, 1972). The Bayóvar rock is considered of high reactivity and the Huila rock is of medium reactivity (Chien and Hammond, 1978; León and Fenster, 1979b).

1. *Comparisons among Sources*

Table XXX shows the agronomic effectiveness of different phosphate rocks as related to triple superphosphate, using *Panicum maximum* as the test crop on an Oxisol from the Llanos Orientales of Colombia. High-reactivity phosphate rocks such as North Carolina, Bayóvar, and Gafsa performed nearly as well as triple superphosphate. Medium-reactivity phosphate rocks such as Huila and Florida, and even the array of low-reactivity materials from Brazil, Colombia, and Venezuela look promising for direct application in acid soils.

The effectiveness of rock phosphates in these soils depends on their solubility, fineness, time of reaction, and soil pH (Khaswahneh and Doll, 1978). On these highly acid soils, even the low-reactivity phosphate rocks are effective with time. Table XXVII shows the results of an experiment conducted on a Carimagua Oxisol with *Brachiaria decumbens* in which six phosphate rocks with varying agronomic effectiveness ratings were compared to triple superphosphate (León and Fenster, 1980). This study included broadcast and incorporated application rates ranging from 0 to 400 kg P_2O_5/ha. After nearly 4 years, the yields of forage

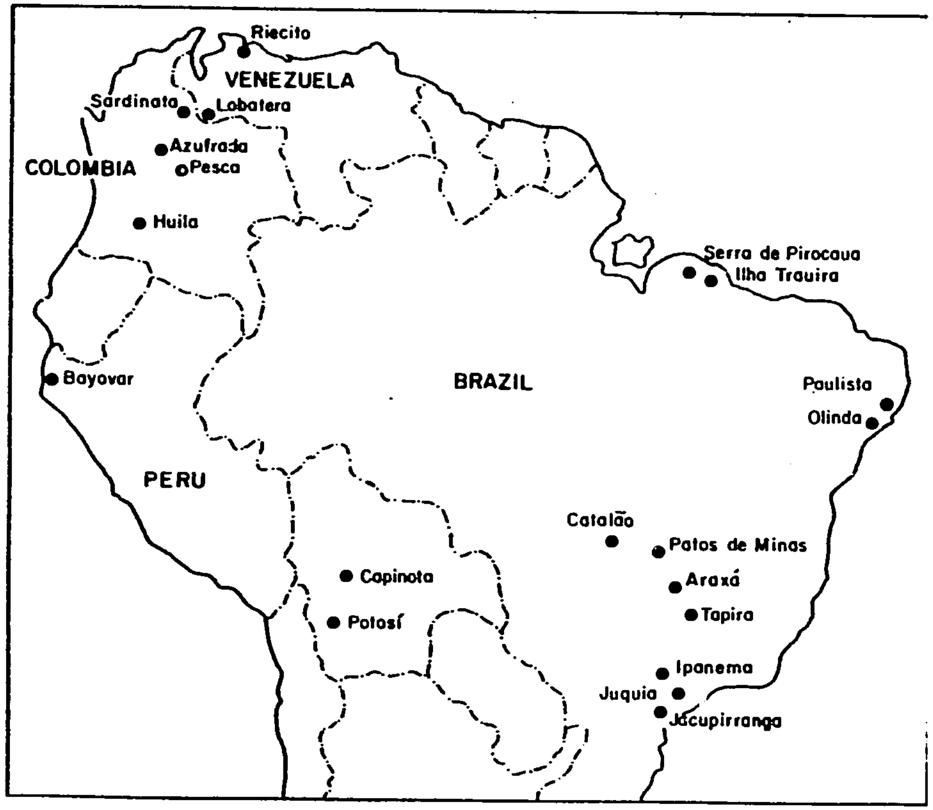

FIG. 28. Principal rock phosphate deposits in tropical South America. (Sources: Fenster and León, 1979a,b, and updated information.)

from the phosphate rock treatments compared favorably with those from triple superphosphate. In many instances the yields with phosphate rocks were considerably higher. For the period of time this experiment has been conducted, a 50 kg P_2O_5/ha application rate appears to be adequate under field conditions.

Similar results have been recorded from a field experiment conducted on Ultisols from Pucallpa and Yurimaguas, Peru (NCSU, 1974; Cano *et al.*, 1978; León and Fenster, 1980), and on an Oxisol of Brasília, Brazil (NCSU, 1975, 1976; Miranda *et al.*, 1980). In the latter case, the higher phosphorus fixation capacity increased the required rate to about 200 kg P_2O_5/ha. The use of the very low-reactivity Araxá phosphate in Brasilia had little effect on *Brachiaria decumbens* growth during the first year of application.

2. *Particle Size of Rock Phosphate Materials*

The effectiveness of all rock phosphates increases with increasing fineness, in contrast to the opposite effect in water-soluble sources (Terman and Englestad, 1972). From the practical standpoint, finely ground phosphate rock presents serious problems of handling and spreading that would limit the farmer or the fertilizer dealer in making widespread use of phosphate rock. To solve the problem, the International Fertilizer Development Center initiated a study to determine whether finely ground phosphate rock could be granulated and still retain its agronomic effectiveness. Preliminary greenhouse experiments were carried out using different rates and granule sizes of phosphate rocks, and the results are shown in Fig. 29. The minigranules (−48 + 150 mesh) proved to be as agronomically effective as the finely ground phosphate rock. Apparently, when these "minigranules" came in contact with the soil the KCl binder dissolved. Their effective surface area therefore is similar to that of finely ground materials. Although the larger-sized granules (−6 + 16 mesh) were not as effective initially, they did release increasing amounts of phosphorus with time (CIAT, 1980, 1981).

Table XXX

Agronomic Effectiveness of Phosphate Rocks as Determined by Yield of *Panicum maximum* Grown on a Las Gaviotas Oxisol in the Llanos of Colombia under Greenhouse Conditions[a,b]

Phosphate rock	Reactivity rating[c]	Percentage relative yield[d] 50	100	200	400
Brazil					
Abaete	Low	11	33	52	55
Araxá	Low	30	33	56	58
Catalão	Low	5	6	22	38
Jacupiranga	Low	12	13	19	51
Patos de Minas	Low	27	42	66	72
Tapira	Low	4	7	10	23
Colombia					
Huila	Medium	58	59	84	84
Pesca	Low	56	61	80	83
Sardinata	Low	29	44	68	74
Peru					
Bayóvar	High	99	79	104	91
Venezuela					
Lobatera	Low	56	56	65	76
Tunisia					
Gafsa	High	63	72	114	105
United States					
Florida	Medium	59	71	86	91
North Carolina	High	70	78	107	108

[a] Source: León and Fenster (1979a,b).
[b] Sum of three cuttings.
[c] Interpreted from Lehr and McClellan (1972) and unpublished sources.
[d] Dry matter yields obtained are with triple superphosphate considered as 100% for each phosphorus rate. Absolute yields: 0.6, 13.3, 19.0, 22.2, and 22.2 g/pot with 0, 50, 100, 200 and 400 mg P/pot as triple superphosphate, respectively.

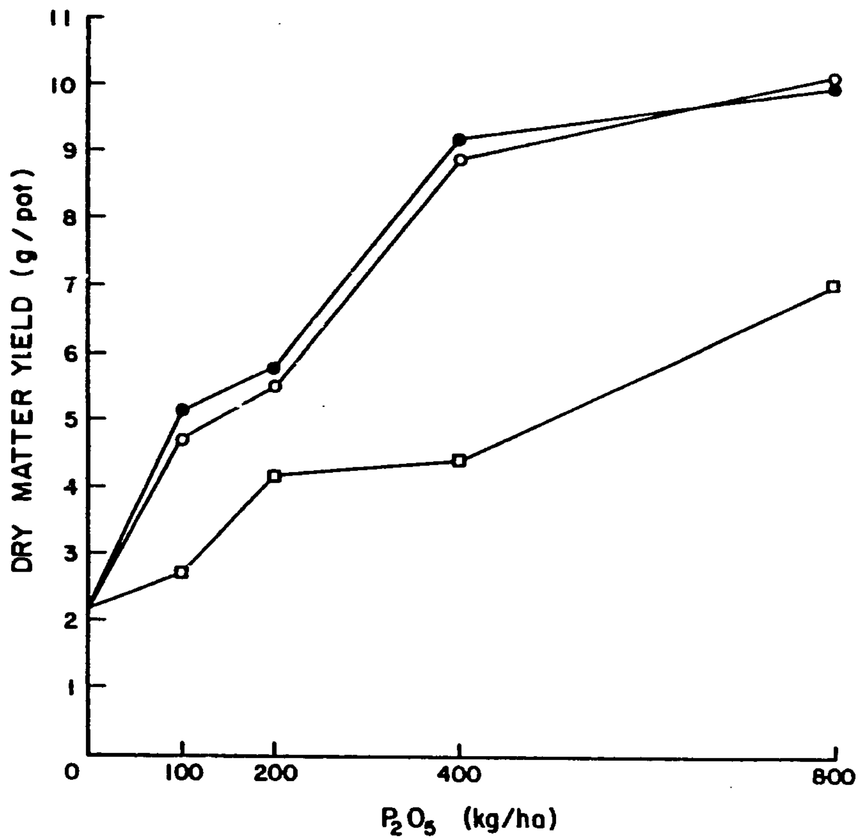

FIG. 29. Effect of rate and granule size of Huila Phosphate Rock (●, ground; ○, minigranule; □, regular-size granule) on yield of *Panicum maximum* grown on a Carimagua Oxisol in the greenhouse (2 cuttings). (Source: CIAT, 1980, 1981.)

3. *Applications before Liming for Acid-Sensitive Crops*

Rock phosphates require an acid soil environment in order to release phosphorus into the soil solution. In some acid soils of tropical America, the effectiveness of high-reactivity rock phosphates decreases if the soil pH increases above 5.0 (Lathwell, 1979). This usually does not pose a problem with most aluminum-tolerant pastures but may inhibit the growth of aluminum-sensitive crop varieties. In terms of crop production, an alternative is to apply the rock phosphate several months ahead of liming in order for it to react at low pH. This procedure is especially advantageous if the first crop to be planted is relatively tolerant to aluminum, as is the case for upland rice. Lime can then be added prior to planting a crop more sensitive to aluminum, such as corn. The time required

for lime to react in acid soils is less than that needed for the high-solubility rock phosphate sources to react (Sanchez and Uehara, 1980).

4. *Combination with More Soluble Sources*

An additional alternative is to broadcast the rock phosphate and apply more soluble phosphorus sources in bands in order to provide phosphorus while the rock phosphate slowly dissolves. Smyth (1981) and CPAC (1980), have shown that broadcasting 200 kg P_2O_5/ha of low-reactivity Patos de Minas phosphate rock plus annual banded applications of simple superphosphate produce soybean yields similar to that of the same rate supplied entirely with simple superphosphate.

