Efficient fertilizer use in acid upland soils of the humid tropics

FAO
FERTILIZER
AND PLANT
NUTRITION
BULLETIN

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by
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EXECUTIVE SUMMARY

Acid upland soils account for about half the land area of the tropics and for a very high proportion of the undeveloped land potentially available for arable cropping. Most of these soils are at present under virgin rain forest, with smaller areas under anthropic savanna, tree crops and shifting cultivation. The main reason for lack of development of these soils is that a high standard of management and costly inputs are needed to bring them into permanent arable cropping.

Most of the acid upland soils of the humid tropics are classified as Oxisols (Ferralsols) and Ultisols (Acrisols). Both groups are very acid with low base status, their mineral horizons containing small amounts of most nutrients. The forest biomass and the organic layers on the soil surface, in contrast, contain large quantities of plant nutrients which are cycled rapidly between the forest and the soil organic matter, often with little contact with the mineral components of the soil. These soils are highly productive under virgin forest but clearing the forest leads to serious problems due to the low soil pH and the Al and Mn toxicities associated with it, P deficiency and P fixation, and low base status; traditional methods of forest clearance result in loss of organic matter, exposure of the soil surface to solar radiation making the surface soil inhospitable to root growth, and serious erosion risks from the impact of heavy rain on the bare soil.

Cutting and burning the forest results in a transfer of nutrients from forest vegetation to soil and a temporary rise in pH, alleviating Al toxicity. Without fertilizer or lime application satisfactory crops can be grown for a short period but yields rapidly fall because of nutrient exhaustion and falling pH and low cost unintensive shifting cultivation with a regenerative long fallow is the only practical cropping system.

Better techniques of forest clearing are being developed. Zero-burn techniques in which the felled forest biomass is broken down under a short term leguminous cover crop followed by moderate applications of lime and P fertilizer show considerable promise. In the early years acid tolerant crops should be grown and at least half the soil area should be under cover crop at any one time, to maintain soil organic matter, avoid nutrient losses and prevent erosion. Liming amounts and methods should avoid excessive increases in pH, which can reduce availability of many nutrients, but should ensure that subsoil as well as topsoil pH is raised, to improve rooting depth.

Three levels of intensity can be distinguished for the use of acid upland tropical soils for arable cropping: shifting cultivation with no lime or fertilizer inputs, relying on long fallow periods for regeneration; continuous cultivation with moderate applications of lime and P fertilizer, using leguminous cover crops or alley crops to provide biologically fixed nitrogen and organic matter; intensive continous cropping with large and continued inputs of NPK fertilizer, lime and other nutrients, a system that is capable of reaching and maintaining very high levels of productivity.

The successful and continued use of acid upland soils of the humid tropics for food crop production is an increasing priority as population pressure rises. The agronomic principles underlying their successful development and use are increasingly well understood, but there is a need for good management and for substantial inputs in terms of time, manpower, lime and fertilizers.

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1 INTRODUCTION

The largest reserves of potential arable land still available in the world are located in the humid tropics. Until recently, population densities in these areas were relatively low because of climatic and soil constraints on agricultural production. In spite of these constraints there is now an increasing need to develop and intensify agricultural production in the humid tropical areas, because of population growth there and the growing food requirements of other regions.

Population density in the tropics is at present highest on alluvial plains and in inter-mountain valleys on soils derived from volcanic materials Most of these soils have an inherent fertility level high enough to make sustained agriculture possible, even with a low level of inputs. On the uplands, in contrast, acid soils predominate and agriculture at a low level of inputs is only possible through shifting cultivation, in which the land is cropped for a few years in alternation with long periods of fallow. Soil acidity, the aluminium and other toxicities associated with it, low contents of major plant nutrients, trace element deficiencies and disease hazards have all hindered the intensification of agricultural production on these soils. Adequate knowledge of their properties and management requirements is crucial for their further development and for their preservation for use by future generations.

During the last twenty years significant advances have been made in the characterisation and management of acid soils in the uplands of the humid tropics. Further research is currently in progress in Latin America, Africa and south east Asia. It is the aim of this bulletin to review the experience already acquired and to summarise the research findings which have recently become available.

2 SOIL ACIDITY IN THE TROPICS

Most well-drained tropical soils which are not currently used for agriculture are acid. This is not generally true for soils presently under cultivation, because since man started to grow crops he has always tended to settle on high base status soils (Sanchez, 1976). Nowhere is this more evident that in Indonesia, where over 60% of the population is concentrated in Java on fertile, high base status, volcanic soils, while less than 5% of the country's population lives in Kalimantan, whose land area is over four times that of Java. Most of the soils in Kalimantan are acid with a very poor base status.