Table XXXI shows that when varying ratios of phosphate rock to single or triple superphosphate, the initial growth response of corn in a Colombian Oxisol was proportionate to the amount of soluble phosphorus in the fertilizer mixture (Fenster and León, 1979a,b). Comparisons between co-minigranulated phosphate rock and triple superphosphate or simple superphosphate with these soluble phosphorus sources alone show that the granulated materials are superior in every instance. These results indicate that the acid produced from the soluble phosphorus in the granule may be reacting with the phosphate rock, which is releasing additional phosphorus for the plants.

Table XXXI
Effect of Ratio of Phosphate Rock to Simple and Triple Superphosphate on Yield of Corn Grown in the Greenhouse on a Carimagua Oxisol[a,b]

Phosphorus source	Percent relative yield[c]				
	1:0[d]	3:1	1:1	1:3	0:1
Simple superphosphate	—	—	—	—	100[e] (18.9)[f]
Triple superphosphate	—	—	—	—	91
Florida/simple superphosphate	71	70	91	99	—
Florida/triple superphosphate	71	72	92	98	—
Pesca/simple superphosphate	27	53	75	99	—
Pesca/triple superphosphate	27	64	70	89	—
Check: 16%					

[a] Source: León and Fenster (1980).
[b] Sum of two harvests.
[c] All phosphorus rates were averaged. Granule size used: minigranule (−48 + 150 mesh)
[d] Ratio of phosphate rock to simple and triple superphosphate.
[e] Simple superphosphate assumed at 100%.
[f] Tissue yield in g/pot.

5. *Partial Acidulation*

From the aspects discussed previously, it is apparent that many phosphate rocks, although they perform well with time, are initially inferior to the more soluble phosphorus sources for crop production and for certain pastures as well. The work of McLean and Wheeler (1964) indicates that partially acidulating phosphate rock to levels of 10 or 20% could overcome this problem. The partially acidulated phosphate rock would provide a soluble source of phosphorus initially while still maintaining the residual value of the phosphate rock (Hammond *et al.*, 1980). Howeler (CIAT, 1979) has shown very encouraging results with beans. Studies on a Carimagua Oxisol have shown that partial acidulation of low-reactivity Colombian phosphate rocks with H_2SO_4, however, did improve yields when compared with the North Carolina and Florida phosphate rocks (Mokwunye and Chien, 1980). Recent IFDC estimates, however, indicate that cost per unit P of partially acidulated phosphate rocks equals that of superphosphate.

6. *Thermal Alterations*

Another group of potentially cheaper souces of phosphorus for acid high-fixing soils are basic slag and fused magnesium phosphates, both water-insoluble products of thermal alteration. These types of fertilizers have been used primarily in Europe, but their potential in tropical areas with phosphorus fixation problems is receiving increased attention, particularly since steel industries develop where there are cheaper sources of energy.

Basic slag (called "Escorias Thomas" in Latin America) is a by-product of steel manufacture from iron ore high in phosphorus. It has an average content of 4–8% phosphorus and 32% calcium mostly as calcium silicophosphates and calcium silicates. It has been found to be equally or more effective than superphosphates at the same rates of phosphorus application in Oxisols of Brazil and Colombia (Spain, 1979; Sanchez and Uehara, 1980).

The Rhenania phosphates are produced by fusing rock phosphates of low citrate solubility with silica and soda ash. When serpentine or magnesium silicates are fused to give calcium or magnesium silicophosphates, the products are called fused magnesium phosphates or thermophosphates in Brazil. These products vary in composition in the ranges 10–12% P, 20–30% Ca, and 0–8% Mg. They have been found to be as effective or more effective than superphosphates in high-fixing Oxisols and Ultisols, particularly if the soils are not limed (NCSU, 1976; CPAC, 1980; Sanchez and Uehara, 1980).

Ongoing experiments in Oxisols of Brasília indicate that an application of 152 kg P/ha as "Termofosfato" decreased aluminum saturation from 70 to 38%,

while no such change was observed with an equal rate of triple superphosphate that produced similar pasture yields. (NCSU, 1976, 1978; CPAC, 1979, 1980).

The main disadvantage of the Rhenania phosphates is their high cost of production. In Brazil, for example, the price per kilogram P is almost equal to that of triple superphosphate. Although the liming effect and silicon content may make their use more profitable, the high cost of Rhenania phosphates is a major limiting factor. In areas with ample supply of hydroelectric energy for thermal alteration, the situation may be different.

Production of thermally altered phosphates is sometimes suited to small fertilizer plants employing intermediate technology. While fertilizer plants with production capacity as low as 50,000 tons/yr may not be feasible in industrialized nations, developing countries may find it profitable and appropriate to use intermediate technology that depends on utilization of local resources and skills (Sanchez and Uehara, 1980). Unlike superphosphates, thermally altered phosphates do not require sulfur or sulfuric acid plants. Also, phosphate rocks with high silica content can be used for thermal alteration.

D. Decrease of Phosphorus Fixation with Liming

The third component of this low-input strategy is to decrease the phosphorus fixation capacity of these acid soils by applying amendments such as lime and silicates. Considerable controversy exists as to whether liming decreases phosphorus fixation or not (Amarasiri and Olsen, 1973; Pearson, 1975). Part of this problem is attributed to reactions of the added phosphorus with freshly precipitated iron and aluminum hydroxides. Therefore the effects of lime on phosphorus availability may depend on the extent to which phosphorus is fixed by the adsorbing surfaces or by reactions with exchangeable aluminum (Smyth and Sanchez, 1980a). Several studies with acid soils in tropical America show that when exchangeable aluminum was neutralized by liming, phosphorus fixation decreased (Mendez and Kamprath, 1978; Leal and Velloso, 1973a,b; Vasconcellos *et al.*, 1975).

Table XXXII shows the results of Smyth and Sanchez (1980a) for Oxisols from Brazil on which lime, silicate, and mixtures of lime and silicate were applied at agronomically relevant rates in an attempt to decrease phosphorus fixation. All amendment treatments decreased phosphorus fixation by about 20–30% in treatments that did not receive phosphorus. These results imply that determination of the amounts of phosphorus required to obtain a given solution concentration should be performed after lime or silicate applications and after sufficient time has been allowed for their reaction; otherwise, the phosphorus requirements may be overestimated (Smyth and Sanchez, 1980a). In the case of

Table XXXII
Effects of Soil Amendment and P Applications on the Amount of Sorbed P Needed to Provide 0.1 ppm P in Solution in a Brazilian Oxisol[a]

		Percent decrease in P sorption			
Level[b]	Amendment / Applied P (ppm):	0	380	460	540
0	Control	0	44	54	65
1	$CaCO_3$	18	59	68	77
	$CaSiO_3$	24	65	77	84
	Combined	18	65	71	82
2	$CaCO_3$	16	62	77	85
	$CaSiO_3$	28	75	82	91
	Combined	32	74	77	85

[a]Source: Smyth and Sanchez (1980a).
[b]Amendment level is relative to neutralization of exchangeable Al by the factor of 1 and 2, respectively. Initial exchangeable Al 1.45 meq/100 g.

using soil tests as a key to fertilizer recommendations, improvements could be made if samples are taken after lime has reacted.

Liming has little or no effect in decreasing phosphorus fixation in soils with pH values of 5-6. Although still acid, they have aluminum saturation levels lower than 45% (Sanchez and Uehara, 1980; Leal and Velloso, 1973b). Furthermore, liming to pH values near or above neutrality may increase, rather than decrease phosphorus fixation because of the formation of relatively insoluble calcium phosphates (Sanchez and Uehara, 1980). Consequently, the effect of lime on phosphorus fixation depends on pH levels

E. Selection of Varieties Tolerant to Low Levels of Available Soil Phosphorus

A fifth component of the low-input phosphorus management strategy is to select plant species or varieties that grow well and produce about 80% of the maximum yields at low levels of available soil phosphorus. Although screening and selection of germplasm for "phosphorus efficiency" or "tolerance to low phosphorus" is less advanced than that for aluminum toxicity, research in that direction is also being conducted in tropical America.

1. *Annual Crops*

Salinas (1978) screened a number of commercial varieties of upland rice, corn, and beans for tolerance to low phosphorus availability in the Cerrado of Brazil.

Figure 30 shows the results with rice expressed as yields relative to a high rate of broadcast superphosphate applications (1363 kg P_2O_5/ha). This rate provided a high level of available soil phosphorus (26 ppm P by the Mehlich 2 extraction). Most of the rice varieties produced maximum yields at the high soil phosphorus rate, but at different aluminum saturation levels. When aluminum saturation decreased to 63%, by adding 0.5 tons lime/ha, which supplied mainly calcium and magnesium as nutrients, the first three rice varieties (Batatais, Flotante, and IAC-1246) did not approach 80% maximum yield as did IAC-47 and Pratão Precoce. The latter variety had the lowest external phosphorus requirement (10 ppm P) under aluminum stress.

These results clearly show differential varietal response to available soil phosphorus under aluminum stress. When aluminum saturation was reduced to 38% by adding 1.5 ton lime/ha, the rice varieties Flotante and IAC-1246 produced 80% of the maximum yield, but with a significant difference in the external phosphorus requirement. The Flotante variety required almost four times more available phosphorus than did IAC-1246. On the other hand, IAC-47 and Pratão

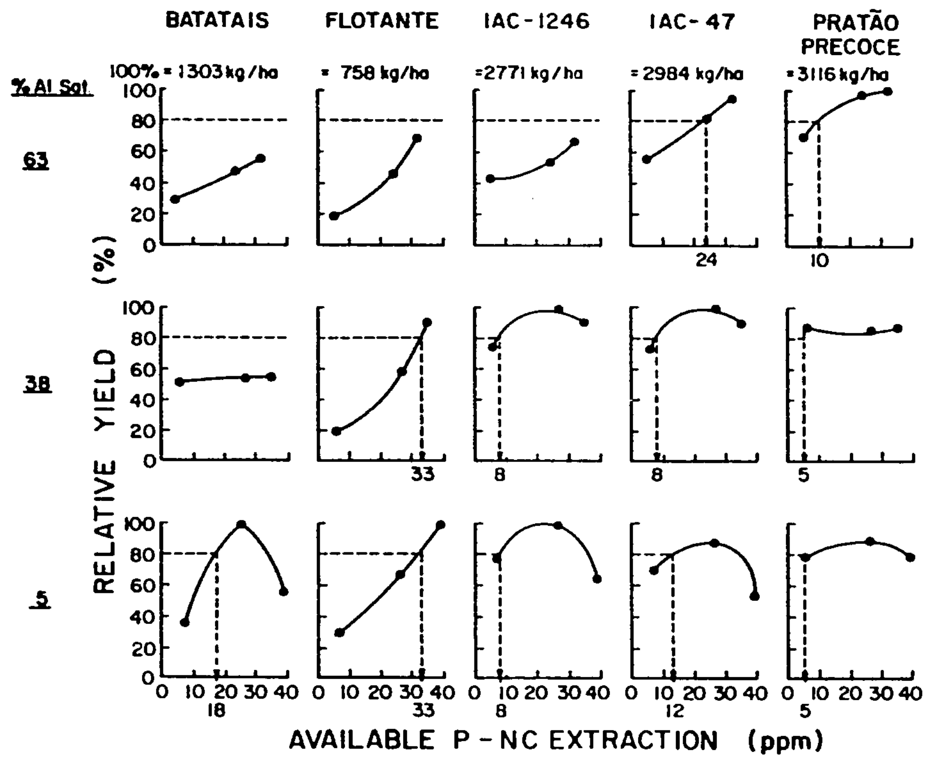

Fig. 30. Relative yields of rice varieties (percentage of maximum yield of each variety) as a function of soil available P under three levels of Al stress in Brazilian Oxisol. (Source: Salinas, 1978.)

Precoce decreased their external requirements, which indicates a better utilization of phosphorus at low rates when aluminum toxicity is reduced. The economic implications of these results suggest a trade-off between lime and phosphorus. Using 1.5 tons lime/ha could decrease phosphorus requirements. Lime is likely to remain cheaper than phosphorus fertilizers.

Under no aluminum stress, all rice varieties approached 80% of maximum yield, but at different available phosphorus levels. The Flotante rice variety always required more available phosphorus to produce well, whereas Pratão Precoce was able to produce over 80% of the maximum yield at one-sixth the phosphorus rate.

Figure 31 shows a similar trend with corn varieties, but in all cases with a higher external phosphorus requirement than was the case with rice varieties. These results also confirm the general observation that the recommended rates of

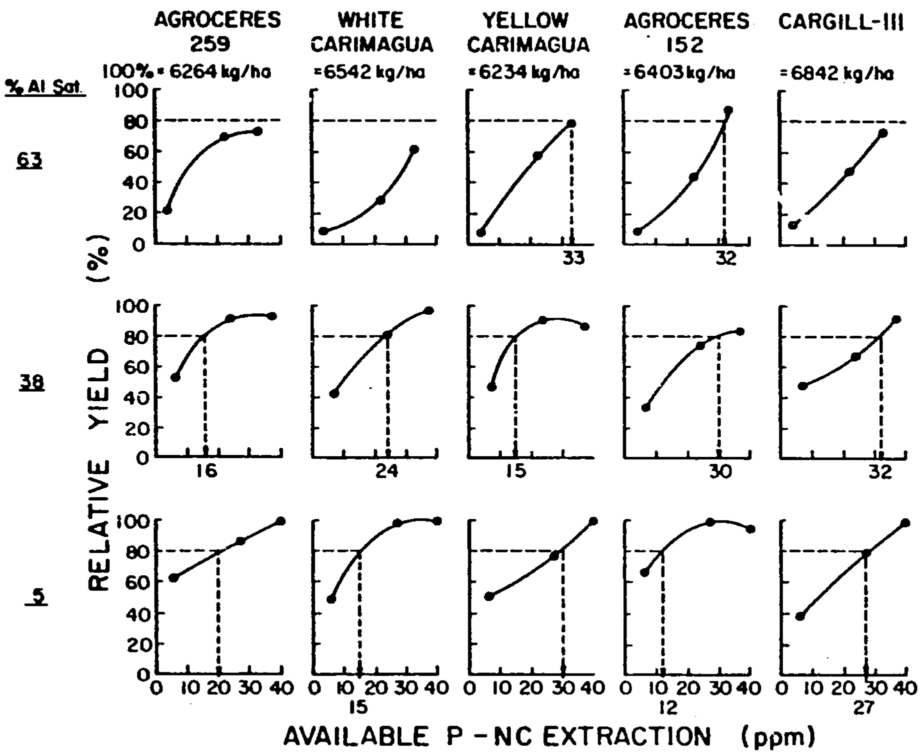

Fig. 31. Relative yields of corn varieties (percentage of maximum yield of each variety) as a function of soil available P under three levels of Al stress in a Brazilian savanna Oxisol. (Source: Salinas, 1978.)

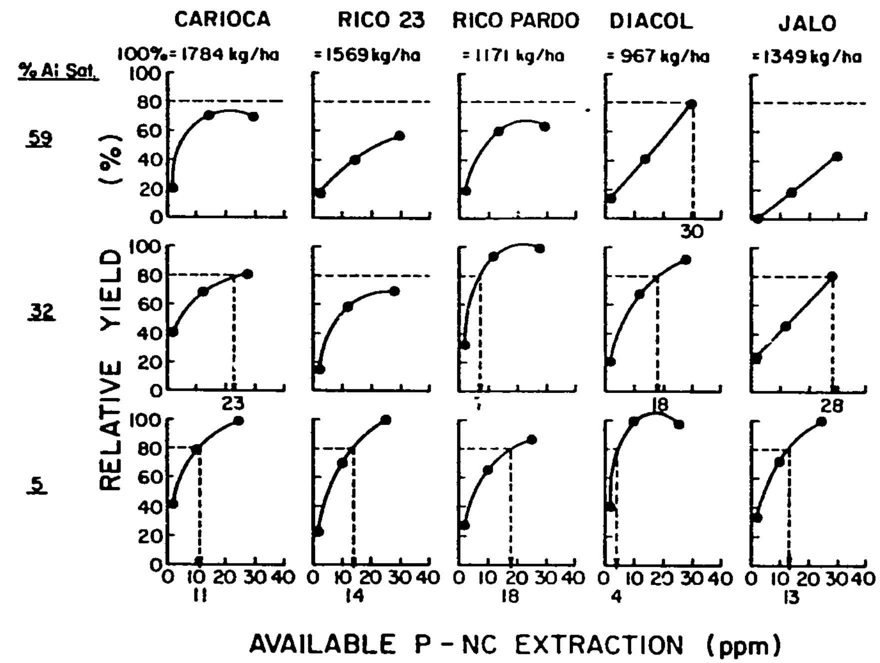

Fig. 32. Relative maximum bean yield as affected by available soil P and Al saturation levels of a Typic Haplustox from Brasilia, Brazil. (Source: Miranda and Lobato, 1978.)

phosphorus for upland rice are much lower than those for corn in Latin America (Kamprath, 1973). Under aluminum stress (63% aluminum saturation), the corn varieties Yellow Carimagua and Agroceres-152 approach 80% of maximum yield. When aluminum saturation was decreased to 38% by adding 1.5 tons lime/ha, the five corn varieties showed lower external phosphorus requirements to approach 80% of maximum yield. This observation underscores the important role that the lime plays in efficiency of phosphorus fertilization. Also, it appears that liming this Oxisol with 1.5 tons/ha enabled the corn plants to utilize both native and fertilizer phosphorus more efficiently (Salinas, 1978).

Figures 32 and 33 also show the differential responses of bean and wheat varieties. With the exception of the variety Rico Pardo, the bean varieties had lower external phosphorus requirements because aluminum was neutralized by liming. In addition, varieties differed in their phosphorus requirements under the same level of aluminum stress. In the case of wheat varieties (Fig. 33), the Mexican varieties Sonora and Jupateco, which were developed in calcareous soils, produced significant yields only under no aluminum stress and had higher phosphorus requirements than those of the Brazilian wheat varieties BH-1146 and IAC-5. Although IAC-5 had a high external phosphorus requirement, it was

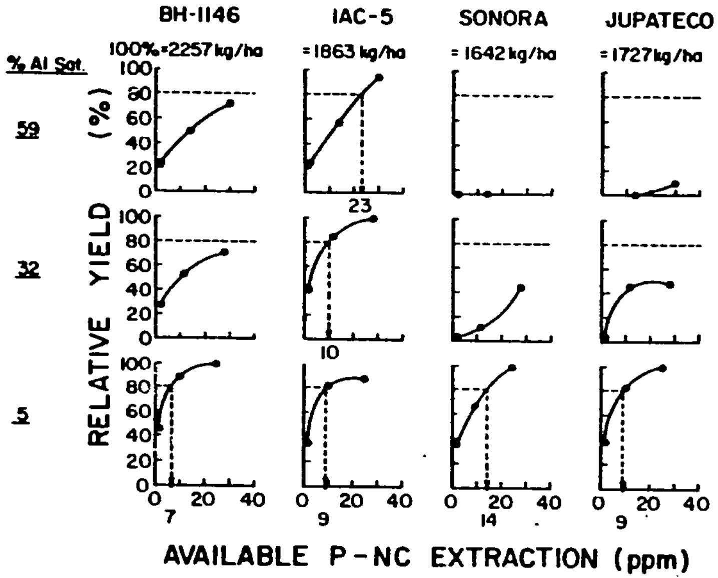

Fig. 33. Relative maximum wheat yields as affected by available soil P and Al saturation levels of a Typic Haplustox from Brasília, Brazil. (Source: Miranda and Lobato, 1978.)

the only wheat variety that produced 80% of its maximum yield under aluminum stress. As aluminum stress decreased, the external phosphorus requirements of all varieties also decreased.

2. *Pastures*

Similar results are being obtained with tropical grasses and legumes (CIAT, 1977, 1978, 1979, 1980). Tables XXXIII and XXXIV show external and internal phosphorus requirements for several tropical grasses and legumes. The data indicate substantial differences among ecotypes in internal and external phosphorus requirements. Excellent pasture establishment with low phosphorus fertilizer inputs and the use of grasses and legumes adapted to the acid, infertile soil conditions is taking place in different ecosystems of tropical America (CIAT, 1980).

F. Potential Utilization of More Effective Mycorrhizal Associations

It is well established that several genera and species of vesicular-arbuscular mycorrhizae form symbiotic associations with roots of certain plants and as a

result increase the uptake of phosphorus from soils low in this element (Sanders *et al.*, 1975). Many of the plant species considered in this review to be tolerant to acid soil constraints are heavily mycorrhizal in Oxisols and Ultisols: cowpea, cassava, citrus, guava, *Brachiaria decumbens*, *Centrosema pubescens*, *Pueraria phaseoloides*, *Stylosanthes guianensis*, soybeans, and others (CPAC, 1979, 1980; Waidyanatha *et al.*, 1979; Yost and Fox, 1979). It seems reasonable to speculate that the ability to enter into mycorrhizal associations may be an important characteristic of plant species and varieties adaptable to low-input systems.