Until the late 1950s hydrogen (H^+) was generally believed to be the dominant cation in acid soils. The work of Coleman and co-workers (Coleman et al., 1958; Coleman et al., 1959; Lin and Coleman, 1960; Coleman and Thomas, 1967) proved that aluminium ion (Al^{3+}) rather than H^+ was the dominant cation in the majority of soils with pH less than 5. In most cases crop growth in acid soils can be directly correlated with Al saturation or Al concentration in the soil solution. Up to a point, a high H^+ concentration (or low pH) per se does not directly affect crop growth (Black, 1967). High H^+ concentrations in the soil solution, however, favour weathering of soil minerals, resulting in the release of Al^{3+} and the leaching of ions such as K^+, Mg^{2+}, Ca^{2+} and Mn^{2+}.

With the exception of peat soils (and to some extent also acid sulphate soils), poor crop growth on acid soils is usually caused by aluminium and/or manganese toxicity and/or by deficiencies of phosphorus, calcium and magnesium.

2.1 SOIL ACIDITY, ALUMINIUM TOXICITY AND CROP GROWTH

Next to silicon, aluminium is the most abundant element in the earth's crust. Higher plants usually contain about 200 ppm Al in their dry matter (Mengel and Kirkby, 1982). Low Al concentrations appear to have a beneficial effect on the growth of most plants while some can tolerate very high concentrations in their tissues. According to Chenery (1955), Al is required for the healthy growth of tea and tea leaves may contain up to 5000 ppm without ill effect. According to Sivas-Ubramaniam and Taliburdeen (1972), cited by Mengel and Kirkby (1982), Al in tea leaves is detoxified by organic compounds, but for most other plants high concentrations are very toxic.

For most plant species the obvious effects of excess Al are on root growth (Plate 1). Roots affected by excess Al are swollen, stunted and crooked and there are few fine feeder roots. A high Al concentration in the soil solution thus prevents plants from utilising soil water and nutrients efficiently. In the plant, free Al binds strongly to the phosphate groups in nucleic acids, so inhibiting cell division (Morimura et al., 1978), affects phosphokinase and ATPase activity (Mengel and Kirkby, 1982) and often inhibits P uptake and translocation.

Al toxicity may, depending on the relative amounts and availability of plant nutrients, manifest itself in plants as Mn or Fe toxicities and Ca or Mg deficiencies (Foy et al., 1978). High Al concentrations in the soil solution lead to the formation of Al phosphates which are precipitated or strongly adsorbed in the soil causing P deficiency.

2.2 SOIL ACIDITY, EXCHANGEABLE Al AND Al SATURATION

At high or intermediate pH, exchangeable Al is held tightly to the negative charges of layer silicates and sesquioxide-coated systems as $Al(OH)^{2+}$ or $Al(OH)_2^+$, but as the pH drops below 5 exchangeable Al increases markedly as does the Al concentration in the soil solution (Figure 1).

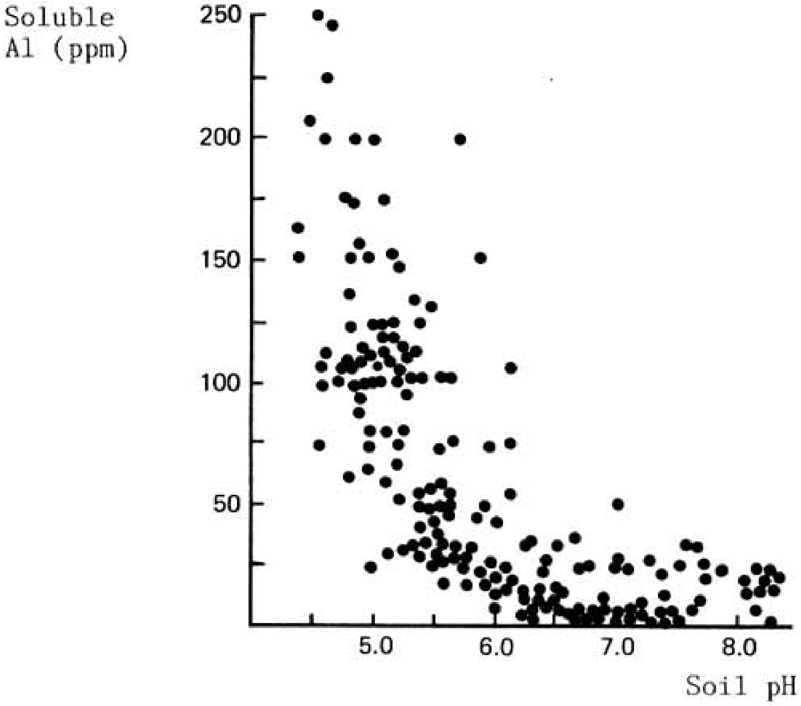

Figure 1 Relationship between soil pH and soluble soil Al
Source: adapted from Lathwell and Peech (1964)

Exchangeable Al is measured by extraction with 1 N solutions of unbuffered salts such as KCl or $CaCl_2$ and titrating the extract with a base (Lin and Coleman, 1960). Another measure of effective soil acidity is the Al saturation of the effective cation exchange capacity. Al saturation is calculated by dividing exchangeable Al (and H where present) by total CEC or by the sum of exchangeable cations, including bases, Al and H. The relationship between soil pH and Al saturation is shown in Figure 2.