The advantage of mycorrhizal associations lies in the use of fungal hyphae as an extension of the plant root system, which results in a larger surface area for nutrient uptake and the tapping of nutrients that move primarily by diffusion (phosphorus, zinc, and others) from a larger soil volume. There is no evidence that mycorrhizal associations are capable of utilizing forms of soil phosphorus that would be otherwise unavailable (Mosse *et al.*, 1973). Nevertheless, the increase in phosphorus uptake can result not only in increased growth and phos-

Table XXXIII
External Critical Phosphorus Levels of Various Tropical Pasture Species[a]

Species and accession number	Critical level of Bray II available P[b]
Legumes	
Stylosanthes capitata CIAT 1978	2.5
Stylosanthes guianensis CIAT 1200	2.5
Zornia latifolia CIAT 728	2.8
Desmodium ovalifolium CIAT 350	3.0
Stylosanthes capitata CIAT 1315	3.2
Stylosanthes capitata CIAT 1097	3.3
Zornia sp. CIAT 883	3.4
Pueraria phaseoloides CIAT 9900	3.5
Stylosanthes capitata CIAT 1019	3.5
Stylosanthes capitata CIAT 1338	3.6
Stylosanthes guianensis CIAT 1153	5.5
Desmodium scorpiurus CIAT 3022	8.0
Macroptilium sp. CIAT 536	9.5
Desmodium gyroides CIAT 3001	11.4
Grasses	
Andropogon gayanus CIAT 621	5.0
Brachiaria decumbens CIAT 606	7.0
Panicum maximum CIAT 604	10.0

[a]Sources: CIAT (1978, 1979, 1980).
[b]Soil test level associated with about 80% of maximum yield.

Table XXXIV
Internal Critical Levels of Phosphorus Associated with Near-Maximum Yields of Tropical Pastures Species

Species	P in tissue (%)
Legumes	
Stylosanthes humilis	0.17
Centrosema pubescens	0.16
Desmodium intortum	0.22
Glycine wightii	0.23
Medicago sativa	0.25
Grasses	
Andropogon gayanus	0.11[a]
Brachiaria decumbens	0.12
Melinis minutiflora	0.18[a]
Panicum maximum	0.19[a]
Pennisetum clandestinum	0.22
Chloris gayana	0.23
Paspalum dilatatum	0.25

[a] The source of these values is CIAT (1978). All other values are from Andrew and Robins (1969, 1971).

phorus concentration but increased nodulation and nitrogen fixation in legumes. Table XXXV shows the results of inoculation with and without high-reactivity rock phosphate additions on *Pueraria phaseoloides* growth in an "acid lateritic soil" or Sri Lanka with pH of 4.5 and 4 ppm Bray II available phosphorus. Mycorrhizal infections indeed produced all these favorable effects and, in addition, increased the efficiency of an application of 12 ppm P of Jordanian phosphate rock comparable to that of 60 ppm P without mycorrhizae.

In an Oxisol from Hawaii, Yost and Fox (1979) compared the field response of various crops to phosphorus by fumigating part of the plots and leaving the rest in its natural state. Since fumigation killed most of the mycorrhizal population, their importance was evaluated in terms of phosphorus response. They found that mycorrhizae did make a difference in terms of phosphorus uptake, not only at low available phosphorus levels, but up to levels on the order of 0.1 ppm P in solution for soybeans, 0.2 for cowpeas, and 1.6 or greater for *Stylosanthes hamata*, *Leucaena leucocephala*, and cassava. At low available phosphorus levels (0.003 ppm P in solution or 3 ppm P Bray I) phosphorus uptake was on the average 25 times greater in mycorrhizal than in nonmycorrhizal plants.

Estimates of internal or external critical phosphorus levels in the absence of mycorrhizal associations, such as those based on sand culture, nutrient solution, or fumigated soil, may be grossly exaggerated. Yost and Fox (1979) estimate that the phosphorus requirement of cassava can be exaggerated by a factor of 100 times if estimated in the absence of mycorrhizae.

The problem with such data is that they only document what is happening in Oxisols and Ultisols under natural conditions, where native mycorrhizae strains are already operating. This information, although highly enlightening, does not produce a new management practice. What is needed is to determine whether inoculation with more effective strains of mycorrhizae can enhance phosphorus uptake. Two questions need to be answered in order to reach a determination: (1) How can mycorrhizae be inoculated on a practical basis? (2) Are there more effective strains that can compete with the native ones and persist in the soil?

Unlike rhizobia inoculation, mycorrhizae must be inoculated as fresh hyphae and cannot be mixed with peat and dried. At the experimental level, field inoculation can be carried out by adding soil from mycorrhizal area, but the tonnage required impedes its practical application. Some advances are being made toward answering the second question. Researchers at the Cerrado Center near Brasília (CPAC, 1980) were able to produce good infection of the mycorrhiza species *Anaulospora laevis* in the acid-tolerant soybean cultivar UFV-1 in an Oxisol. More work in this direction is needed before mycorrhizae can be a component of low-input soil management technology.

G. Conclusions

Phosphorus is frequently the most expensive purchased input in Oxisols and Ultisols of tropical America. Except for lands recently cleared of rain forests, phosphorus fertilization is almost always essential for sustained crop or pasture production systems. The high phosphorus fixation capacity of loamy and clayey Oxisols and Ultisols has raised fears of huge quantities of phosphorus needed for

Table XXXV
Effects of Vesicular Arbuscular Mycorrhiza Inoculum in Sterilized "Acid Lateritic Soil" of Sri Lanka on Growth, Phosphorus Uptake, and Nitrogen Fixation by *Pueraria phaseoloides* under Pot Conditions[a]

Treatment	Dry matter production (g/pot)	Mycorrhizal infection (%)	Plant P (%)	No. of nodules per pot	C_2H_4 reduction (μmol/pot/hr)
Unsterilized check	2.4	0	0.18	1	0.1
Mycorrhiza only	28.8	76	0.27	230	55.0
Mycorrhiza + 12 ppm P as PR[b]	31.0	67	0.28	241	69.1
Mycorrhiza + 60 ppm P as PR[b]	37.8	74	0.31	354	123.4
12 ppm P as PR[b]	3.9	11	0.25	11	1.6
60 ppm P as PR[b]	24.6	0	0.25	96	24.8

[a] Adapted from Waidyanatha *et al.* (1979).
[b] Jordan phosphate rock.

these vast areas. Five of the major components of low-input soil management technology, either individually or preferably together, can markedly reduce phosphorus requirements and thus increase the efficiency of utilization of this basic resource.

VII. MANAGEMENT OF LOW NATIVE SOIL FERTILITY

In addition to aluminum and manganese toxicities, calcium, magnesium, and phosphorus deficiencies, and high phosphorus fixation, many Oxisols and Ultisols of tropical America are also deficient in other essential nutrients, particularly nitrogen, potassium, sulfur, zinc, copper, boron, and molybdenum (Sanchez, 1976; Spain, 1976; Lopes, 1980). This low-fertility syndrome has sometimes caused the least fertile Oxisols to be considered as "fertility deserts" (Spain, 1975). In somewhat less infertile Ultisols of the Peruvian Amazon, Villachica (1978) and Sanchez (1979) recorded deficiencies of all essential plant nutrients except for iron, manganese, and chlorine in continuous crop production systems, now in its 20th consecutive crop.

Table II shows that 93% of the Oxisol–Ultisol regions suffer from nitrogen deficiency, 77% have low potassium reserves indicative of potassium deficiency, 71% have sulfur deficiency, 62% have zinc deficiency, and 30% have copper deficiency. The areal extent of other micronutrient deficiencies cannot be ascertained with the data available. Although these figures give an indication of the extent of the individual constraint, they are also fairly rough estimates (Sanchez and Cochrane, 1980).

The main low-input technologies required to manage low native soil fertility center on (1) maximum use of nitrogen fixation by legumes in acid soils, (2) increasing the efficiency of nitrogen and potassium fertilization, (3) identification and correction of sulfur and micronutrient deficiencies, and (4) promotion of nutrient recycling.

A. Maximum Use of Biological Nitrogen Fixation

The best known low-input soil management technology is the use of legume–rhizobium symbiosis to meet the plant's nitrogen demand without having to purchase nitrogen fertilizers. Biological nitrogen fixation is limited to legume–rhizobium symbiosis in these soils in terms of practical management. Associative symbiosis between nitrogen-fixing bacteria such as *Spirillum lipoferum* in the rhizosphere of tropical grasses has created widespread expectation about the possibility of nitrogen-fixing grasses, many of which are acid-tolerant (National

Academy of Sciences, 1977a; Neyra and Dobereiner, 1977). Unfortunately, evidence to date indicates that the practical exploitation of such symbiosis in Oxisols and Ultisols appears to be minimal at this time (Hubbell, 1979). This is an example of a low-input component that has not worked to date. Additional basic research, however, may reveal some practical implications in the future and such research should continue.

We are fortunate that many of the plant species of economic importance that are adapted to acid soil conditions are legumes. Among the annual food crops, there are three important acid-tolerant legumes, namely cowpeas, peanuts, and pigeon peas, and several less widespread ones, such as lima beans, mung beans, and winged beans. There is also a wealth of very acid-tolerant forage legumes of the genera *Stylosanthes*, *Desmodium*, *Zornia*, *Pueraria*, *Centrosema*, and many others. Spontaneous legumes also abound in areas cleared of rain forests. Hecht (1979) recorded 69 tree, shrub, and creeping legume species in pastures of the Eastern Amazon of Brazil.

In order for these legumes to fix sufficient nitrogen, it is essential that the nutritional requirements and degree of acid soil tolerance of the associated rhizobium match those of the plant (Munns, 1978). If not, plant growth will be severely hampered because of nitrogen deficiency. Rhizobium strains differ in their tolerance to the various acid soil stresses just as plants do (Munns, 1978; Date and Halliday, 1979; Munns *et al.*, 1979; Halliday, 1979; Keyser *et al.*, 1979). Consequently, soil management practices require the matching of nutritional requirements and tolerances of both legume and rhizobia.

Until recently, it has been assumed that most tropical pasture legumes growing on acid soils develop effective symbiosis with native "cowpea-type" strains of rhizobium, and therefore the selection of specific strains for individual legume species or cultivars is the exception rather than the rule (Norris, 1972). Recent work by Halliday (1979) and collaborators clearly shows that this is no longer the case. A five-stage screening and matching procedure involving laboratory, greenhouse, and field stages has shown a high degree of strain specificity for obtaining effective symbiosis in the most promising forage legume ecotypes. Recent recommendations, including inoculation technology, are available (CIAT, 1980).

Long-term field experiments, however, show that the response to inoculation with selected rhizobium strains generally decreases with time. Protecting the inoculant strain with lime or rock phosphate pelleting often permits an effective infection in an acid soil. The critical point, however, is reached 2–3 months afterward when the primary nodule population decomposes. Then the rhizobia must fend for themselves in an acid soil environment in order to reinfect the plant roots (CIAT, 1979). The selection of effective acid-tolerant strains is therefore highly desirable. Date and Halliday (1979) developed a simple laboratory technique to screen for acid tolerance at the early stages of strain selection, using an agar medium buffered at pH 4.2. Rhizobium strains tolerant to acidity grow in such media, whereas those susceptible die.

With this approach, specific strains have been identified and recommended for low-input pasture production systems on acid soils for several accessions of *Stylosanthes capitata*, *Desmodium ovalifolium*, *Desmodium heterophyllum*, *Zornia* spp., *Pueraria phaseoloides*, *Aeschynomene brasiliana*, and *A. histrix* (CIAT, 1980).