Exchangeable Al concentration is affected by the kind of clay minerals present (Juo and Kamprath, 1979). According to Kamprath (1980), acid topsoils containing both kaolinite and 2:1 clay with aluminium interlayers had on average twice as much exchangeable Al as those containing kaolinite only, even though the clay content was considerably less (Table 1). It is because of the presence of Al-interlayered clays that certain Ultisols and Oxisols contain higher amounts of exchangeable Al than others, even though clay contents and soil pH may be similar.

Al concentration in the soil solution is usually less than 1 ppm where Al saturation of the CEC is below 60%. Above 60% saturation, Al in the soil solution rises sharply resulting in Al toxicity and very poor growth, even of Al tolerant plants. In less tolerant species a decrease in growth may be apparent at 30% Al saturation.

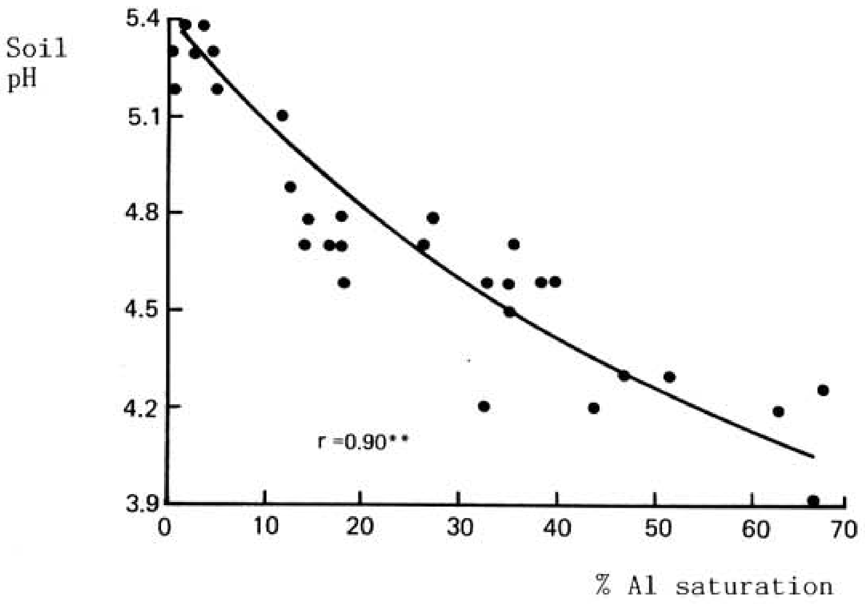

Figure 2 Relationship between soil pH and Al saturation in eight Ultisols (Acrisols) and Oxisols (Ferralsols) of Puerto Rico
Source: Abruna *et al*. (1975)

Table 1 EFFECT OF CLAY MINERAL TYPE ON THE EXCHANGEABLE ALUMINIUM CONTENT OF SOILS

	Clay mineralogy	
	Kaolinitic	Kaolinitic and 2:1 with Al-interlayers
	Topsoil	
Exchangeable Al*	1.80	4.82
pH range	3.5 - 4.7	4.0 - 4.7
Clay content (%)	31	17
	Subsoil	
Exchangeable Al*	1.42	3.30
pH range	4.0 - 4.5	4.7 - 5.0
Clay content (%)	45	36

*me/100 g soil

Source: Juo and Kamprath (1979)

Plate 1 Sugarcane roots affected by Al toxicity on an Ultisol (Acrisol) in Kalimantan, Indonesia. Older roots are dead and new roots short, swollen and running in zigzag lines

Plate 2 Heavy dressings of phosphate and lime give a reasonable crop on an Ultisol (Acrisol) in West Sumatra, Indonesia

2.3 MANGANESE TOXICITY IN ACID SOILS

Manganese is an essential plant nutrient but its presence in excess can readily cause toxicity to plants. Solubility and availability of soil Mn increase steeply with decreasing pH, especially when this falls below 5.6. Availability also increases with increasing soil moisture and decreasing soil aeration. A soil solution concentration of 1 to 4 ppm Mn is considered desirable, while concentrations below or above this range indicate respectively a possible deficiency or toxicity. At pH below 5.5 toxicity may develop in plants on soils with a high content of secondary manganese-bearing minerals such as pyrolusite (MnO_2) and manganite [$MnO(OH)$]. Below pH 4.8, Mn toxicity may occur together with Al toxicity. Mn toxicity is usually characterised by brown spots on older leaves and an uneven distribution of chlorophyll (Bussler, 1958). Morgan et al. (1966) considered Mn toxicity to be an expression of auxin deficiency caused by a high indole acetic acid oxidase activity. High Mn concentrations in plants can induce symptoms of Fe deficiency; the presence of calcium and to an even greater extent magnesium tend to depress Mn uptake.