Differences in acid tolerance among rhizobium strains have also been identified for cowpeas (Keyser *et al.*, 1979) and mung beans (Munns *et al.*, 1979). In both species, the host plant tends to be more tolerant to acidity than many of the rhizobial strains. The opposite is apparently the case with soybeans, for which the current commercial strains of rhizobia appear to be more tolerant than the hosts (Munns, 1980).

In terms of nutritional needs, rhizobia require greater amounts of cobalt and molybdenum for symbiotic nitrogen fixation than do the host legume for growth (Robson, 1978). The relative requirements of other nutrients and the interactions between legume nutrition and rhizobium nutrition merit additional research.

Nevertheless, it seems clear that the nutritional requirements and acid soil tolerance of legume species should not be determined in the absence of nodulation. This is almost invariably the case with culture solution studies. Screening for acid soil tolerance of legumes should be done with soil and with inoculation. In addition to joint work by soil fertility specialists and plant breeders, the microbiologists must also be involved.

B. Increase of the Efficiency of Nitrogen and Potassium Fertilization

1. Nitrogen

It appears that no fertilizer nitrogen is likely to be needed for acid-tolerant, legume-based pastures for the acid, infertile soil regions of tropical America. Fertilizer nitrogen applications, however, are essential for cereal or root crop production systems in these regions. Rotating or intercropping grain legumes with cereals may decrease the overall amounts of nitrogen needed, not because of a significant transfer of fixed nitrogen to the cereals, but because the legumes occupy space in the fields. Most of the nitrogen fixed by grain legumes is removed from the field during harvest (Henzell and Vallis, 1977). Consequently, increasing the efficiency of fertilizer nitrogen utilization appears to be the main avenue for decreasing nitrogen fertilizer inputs for nonlegume crops.

Exceptions of the above statements are few. Nitrogen responses in these soils

are almost universal except during the first crop after clearing rain forests or on Oxisols and Ultisols that have been intensively fertilized with nitrogen for many years. Fox *et al.* (1974) observed no nitrogen responses by corn for six consecutive and relatively high-yielding crops in Ultisols of Puerto Rico, because of a long-term history of intensive fertilization.

Extensive nitrogen fertilization research has been conducted with corn, upland rice, sorghum, cassava, and sweet potatoes in Ultisols and Oxisols of tropical America. A review by Grove (1979) shows that these soils typically supply 60–80 kg N/ha to most of these crops and that applications on the order of 80–120 kg N/ha produced about 95% of the maximum yield, which in the case of corn was on the order of 5 tons/ha. When the most efficient rates, sources, and placement methods (urea incorporated right before the period of most rapid plant uptake) were used, apparent nitrogen recovery was about 56% (Grove, 1979). With upland rice recovery is on the order of 30% (Sanchez, 1972). Sulfur-coated urea has failed to produce significant advantages over regular urea or ammonium sulfate on cereal or root crops in Oxisols and Ultisols of tropical America.

Higher nitrogen rates than those reported by Grove (1979) are often necessary in high rainfall environments due to leaching. Splitting nitrogen applications in two usually increases nitrogen recovery.

The problem with the above summary is that most of the data were collected in experiments in which other fertility constraints had been eliminated. It is not known whether fertilizer nitrogen efficiency would be different when acid-tolerant cereal or root crops are grown under low phosphorus and lime inputs. Although corn varieties are known to differ in their ability to utilize fertilizer nitrogen efficiently (Gerloff, 1978), this has not been tested under low-input technology situations. Well-known plant characteristics that increase yield responses to nitrogen, such as short stature and high tillering in upland rice in high-fertility soil, should have a similar effect in acid, infertile soils.

Soil testing is of little value for nitrogen fertilization because of the mobility of nitrate in well-drained Oxisols and Ultisols and other factors (Sanchez, 1976). Consequently, fertilizer recommendations are based on field experience and plant uptake data. Nitrogen fertilization for cereal and root crops is therefore one of the weakest components in low-input strategy for these soils.

2. Potassium

The situation for potassium is similar to that for nitrogen. As mentioned before, most of the Oxisols and Ultisols have low potassium reserves in their clay minerals and potassium deficiencies increase with time (Ritchey, 1979). Unlike nitrogen, the identification of potassium deficiency via soil test is straightforward. The established critical levels are in the range 0.15–0.20 meq K/100 g for most crops. Unfortunately, there are no obvious shortcuts for low-input potassium management. There are no major inter- or intraspecific differences in terms of "tolerance to low available soil potassium." Potassium fertilizer requirements can reach levels of 100–150 kg K_2O/ha/crop. Although not as costly per unit as nitrogen or phosphorus fertilizers, such outlays represent a significant cost to the farmers. The main avenues for increasing the efficiency of potassium fertilization are split applications and avoidance of removal of crop residues, particularly stover, in order to attain some degree of recycling.

The efficiency of potassium utilization is becoming an increasingly important concern in Oxisol–Ultisol regions of tropical America, as progress in overcoming acidity, phosphorus, and nitrogen constraints increases yield potential and therefore potassium requirements. A major research thrust on potassium efficiency is badly needed.

C. Identification and Correction of Deficiencies of Sulfur and Micronutrients

Oxisols and Ultisols are often deficient in sulfur and several micronutrients, particularly zinc, copper, boron, and molybdenum (Kamprath, 1973; Cox, 1973; Blair, 1979; Lopes, 1980). Unfortunately, very little is known about the geographical occurrence of these deficiencies, their critical levels in the soil, and the requirements of acid-tolerant species and varieties.

Hutton (1979) attributed most of the lack of legume persistence in mixed pastures of Latin America to uncorrected nutrient deficiencies. Many ranchers in tropical America feel that applying triple superphosphate is sufficient fertilization for grass–legume pastures. This fertilizer source provides only phosphorus and some calcium. In tropical Australia, molybdenized simple superphosphate is widely used as the only fertilizer in Alfisols that are very deficient in nitrogen, phosphorus, sulfur, and molybdenum. This source corrects phosphorus, sulfur, and molybdenum deficiencies, allowing the legume to provide nitrogen to the mixture. Given the fundamental differences in soil acidity between soils of tropical Australia where improved pastures are grown (mainly Alfisols) and the Oxisol–Ultisol region of tropical America, it is not possible to extrapolate the Australian fertilization practices (Sanchez and Isbell, 1979). The situation is not much better for crop production because most of the fertilizers available are straight NPK formulations. With the use of higher-analysis sources such as urea, triple superphosphate, and KCl, the sulfur content of such mixtures has decreased and sulfur deficiency has become more widespread.

Surveys of the nutritional status of Oxisol–Ultisol regions, such as the one Lopes and Cox (1977a) did in the Cerrado of Brazil, plus on-site field experiments on the nutrients, such as those conducted in Carimagua, Colombia (CIAT, 1977, 1978, 1979, 1980; Spain, 1979) and in Yurimaguas, Peru (Villachica,

1978), contribute significantly to identifying which nutrients are deficient and which practices are best to correct them. They also aid in identifying possible nutrient imbalances that may be induced by fertilization. Therefore site-specific identification is necessary. These efforts must be related to the nutritional requirements of the main species and varieties. Relatively little is known about the acid-tolerant species mentioned in this article. Table XXXVI shows tentative external and internal critical sulfur levels for important grasses and legume species under Oxisol conditions.

When one of these constraints is identified, the results can be extremely positive. Wang *et al.* (1976) identified sulfur deficiency in rice-growing areas in the lower Amazon of Brazil. By switching from urea to ammonia sulfate applications and thereby applying sulfur, rice production improved dramatically. Similar experiences with micronutrient identification and correction have been recorded elsewhere (Cox, 1973; Lopes, 1980).

Insufficient knowledge of nutrient deficiencies is probably the weakest component of low-input technology. This gap can be corrected by systematic determination of critical nutrient levels in the soil and in the plants. Fortunately, the application costs are low, and zinc and copper fertilization produce long residual effects.

Table XXXVI
Tentative External and Internal Critical Sulfur Levels of Acid-Tolerant Forage Grasses and Legumes Grown in a Carimagua Oxisol in the Greenhouse[a,b]

Species	Critical soil test level[c] (ppm S)	Critical tissue concentration (% S)
Grasses		
Brachiaria humidicola 679	11	0.14
Andropogon gayanus 621	12	0.15
Brachiaria decumbens 606	13	0.16
Panicum maximum 604	14	0.15
Legumes		
Stylosanthes capitata 1315	12	0.15
Desmodium ovalifolium 350	13	0.12
Zornia latifolia 728	14	0.14
Stylosanthes capitata 1019	15	0.17

[a]Source: CIAT (1981).
[b]Estimated from Cate-Nelson diagrams.
[c]Calcium phosphate extraction.

D. Promotion of Nutrient Recycling

Soil management practices in low-fertility soils should encourage nutrient recycling as much as possible. Nutrient recycling is the main reason why acid, infertile Oxisols and Ultisols are able to support exuberant tropical rain forest vegetation in udic environments. The magnitude of this natural recycling is of interest. Two detailed studies conducted on an Oxisol from Manaus, Brazil (Fittkau and Klinge, 1973) and an Oxisol from Carare-Opón, Colombia (Salas, 1978) show that the annual nutrient additions via litter layer ranged as follows (in kg/ha): 106–141 N, 4–8 P_2O_5, 15–20 K_2O, 18–90 Ca, and 13–20 Mg. Nutrient additions through rainwash, wood decomposition, and root decomposition may double the above estimates.

In crop production systems, a significant portion of nutrients are removed from the soil at harvest. Simple "maintenance" fertilizer applications aimed at replacing what harvests took away are seldom sufficient for sustained crop yields (NCSU, 1974, 1975). Nutrient recycling therefore offers limited possibilities in crop production systems. One possible application may be leaving crop residues as mulches, particularly in the case of corn stover and rice straw, in order to recycle potassium back into the soil. There is little data on the effect of these or other mulching practices on nutrient recycling.

In pasture production systems, there is a natural recycling mechanism by which about 80% of the nitrogen, phosphorus, and potassium consumed by cattle are returned to the soil via excreta (Mott, 1974). This percentage is a very rough estimate and depends considerably on stocking rate, grazing management, and other factors. The limited data available in Oxisol–Ultisol regions show that this is an important mechanism. Figure 34 shows the changes in the top 20 cm of an Orthoxic Palehumult from Quilichao, Colombia, caused by dung deposition in a *Brachiaria decumbens* pasture under rotational grazing every 15 days. This figure shows that the topsoil inorganic nitrogen content doubled within 15 days within a 1-m radius from the excreta and declined afterward. Available phosphorus, potassium, calcium, and sulfur also showed a similar increase, followed by a more gradual decrease with time than nitrogen. The effects of urine (not shown) indicate a sharper increase in potassium and sulfur than with feces, but a smaller increase in the availability of nitrogen, phosphorus, and calcium (CIAT, 1981). The overall effects of these additions were favorably reflected in increases of all five elements in plant tissue concentration within the first 30 days after excreta deposition.