The Mn concentration in normal plants is usually between 40 and 120 ppm, while the leaves of Mn deficient plants contain 15 to 25 ppm. Tolerance to high Mn concentrations varies greatly between plant species and between cultivars within species, but for most plants concentrations above 180 ppm indicate an excess.

2.4 PHOSPHORUS DEFICIENCY IN ACID SOILS

Most acid tropical soils have low total P contents, usually below 200 ppm (Nye and Bertheux, 1957; Cabala and Fassbender, 1970). In highly weathered Oxisols and Ultisols (Ferralsols and Acrisols), the two most important groups of acid, upland tropical soils, up to 80% of all P can be in the organic form and thus highly concentrated in the Ap horizon; this in spite of the fact that the P content of the organic matter itself is relatively low. According to Nye and Bertheux (1957), the C:P ratios of organic matter in representative soils of Ghana are of the order of 240:1, whereas in the United States they average 110:1.

As soil pH decreases the increasing concentrations of Fe and Al ions, and also possibly Mn ions, in the soil solution combine with phosphate ions to form compounds of very low solubility. In addition, phosphate ions combine with Al on the exchange complex to form insoluble compounds of the general formula $Al(OH)_2.H_2PO_4$ (Coleman et al., 1960). Applied phosphate can thus precipitate Al and reduce or eliminate Al toxicity. This process is often referred to as "liming with phosphate" but unless an excess of P is applied P may still remain deficient.

In addition to Fe and Al contents, the degree of crystallinity of their hydrous oxide clay minerals affects the speed and magnitude of P fixation (Pratt et al., 1969). Al freshly precipitated by liming remains rather reactive for a considerable time.

In acid soils it is often difficult to distinguish between Al toxicity and P deficiency. Plant species and cultivars within species differ widely in their abilities to absorb, translocate, and utilise P for growth, a fact of great practical importance which should be considered when selecting crops for highly P-fixing soils.

2.5 CALCIUM, MAGNESIUM AND POTASSIUM DEFICIENCIES IN ACID SOILS

Acid tropical soils usually have a low CEC and a very low base saturation. Although poor crop performance on acid soils is most frequently caused by Al or Mn toxicity and P deficiency, deficiencies of Ca, Mg and K are also often a cause of poor growth. This is particularly true for the Oxisols (Ferralsols) and Ultisols (Acrisols) of the tropics. Available soil K and Mg status often become the limiting factors once low pH and P deficiency have been corrected and yields begin to improve.

2.6 CATION EXCHANGE CAPACITY AND pH IN ACID TROPICAL SOILS

Clay minerals in most temperate soils have a constant and permanent surface charge density or CEC. The minerals in this group include chlorite, illite, montmorillonite, smectite and vermiculite. For soils containing such minerals, good management parameters based on surface charge and ion exchange properties have been developed and applied with success (Uehara and Keng, 1975).

In the tropics, on the other hand, many soils contain a high content of clay minerals whose surface charge is pH-dependent - crystalline and non-crystalline oxides and hydrous oxides of Al, Fe, Mn and Ti, allophane, amorphous silica, kaolinite, and halloysite. Whether the surface charge of these minerals and of organic matter is positive or negative depends on pH. At some point on the pH scale the charge is therefore zero; this is referred to as the zero point of charge or ZPC.

Information on ZPC is important for the management of soils whose minerals give a pH-dependent surface charge. The ZPC is largely a function of the types and amounts of alumino-silicate clays and of the amounts of free sesquioxides and organic matter. It can be measured by addition of hydrochloric acid or sodium hydroxide to soil suspended in 1.0, 0.1, 0.01 and 0.001 N sodium chloride solution (Van Raij and Peech, 1972). The ZPC corresponds to the pH where the titration curves of several electrolyte concentrations intersect (Figure 3). The ZPC occurs at a higher pH in the subsoil than the topsoil. This is partly because of the decrease in organic matter with increasing soil depth (Uehara and Keng, 1975), since organic matter tends to depress ZPC.

To reduce leaching losses on soils with pH-dependent charge minerals, the pH should be raised and kept above the ZPC by liming and P application.

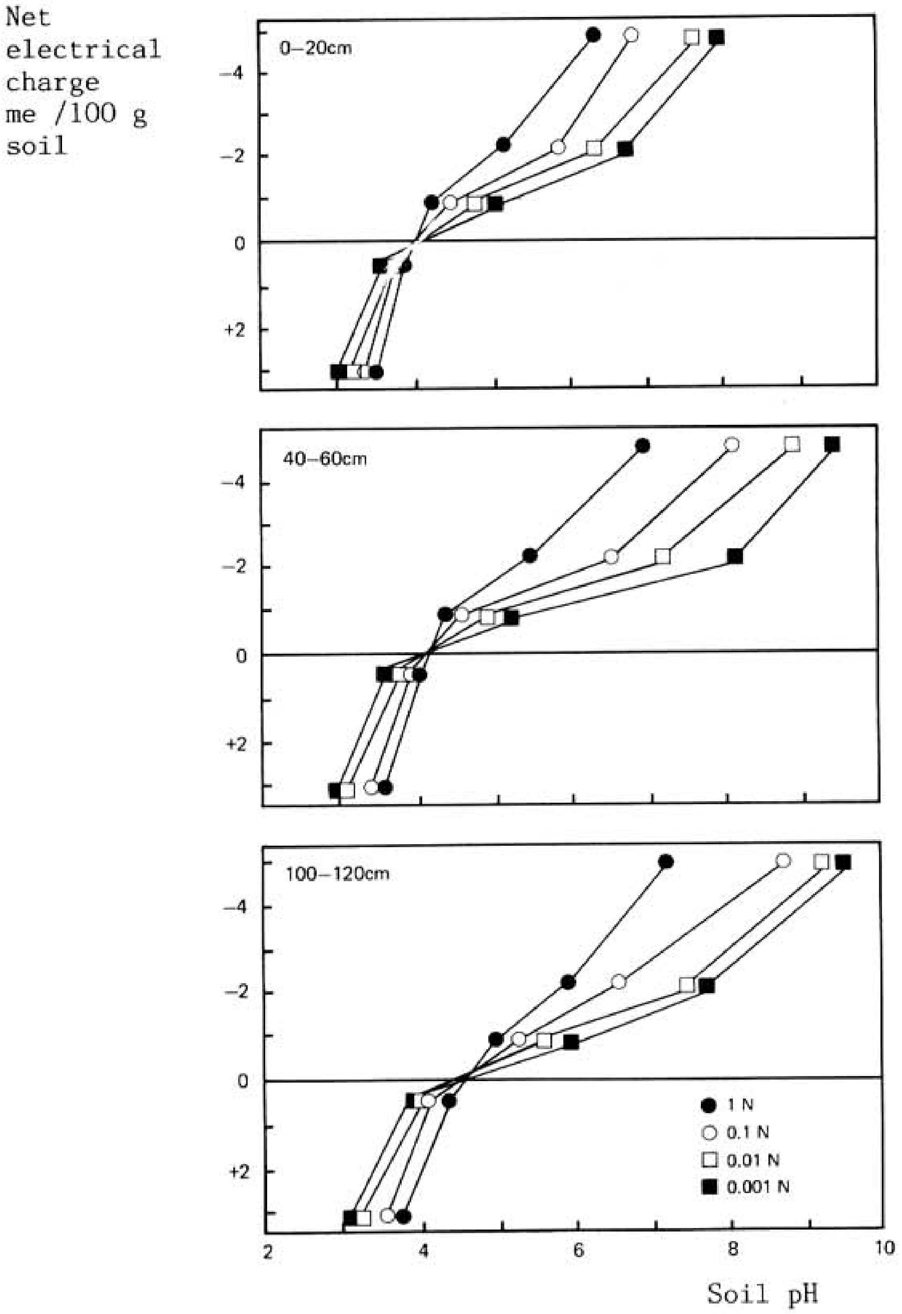

Figure 3 Net electrical charge of a Yellowish Red Latosol from the Central Plateau of Brazil as a function of electrolyte (NaCl) concentration and equilibrium pH. Source: Uehara and Keng (1975)

3 CLASSIFICATION OF ACID UPLAND SOILS OF THE HUMID TROPICS

It is estimated that acid upland soils occupy about 50% of the land area of the tropics (FAO, 1971-1981). The two systems of classification which are most commonly used to characterise and map these soils are the USDA Soil Taxonomy (USDA, 1975) and the legend of the FAO/Unesco Soil Map of the World (FAO, 1974). The nomenclature used here is that of the USDA Soil Taxonomy with the FAO/Unesco equivalent given in brackets.

3.1 OXISOLS (Ferralsols)

Oxisols occupy about 22% of the land area of the tropics. They are the most widespread soil group in South America and are important in Africa, but less well represented in Asia.

Oxisols are mineral soils which have an oxic horizon within two metres of the soil surface. The dominant clay mineral is kaolinite. By definition, they have <16 me total CEC per 100g clay, of which <10 me is due to permanent charge; these limits reflect the strongly weathered state of the primary minerals.

Oxic horizons contain only traces of weatherable minerals, so that oxisols are poor in K, Ca and Mg. Moreover, if the pH is close to or below the ZPC there can be considerable leaching of K, even in fine-textured soils with pH-dependent surface charge minerals.