Indirect evidence of nutrient recycling in poorly managed pastures is shown in Fig. 35 in Oxisols of the eastern Amazon of Brazil, where the forest was cut by the slash-and-burn method and *Panicum maximum* was planted. Serrão *et al.* (1979) sampled soils in unfertilized *Panicum maximum* pastures of known ages

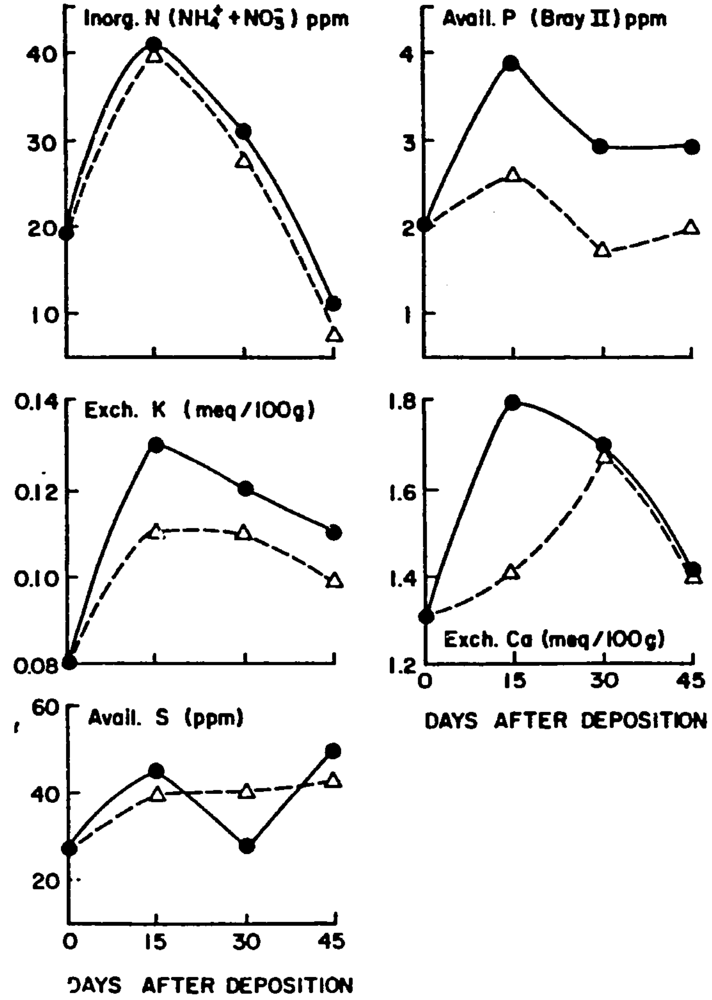

Fig. 34. Nutrient recycling on the top cm of an Orthoxic Palehumult from Quilchao, Colombia, as a result of dung deposition by cattle grazing a *Brachiaria decumbens* pasture. Distance from dung (cm): ●, 20; △, 100. (Source: Salinas and Campos, unpublished results.)

in two sites. Soil pH increased from about 4.5 to between 6 and 7 right after burning, and remained constant up to 13 years. Aluminum toxicity was completely eliminated as calcium and magnesium levels were maintained at fairly high levels. Organic matter and nitrogen levels also remained high over the 13-year period. Potassium values remained close to the critical level, while available phosphorus decreased below the critical level (5 ppm P by Mehlich 2) within a few years. These results are from samples of different fields of known

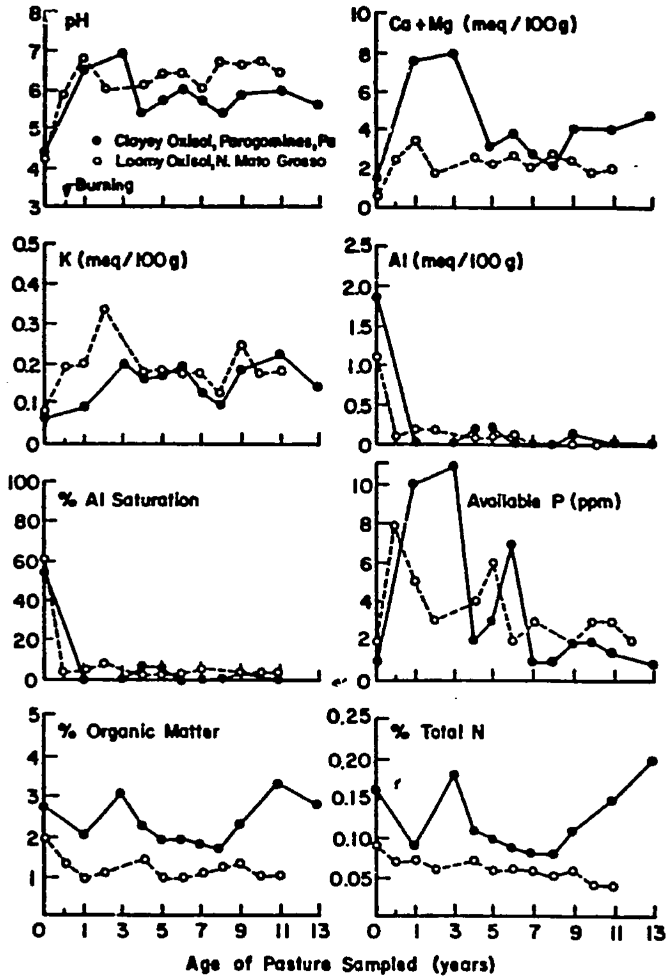

Fig. 35. Changes in topsoil properties of *Panicum maximum* pastures of known age sampled at the same time in two regions of the Eastern Amazon of Brazil (Adapted from Serrão *et al.*, 1979.)

age after clearing taken at the same time; therefore they confound time and space variability. Nevertheless, it seems clear that many of the chemical properties of thses Oxisols were definitely improved by clearing and grazing.

These soil dynamics are in sharp contrast with the rapid fertility decline observed after clearing rain forests and growing annual crops in udic areas of Peru (shown in Fig. 10). The reasons for these differences are not clearly understood and deserve more thorough study. Some factors favoring a less marked decline in eastern Amazonia may be an ustic soil moisture regime that allows for a more

thorough burn and more ash deposition, and possibly upward movement of cations and anions during the dry season. Also, the periodic burning every few years practiced in these areas and some degree of nutrient recycling by the grazing animal may contribute to the effects shown in Fig. 35. Whatever the reasons, the improvement in the chemical properties of acid, infertile Oxisols is remarkable and shows promise for better managed grass–legume pastures in the Amazon region.

Farming systems that include trees are expected to produce better nutrient recycling. Trees of economic importance such as cocoa and oil palm are expected to have a nutrient recycling mechanism similar to that of the rain forest (Alvim, 1981). Actual data to support this hypothesis, however, are very limited. Silva (1978) observed evidence of incipient nutrient recycling of several permanent crops in an Oxic Paleudult of Barrolândia, Bahia, Brazil, in terms of an increase in the exchangeable base content of the top 5 cm of the soil 34 months after burning. The increase is most marked in the young oil palm plantation with a *Pueraria phaseoloides* ground cover, followed by the pasture, and to a lesser degree in the cassava–banana intercropping that precedes cocoa planting. Similar observations have been made with some planted forestry species with a kudzu understory in an Oxisol of Manaus, Brazil (P. T. Alvim, personal communication). More data covering a longer time span are needed in order to fully ascertain the importance of nutrient recycling in cropping systems of Oxisol–Ultisol regions in tropical America.

E. Conclusions

The low native fertility of Oxisol–Ultisols cannot be eliminated as a major constraint without significant fertilizer inputs. Several avenues are available for lowering the overall fertilizer requirements. The need for nitrogen fertilization, however, can be essentially eliminated in legume-based pasture systems with the use of acid-tolerant *Rhizobium* strains in association with acid-tolerant legume species. This is also possible for the acid-tolerant grain legumes, but definitely not for cereal and root crop species. The carryover effect of nitrogen fixed by a legume to a nonlegume crop either intercropped or in rotation appears to be very small since most of the nitrogen is removed in the harvest. Increasing the efficiency of nitrogen fertilization for nonlegumes can be accomplished through improved timing and placement of fertilizers. Little is known about fertilizer nitrogen efficiency of acid-tolerant cereal crops under low-input systems.

Potassium and sulfur deficiencies are widespread and in the case of the latter, become more widespread with the use of higher-analysis fertilizers. The identification of deficiencies of these nutrients and the micronutrients is a major gap in tropical America. This can be overcome by effective soil fertility evaluation services, including the establishment of critical levels and fertilizer recommendations.

Nutrient recycling should be promoted, but in crop production systems the possibilities seem largely limited to crop residue utilization. The magnitude of nutrient recycling in pastures and tree systems needs substantial quantification.

VIII. DISCUSSION

The previous sections have described the various components for low-input soil management technology that can be used in the acid, infertile soils of the American tropics. Obviously each component is not applicable to all situations or farming systems in the vast target area; some components are mutually exclusive. Also, several components are reasonably well developed and ready for local validation, whereas others are barely more than preliminary observations. As a whole, however, they represent a philosophy of soil management for marginal lands of the tropics. The same philosophy can also be applied to other aspects of agriculture, particularly plant protection. This section of the review examines some of the implications of the use of such technology.

A. Low- versus High-Input Approaches

There is considerable ambiguity in the term "low-input technology." How low is low, and relative to what? The terms "zero input" and "minimum input" have also been used. The first one is not appropriate because in most systems zero input results in zero output. Low input as opposed to medium or high input deserves some quantification. *In this review, we would like to consider low-input technology for acid soils of the tropics as that targeted at obtaining about 80% of the maximum yields of acid-tolerant germplasm with the most efficient use of soils, fertilizers, and lime.* This review shows that it is biologically feasible to reach these yield levels with available technology and germplasm at a substantially lower level of input use than by using traditional technology and germplasm.

What is wrong with the traditional high-input technology that has been the base of much of our present world food production? There is little wrong with it from an agronomic point of view. If we were farmers in an Oxisol region and the government gave us a choice between overcoming the main soil constraints by financing massive phosphorus applications, sufficient liming, and supplemental irrigation systems, or puttling into practice the components described in this review, we would immediately follow the first alternative. As farmers, we would

see the value of our land increasing as it is transformed from marginal to excellent land by the application of inputs. The senior author, in fact, saw his father do exactly that in a 50-ha Oxisol farm, where he grew 3 crops/yr with irrigation and profited handsomely from it. It is difficult to find better soil to manage than an Oxisol once its chemical constraints are eliminated.

Such opportunities, however, are the exception rather than the rule in the acid, infertile soil regions of tropical America. The magnitude of investment capital needed to apply high-input technology to these soils is commonly beyond the resources of most governments and private organizations. Political priorities also dictate that farm intensification through high-input use be located where the large concentrations of farmers are, usually in high-base status soils.