Oxisols usually have excellent physical properties and are not prone to compaction. Low fertility (poor base saturation) and poor water retention are the most serious constraints.

3.2 ULTISOLS (Acrisols)

Ultisols (Acrisols and some Nitosols) cover 11% of the tropics. They are of particular importance in southeast Asia, where they account for over 50% of the land area. Ultisols are characterised by an argillic horizon (one in which clay has accumulated), with a base saturation below 35%, at least in its lower part.

Ultisols and Oxisols are similar in that both groups suffer from an inadequate supply of the major plant nutrients (P deficiency and P fixation are common), low CEC, high exchangeable Al and deficiencies or toxicities of trace elements. Ultisols usually have a higher content of weatherable minerals than Oxisols, but they have less favourable physical properties. Ultisols can be very sensitive to compaction and the use of heavy equipment should be minimised, especially when the soil is wet.

4 PLANT NUTRIENT BEHAVIOUR

4.1 NUTRIENTS IN THE PLANT-SOIL SYSTEM

The potentially cultivable but currently unutilised or under-utilised acid soils in the tropics tend to have a number of problems in common, most of which are directly or indirectly associated with acidity. The major constraints to the establishment of viable, long term food production systems are poor inherent fertility, low P content, low CEC, Al toxicity, shallow rooting, moisture stress, high surface temperature, and in many cases a sensitivity to erosion.

Most attempts to develop permanent food crop production systems on Oxisols and Ultisols (Ferralsols and Acrisols), which together account for possibly as much as 90% of tropical land potentially available for agriculture have so far failed. Very extensive areas of these soils are currently under tropical rain forest or under anthropic savanna dominated by the grass *Imperata cylindrica*. Permanent agricultural use is largely limited to tree crops such as rubber, oil palm and coffee. Shifting cultivation is the predominant land use system, as most soils deteriorate quickly under the exploitive management practices adopted by the general run of farmers.

Where man usually fails or has limited success, nature seems to have little trouble in maintaining a tropical forest vegetation that can produce up to 35 tonnes of dry matter per year. Under food crops, in contrast, the same soils rarely produce more than 5 tonnes of dry matter per year and after several years of continuous cropping yield significantly less. Thus the components of the natural system provide conditions that man has had limited success in copying. A forest type of vegetation (tree crops) and paddy rice are so far the only cropping systems that provide stable "climax" vegetation in the tropics (Figure 4).

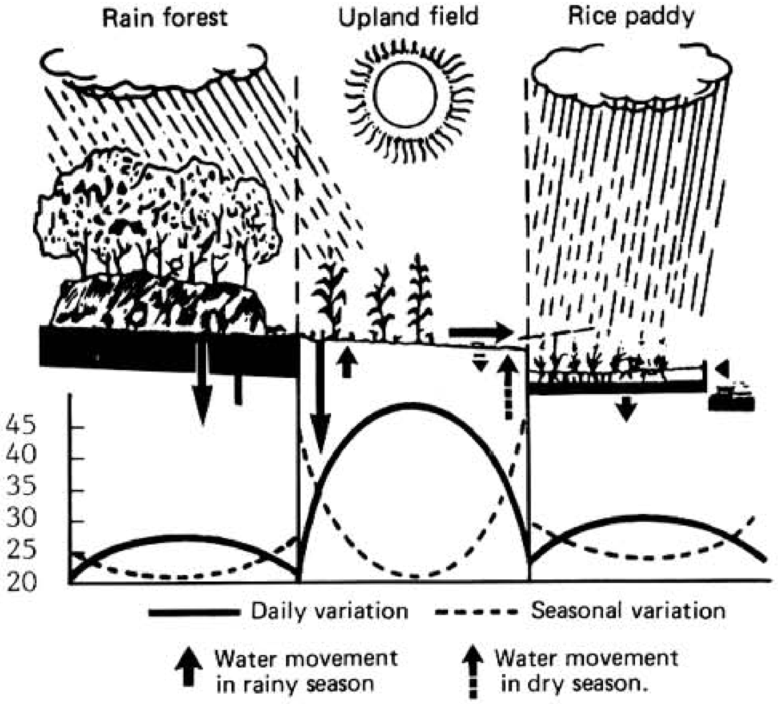

Figure 4 Soil cover and soil fertility in the tropics

An important pre-requisite for the maintenance of soil fertility and plant growth in the tropics is the retention of soil cover; such cover can be forest vegetation, live or dead mulch or impounded water. For the amelioration of most acid soils in the tropics organic matter, lime and P are essential. In comparison the other soil ameliorants and fertilizers are secondary, though N and K may assume primary importance once basic soil properties have been improved by continued topsoil protection and applications of organic matter, lime and P (Plate 2).