The increasing costs of petroleum-related inputs and the worldwide emphasis on conserving the earth's natural resources pose additional restraints to the "maximum input" approach. The development policy goals of many tropical countries require that both producers and consumers with limited resources be the major beneficiaries of improved agricultural technology. Nickel (1979) observed that if low-income consumers are to benefit, food production increases must be achieved at lower unit costs. These low unit costs can be achieved through biologically based technology that is often scale neutral. To assure that producers with limited resources have access to the benefits of this technology, it should not depend on large amounts of purchased inputs. *Consequently, the main justification of low-input soil management technology in Oxisol–Ultisol regions of tropical America is socioeconomic and not agronomic in nature.*

In the past, farmers adjusted to their lack of purchasing power by applying low amounts of inputs to a farming system designed to operate best at high-input levels. Examples of this abound in Latin America, where nutrient deficiency symptoms are obvious in many fields. Many farmers know that their crops could yield more if more fertilizer were applied to high-yielding varieties, but they either cannot afford to purchase more or do not dare to because of the high risk involved. Another example is the large-scale attempt of beef production in Oxisols and Ultisols of the Amazon of Brazil by planting *Panicum maximum* without phosphorus fertilization. This clearly is a case of ignoring very obvious soil constraints. As Paulo Alvim has repeatedly mentioned in meetings about the Amazon, "agriculture is different from mining." Farmers must add fertilizers in order to have sustained production, even in the best soils of the temperate region.

Low-input soil management technology for these acid soils is different from the partial adoption of high-input technology. *Low-input technology is not less of the same but a different way of managing the soil.* The fundamental breakthrough has been the identification of important plant species and varieties that can tolerate significant degrees of acid soil constraints. Then it is a matter of determining how much fertilizer and lime these tolerant species require to produce about 80% of their maximum yield on a sustained basis.

Finally, a better understanding of the favorable attributes of acid, infertile soils converts certain soil constraints into management assets. Four examples follow:

1. By keeping the soil in its acid state, low-reactivity phosphate rocks, abundant in tropical America, can be used directly at a fraction of the cost of superphosphates. In effect, the chemistry of soil acidity replaces the superphosphate factory at considerable energy savings, provided that aluminum-tolerant plants are grown.
2. Extreme acid soil infertility can prevent weed infestations while localized fertilizer applications promote vigorous growth of the desired crop or pasture.
3. Low effective cation-exchange capacity can be considered an asset in many of these soils. Clayey soils with low ECEC generally have better structure and are less erodible than soils with high-activity clays and similar clay content.
4. Low effective cation-exchange capacity permits the gradual increase in the base status of the subsoil through the downward movement of calcium and magnesium. Instead of deterioration, the fertility of these soils actually improves, permitting deeper root development, which, in turn, permits the utilization of hitherto unavailable soil moisture. This is an attractive alternative to the more expensive supplemental irrigation systems.

B. Productivity of Low-Input Systems

Agronomically sound high-input soil management systems almost invariably produce higher yields than the low-input systems defined here. There are several reasons that account for this observation. When soil constraints are eliminated by fertilization, liming, and irrigation, it is possible to use plant species and varieties that have a higher absolute yield potential and the acid-tolerant varieties presently available. The reason for this difference is very simple. Plant breeders have traditionally concentrated on increasing the yield potential in the absence of soil constraints. Breeding to combine the various high-yielding attributes with acid soil tolerance is in its infancy. As yet, there are no aluminum-tolerant rice varieties with the yield potential of IR8. *Andropogon gayanus* does not have the production potential or the nutritional quality to match intensively fertilized *Pennisetum purpureum*, although it has high platibility. *Stylosanthes guianensis* cannot outproduce alfalfa in terms of quality under optimal conditions.

This limitation is probably a matter of time because some tolerances to acid soil stresses are controlled by one or two genes, which are often dominant (Rhue, 1979). Consequently combining acid tolerance with high-yield potential appears feasible from the breeding point of view. Breeding for acid soil tolerance, however, is just beginning. Most of the screening work is based on selecting preexistent germplasm and not segregating populations produced by a breeding

program for acid tolerance. Joint work of breeders and soil scientists should be intensified. Its payoff could be as important as the successful efforts of plant breeders with pathologists and entomologists in breeding for disease or insect resistance. In fact, the payoff may be even greater because the acid-tolerant varieties may have a longer useful time span than insect- or disease-tolerant varieties. The aluminum ion does not mutate into a more virulent race as many fungi or bacteria strains do.

C. Soil Mining or Soil Improvement?

Concerns have been experssed that plant species tolerant to acid soil constraints, particularly those tolerant to lower levels of available phosphorus, may completely deplete the low reserve of nutrients that these soils have and render them totally useless. Low-input technology is sometimes viewed as a last ditch effort to extract the last bit of fertility out of these soils.

This argument must be viewed in terms of the total reserves of the soil, the amounts of fertilizers to be added, and total nutrient extraction.

With continuous plant growth the supply of certain available nutrients in the soil eventually decreases below the critical level. In Oxisols and Ultisols, this happens rather quickly with nitrogen and potassium, elements that are very mobile in their available form. Nitrogen depletion is very unlikely because of the large reservoir in the organic fraction and its replenishment by root decomposition, nitrogen fixation, and other factors in a farming system. Organic matter contents of these soils are not generally different from the main soils of the temperate region (Sanchez, 1976). The situation with sulfur is similar. The rate of potassium depletion depends on the soil's reserve in nonexchangeable form, mainly in clay minerals. The potassium reserves of these soils usually provide less than the generally accepted critical level of 0.15 meq/100 g. An equilibrium between available (exchangeable) potassium and nonexchangeable is then established. This level will not support rapid plant growth but will not decrease the soil's potassium reserves to zero. Since crop residues or mature pastures are usually high in this element, some degree of recycling normally takes place.

The "mining" potential for calcium, magnesium, zinc, iron, copper, boron, manganese, and molybdenum appears less likely because the amounts removed by plant harvests are very small in comparison to total soil reserves in Oxisols and Ultisols. Also, the available forms of these elements are less mobile in soils and thus less subject to loss.

This leaves phosphorus, the element around which most of the "soil mining" arguments revolve. Total phosphorus contents in the topsoil of Oxisols and Ultisols are on the order of 100–200 ppm P, as compared with about 3000 ppm P in high-base status, high-activity clay soils of the midwestern United States and

Table XXXVII
Soil Phosphorus Fractions in the Profile of an Oxisol of Carimagua, Llanos Orientales, Colombia[a]

Horizon (cm)	pH	Organic C (%)	Base saturation (%)	Total P (ppm)	Percentage of total P					
					Organic P	Ca-P	Al-P	Fe-P	Reductant-Sol. Fe-P	Occluded Al-P
0-6	4.5	2.26	7	185	77	0.9	0.8	10	9	1
6-15	4.6	1.84	7	151	75	0.6	0.9	11	11	1
15-40	4.6	1.13	13	126	73	0.7	1.2	6	17	1
40-70	4.9	0.53	15	114	55	0.8	1.3	7	34	1
70-100	5.1	0.43	29	90	47	0.6	1.0	9	41	1
100-150	5.1	0.24	21	84	35	0.7	1.2	4	53	4

[a]Source: Benavides (1963).

similar temperate regions (Sanchez, 1976). Some Oxisols, however, have very high total phosphorus contents, such as Eutrustox of the Cerrado of Brazil (Moura *et al.*, 1972), but the limited data base shows that most Oxisols and Ultisols are generally low in total phosphorus.

Table XXXVII shows the total phosphorus content of an Oxisol profile from Carimagua, Colombia, representing the least fertile range of the Oxisol–Ultisol regions of tropical America. The total phosphorus reserves of the top 150 cm average 106 ppm P, which is equivalent to 4830 kg P_2O_5/ha of total phosphorus. Roots of acid-tolerant plants, however, may penetrate deeper than 150 cm.

Table XXXVIII shows the total uptake of phosphorus of two acid-tolerant grasses under grazing at Carimagua. Total phosphorus uptake by the forage available to the animals was in the range 3–12 kg P/ha/yr (7.5–28 kg P_2O_5/ha). Assuming all the phosphorus is removed from the sward, and thus ignoring recycling, the amounts added as fertilizer (50 kg P_2O_5/ha/yr) more than compensate for the removal. Therefore there is no soil mining but actually a slow buildup of phosphorus. Table XXVIII confirms that there is a gradual buildup of total phosphorus in these soils of about 16 ppm P/yr on the topsoil with application rates of 50–100 kg P_2O_5/ha/yr.

In the case of crop production, phosphorus removal rates are higher. Wade (1978) reports that four consecutive harvests of cowpeas, corn, peanuts, and rice, after which the residues were left in place, produced a total removal of up to 68 kg P_2O_5/ha/yr in Yurimaguas. The total amount added was 50 kg P_2O_5/ha suggesting a very close balance. An annual application rate of 100 kg P_2O_5/ha/yr would probably produce a gradual increase in available phosphorus. Long-term soil dynamics data at Yurimaguas show major buildups in available phosphorus

calcium, zinc, and copper with continuous cropping in this region (Sanchez, unpublished results).

It is well known that plants remove less phosphorus than is applied as fertilizers. Since low-input technologies described in this review do involve fertilization, the soil mining argument appears to have very limited validity.

D. Research Needs

This review has shown the feasibility of the low-input approach and presented examples of low-input soil management technology components. Research institutions responsible for developing low-input farming systems for representative soils may want to integrate the components that are relevant to their situation into their farming systems. The authors of this review are not aware of improved low-input farming systems that have all the necessary components sufficiently well developed. Hence, the first research priority in most situations is to fully develop the components of low-input technology for a particular farming system. The items listed in Section I,C of this review could serve as a rudimentary check list, subject to local modification.

This review has also identified several major knowledge gaps. A partial list is as follows:

Table XXXVIII
Phosphorus Content of *Andropogon gayanus* and *Bracharia decumbens* Available by Swards under a Stocking Rate of 1.7 Animal Units/ha in a Tropeptic Haplustox of Carimagua, Colombia, Fertilized with 50 kg P_2O_5/ha as Triple Superphosphate plus Small Quantities of Ca, Mg, K, and S[a]

Species	Season	Dry matter on offer (tons/ha)	P content (%)	Phosphorus uptake (kg P/ha)	Annual liveweight gains (kg/ha)
A. gayanus (1-yr mean)	Rainy	4.7	0.16	7.5	288
	Dry	5.5	0.09	4.9	−23
	Annual	10.2	0.12	12.4	265[b]
B. decumbens (4-yr mean)	Rainy	0.8	0.15	1.2	125
	Dry	1.6	0.13	2.1	4
	Annual	2.4	0.14	3.3	129

[a]Adapted from O. Paladines and P. Hoyos (unpublished data) and CIAT (1980).
[b]Stocking rate of 2.4 animal units/ha.