4.2 ORGANIC MATTER

Maintenance of a satisfactory organic matter status is essential to the productivity of most tropical soils, especially for Ultisols (von Uexkull, 1982). The most drastic changes that occur when tropical rain forest is converted to agricultural use are the large losses of organic matter during land clearing and burning, and the serious decrease in the amount of organic matter deposited on and in the soil after the destruction of the forest.

Greenland and Dart (1972) pointed out the benefits of organic matter in agricultural systems in which no fertilizer is used:

(i) Organic matter supplies most of the N and S and half of the P taken up by unfertilized crops. The slow release of N and S from organic matter by mineralisation reactions offers well defined advantages over soluble fertilizers, which are especially susceptible to leaching, volatilisation or fixation losses.

(ii) Because organic matter supplies most of the cation exchange capacity of acid, highly-weathered soils, rapid decreases in organic matter content result in marked reductions in CEC and nutrient holding capacity (Figures 5 and 6).

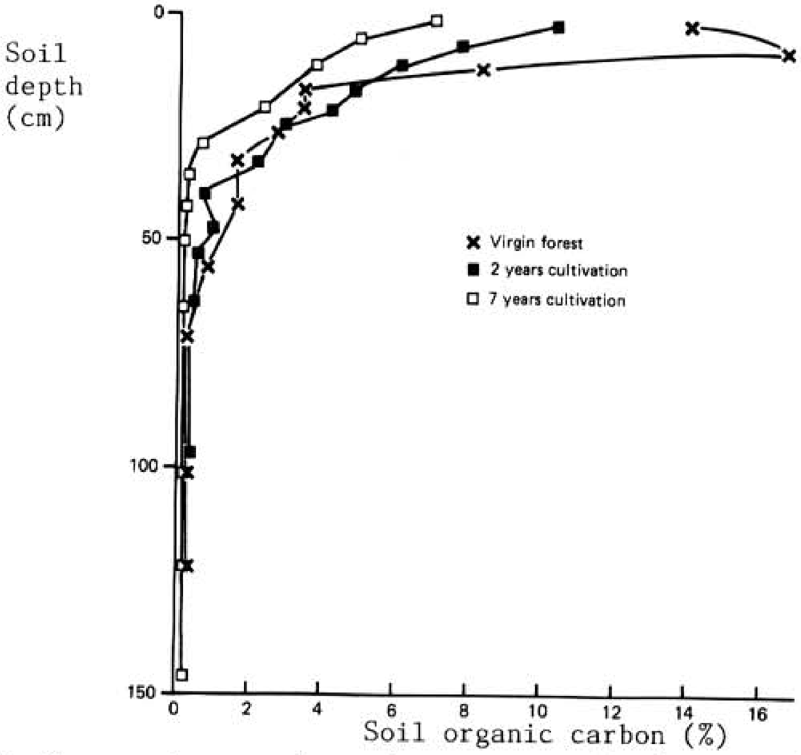

Figure 5 Changes in organic carbon content of a 'podzolic' soil in Kalimantan after cultivation. Source: Driessen *et al*. (1976)

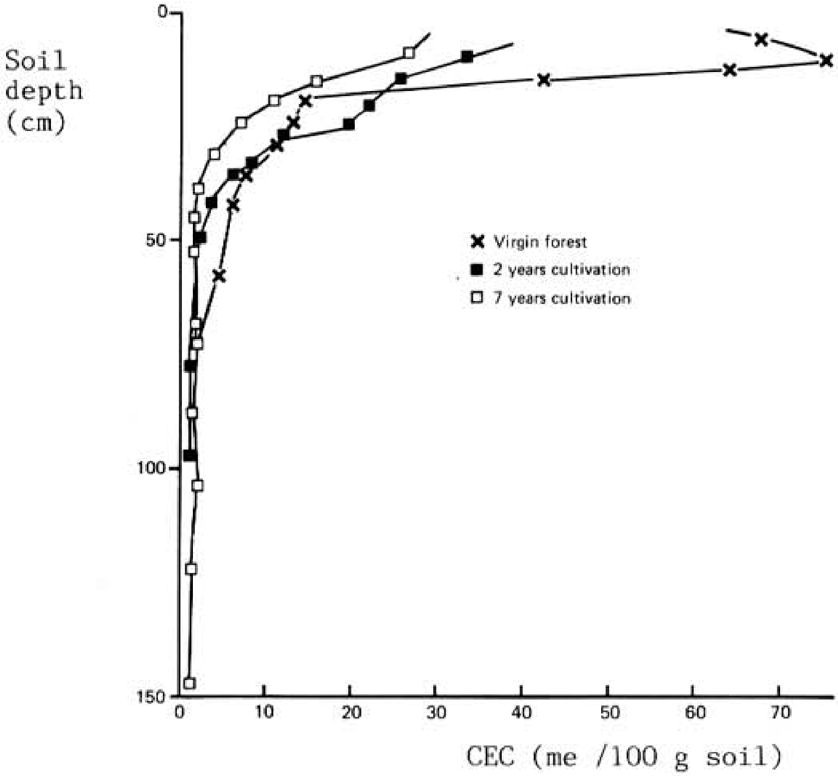

Figure 6 Changes in cation exchange capacity of a 'podzolic' soil in Kalimantan after cultivation. Source: Driessen et al. (1976)

(iii) Amorphous oxides of Fe and Al form complexes with organic matter and therefore do not crystallise. P fixation by these oxides is decreased by organic radicals blocking the fixation sites.