1. *Characterization of main varieties of promising ecotypes of the principal annual crops, pastures, and permanent crop species for their tolerance to the various acid soil constraints in terms of quantitative critical levels.* Given the interactions between aluminum, calcium, and available phosphorus levels in the soil, the factors that are held constant should be specified. These constant factors should reflect levels found in the particular soil-farming system, not necessarily eliminating them as constraints. For legume species, plants inoculated with the appropriate rhizobium strain should be used.

2. *Characterization of the critical soil test levels for nutrient deficiency or toxicity* in the principal soil types for plant species and varieties used in low-input systems. The main gaps are in the secondary nutrients and the micronutrients.

3. *Development of means for interpreting land evaluation systems in terms of requirements for low-input technology.*

4. *Study of the changes in soil properties, both chemical and physical, with time in major soil-farming system situations.* This monitoring would enable the prediction of changes in nutrient dynamics or soil physical deterioration that could occur, and correction of them before they actually happen. Soil dynamics data are scanty and usually reflect too short a period of time. Long-term monitoring of the changes in soil properties is also needed to establish a better fundamental understanding of what happens to soils managed under low-input systems. Questions about the degree of nutrient recycling, the amount of nitrogen turnover in systems involving legumes, and the efficiency of fertilizer use could be ansered by long-term monitoring of soil properties and their relationships to plant production.

5. *Agroforestry systems must be quantified.* Most of the quantitative data in this article are related to annual food crops and pastures. A data base on farming systems that involve either trees alone or trees in combination with annual crops and pastures needs to be established.

6. *Increasing subsoil fertility requires substantial, additional work.* A more basic understanding of the chemistry of calcium and magnesium movement is needed, as well as other factors that alleviate subsoil aluminum toxicity through leaching.

7. *Tolerance to low available phosphorus needs further understanding.* Theories and greenhouse studies on the differential ability of plants to acidify its rhizosphere (Israel and Jackson, 1978; Van Raij and Van Diest, 1979) should be tested and validated in Oxisol-Ultisol conditions.

8. *The various components of low-input phosphorus management technology should be put together as a package.* The best source combinations, rates, placement, and the interaction with varieties tolerant to low available phosphorus, rhizobium inoculum, and potential inoculation of improved mycorrhizal strains could be combined for specific soil-farming systems. Improved or less expensive phosphorus fertilizer sources should be developed.

9. *Matching of acid soil tolerance of legume species or varieties with rhizobia strains,* in order to make them both compatible to the same degree of acid soil stresses and to favor rhizobia persistence in the soil.

10. *Development of novel methods for improving the efficiency of nitrogen fertilization in nonlegume crops and potassium fertilization in all crops.* The low recovery of nitrogen and potassium fertilizers is a considerable obstacle preventing decreasing unit costs.

IX. SUMMARY

Low-input technology for acid soils of the tropics can be defined as a group of practices that can produce about 80% maximum yields of acid-tolerant plant species and varieties with the most efficient use of soils and chemical inputs. The term "low" is used in relation to "high"-input technology where the application of fertilizers and amendments largely eliminate chemical soil constraints. The identification of plant species and ecotypes tolerant to the main acid soil stresses allows the development of low-input soil management systems for Oxisol-Ultisol regions where socioeconomic constraints prevent the widespread application of large quantities of lime and fertilizers. The basic approach is to use plants adapted to acid soil constraints, to maximize the use of fertilizers and lime needed to produce about 80% of their maximum yield, and to take advantage of favorable attributes of acid, infertile Oxisols and Ultisols. Several technology components are reasonably well identified and could be used as building blocks for specific management systems:

1. Selection of lands dominated by well-drained Oxisols or Ultisols without steep slopes, and identification of the major soil constraints encountered.

2. Selection of species and varieties of annual crops, pastures, or tree crops that can tolerate a reasonable degree of aluminum toxicity, low available phosphorus levels, and/or manganese toxicity, as well as being adapted to climatic, insect, and disease stresses.

3. Land clearing methods in rain forests should include burning in order to take advantage of the fertilizer value of the ash, to minimize soil compaction, and to permit the rapid establishment of a crop or pasture canopy to decrease erosion hazards. Land clearing methods in the savanna are less complicated but should also aim at the quick establishment of a plant canopy.

4. Low-cost pasture establishment techniques include the introduction of improved species into native savanna, its gradual replacement, low-density seeding methods, and crop-pasture relay intercropping. Pasture maintenance techniques must consider the frequency of fertilizer applications.

5. Further soil cover protection can be obtained by mulching annual crops and green manuring, although the results are not always positive. Intercropping and agroforestry combinations are poorly characterized and quantified.

6. Soil acidity constraints can be attenuated without massive lime applications by (*a*) the use of plant species and varieties tolerant to aluminum and manganese toxicities, (*b*) the application of sufficient lime to satisfy the calcium and magnesium requirements of plants, (*c*) the application of sufficient lime to decrease aluminum saturation below toxic levels, if needed, and (*d*) the promotion of the downward movement of calcium and magnesium into the subsoil.

7. Efficient phosphorus management in these soils consists of (*a*) determination of the most appropriate combination of rates and placement methods that enhance initial and residual effects, (*b*) improvement of soil fertility evaluation methods for making fertilizer recommendations, (*c*) use of less costly sources, such as phosphate rock, (*d*) selection of species and varieties that grow well at lower levels of available soil phosphorus, and (*e*) exploration of the practical possibilities of mycorrhizal inoculations to increase phosphorus uptake by plants.

8. The main low-input technologies to manage low native soil fertility center on (*a*) the maximum use of nitrogen fixation by legumes using acid-tolerant rhizobia, (*b*) increase of the efficiency of nitrogen and potassium fertilization, (*c*) identification and correction of sulfur and micronutrient deficiencies, and (*d*) promotion of nutrient recycling.

9. Concerns have been expressed that the use of plants tolerant to acid soil constraints may completely deplete the low nutrient reserves of Oxisols and Ultisols and render them totally useless. An analysis of the total nutrient reserves of such soils, nutrient removal by crops and pastures, and the amounts of fertilizers to be added indicates no evidence of soil reserve depletion, but rather a gradual increase in total soil phosphorus and other nutrients. Since low-input technologies described in this review include fertilization, the soil mining argument appears to have little validity.

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these vast areas. Five of the major components of low-input soil management technology, either individually or preferably together, can markedly reduce phosphorus requirements and thus increase the efficiency of utilization of this basic resource.

VII. MANAGEMENT OF LOW NATIVE SOIL FERTILITY

In addition to aluminum and manganese toxicities, calcium, magnesium, and phosphorus deficiencies, and high phosphorus fixation, many Oxisols and Ultisols of tropical America are also deficient in other essential nutrients, particularly nitrogen, potassium, sulfur, zinc, copper, boron, and molybdenum (Sanchez, 1976; Spain, 1976; Lopes, 1980). This low-fertility syndrome has sometimes caused the least fertile Oxisols to be considered as "fertility deserts" (Spain, 1975). In somewhat less infertile Ultisols of the Peruvian Amazon, Villachica (1978) and Sanchez (1979) recorded deficiencies of all essential plant nutrients except for iron, manganese, and chlorine in continuous crop production systems, now in its 20th consecutive crop.

Table II shows that 93% of the Oxisol–Ultisol regions suffer from nitrogen deficiency, 77% have low potassium reserves indicative of potassium deficiency, 71% have sulfur deficiency, 62% have zinc deficiency, and 30% have copper deficiency. The areal extent of other micronutrient deficiencies cannot be ascertained with the data available. Although these figures give an indication of the extent of the individual constraint, they are also fairly rough estimates (Sanchez and Cochrane, 1980).

The main low-input technologies required to manage low native soil fertility center on (1) maximum use of nitrogen fixation by legumes in acid soils, (2) increasing the efficiency of nitrogen and potassium fertilization, (3) identification and correction of sulfur and micronutrient deficiencies, and (4) promotion of nutrient recycling.

A. Maximum Use of Biological Nitrogen Fixation

The best known low-input soil management technology is the use of legume–rhizobium symbiosis to meet the plant's nitrogen demand without having to purchase nitrogen fertilizers. Biological nitrogen fixation is limited to legume–rhizobium symbiosis in these soils in terms of practical management. Associative symbiosis between nitrogen-fixing bacteria such as *Spirillum lipoferum* in the rhizosphere of tropical grasses has created widespread expectation about the possibility of nitrogen-fixing grasses, many of which are acid-tolerant (National Academy of Sciences, 1977a; Neyra and Dobereiner, 1977). Unfortunately, evidence to date indicates that the practical exploitation of such symbiosis in Oxisols and Ultisols appears to be minimal at this time (Hubbell, 1979). This is an example of a low-input component that has not worked to date. Additional basic research, however, may reveal some practical implications in the future and such research should continue.

We are fortunate that many of the plant species of economic importance that are adapted to acid soil conditions are legumes. Among the annual food crops, there are three important acid-tolerant legumes, namely cowpeas, peanuts, and pigeon peas, and several less widespread ones, such as lima beans, mung beans, and winged beans. There is also a wealth of very acid-tolerant forage legumes of the genera *Stylosanthes*, *Desmodium*, *Zornia*, *Pueraria*, *Centrosema*, and many others. Spontaneous legumes also abound in areas cleared of rain forests. Hecht (1979) recorded 69 tree, shrub, and creeping legume species in pastures of the Eastern Amazon of Brazil.

In order for these legumes to fix sufficient nitrogen, it is essential that the nutritional requirements and degree of acid soil tolerance of the associated rhizobium match those of the plant (Munns, 1978). If not, plant growth will be severely hampered because of nitrogen deficiency. Rhizobium strains differ in their tolerance to the various acid soil stresses just as plants do (Munns, 1978; Date and Halliday, 1979; Munns *et al.*, 1979; Halliday, 1979; Keyser *et al.*, 1979). Consequently, soil management practices require the matching of nutritional requirements and tolerances of both legume and rhizobia.

Until recently, it has been assumed that most tropical pasture legumes growing on acid soils develop effective symbiosis with native "cowpea-type" strains of rhizobium, and therefore the selection of specific strains for individual legume species or cultivars is the exception rather than the rule (Norris, 1972). Recent work by Halliday (1979) and collaborators clearly shows that this is no longer the case. A five-stage screening and matching procedure involving laboratory, greenhouse, and field stages has shown a high degree of strain specificity for obtaining effective symbiosis in the most promising forage legume ecotypes. Recent recommendations, including inoculation technology, are available (CIAT, 1980).

Long-term field experiments, however, show that the response to inoculation with selected rhizobium strains generally decreases with time. Protecting the inoculant strain with lime or rock phosphate pelleting often permits an effective infection in an acid soil. The critical point, however, is reached 2–3 months afterward when the primary nodule population decomposes. Then the rhizobia must fend for themselves in an acid soil environment in order to reinfect the plant roots (CIAT, 1979). The selection of effective acid-tolerant strains is therefore highly desirable. Date and Halliday (1979) developed a simple laboratory technique to screen for acid tolerance at the early stages of strain selection, using an