(iv) Organic matter contributes to soil aggregation and thus improves physical properties and reduces susceptibility to erosion.

(v) Water retention properties are improved by organic matter, particularly in sandy soils. In Ghana, the soil water-holding capacity decreased from 57% to 37% when the soil organic matter content decreased from 5% to 3%.

(vi) Organic matter may form complexes with micro-nutrients and thus prevent their leaching. The availability of micro-nutrients is also improved

Further benefits from organic matter include:

(vii) The formation of complexes with Al and Mn, thereby decreasing their concentration in the soil solution and reducing their toxicity to plants.

(viii) The stimulation of soil flora and fauna activity, further improving physical properties through the formation of more stable soil aggregates and aeration channels.

(ix) Provision of a soil cover preventing the build-up of high temperatures in the topsoil, so that roots develop more freely in this zone.

For two reasons, the rapid decomposition of organic matter and the inability of clay minerals with low surface charge (such as kaolinite) to form stable organo-mineral complexes[1], the beneficial effects of organic matter diminish rapidly after land clearing. While there is a continuous supply of organic matter under forest, clearing it and cropping the land interrupts this supply, at the same time accelerating the decomposition of the organic matter already present.

In east Asia, where population pressure has necessitated the use of soils with low base saturation and where intensive cropping has been practiced for centuries, the central role of organic matter is well understood. In contrast, organic matter as a key element in the management of poor acid soils is still grossly underestimated and neglected in most other tropical areas, where only fertile soils with high base saturation have been intensively utilised. In too many cases the short-term effect of organic matter as a source of nutrients has been compared with the effects of mineral fertilizer, neglecting the direct and indirect effects of organic matter in improving the root environment (chemical as well as physical) and thus the potential for plants to make better use of both the indigenous soil fertility and applied fertilizer. What makes organic matter so important is that it is the only soil amendment that can be preserved and produced on or around the farm.

4.2.1 Organic matter as a source of nutrients

Under forest or tree crop cover leaves and other organic residues accumulate on the soil surface. The continuously humid, shady and cool conditions in this organic horizon enable roots to thrive in it and a large proportion of the nutrients in these plant-soil systems are cycled and recycled between the living and dead organic matter without contact with the mineral soil. Large quantities of nutrients are held within the system in this way (Table 2), which is why undisturbed rain forest is a productive and stable ecosystem, even on poor soils.

Table 2 PLANT NUTRIENTS IN CIRCULATION UNDER UNDISTURBED RAIN FOREST IN THE TROPICS

	Dry matter	N	P	K	Ca	Mg
				kg/ha/annum		
Rainwash	-	12	3.7	220	29	18
Litter fall	10528	199	7.3	68	206	45
Timber fall	11200	36	2.9	6	82	8
Root decomposition	2576	21	1.1	9	15	4
Total added	24304	268	15.0	303	332	75
% total biomass	7	13	11	33	12	19

Source: Nye (1961)

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[1] Amorphous hydrous oxides of Fe and Al (allophane) found in acid volcanic ash, on the other hand, react with organic radicals to form stable organic complexes which remain relatively resistant to mineralisation.

In most food production systems, in contrast, the nutrient cycle is broken and the amounts of nutrients contained in organic matter are greatly reduced and fluctuate with the cropping cycle. To maintain and to increase production (of both food and organic matter) in such systems, additions of supplementary nutrients in the form of fertilizers and lime become essential.

4.2.2 Organic matter and CEC

An effective CEC of at least 4 me /100g soil is needed to retain most cations against leaching (Sanchez, 1976). In practice, many highly weathered tropical soils have lower effective CEC values; Driessen et al. (1976) studied the effects of cultivation on a number of soil physical and chemical parameters and found the changes in organic carbon content and CEC shown in Figures 5 and 6. The carbon and CEC curves are nearly identical, indicating the overriding importance of organic matter in the surface soil for storage and supply of nutrients.

4.2.3 Organic matter and soil physical properties

The net primary production of native vegetation on acid soils is in most cases related more to physical than chemical soil properties (Sanchez, 1981). In pioneering farming systems, productivity is initially but temporarily related to chemical properties but in intensive, continuous agricultural systems the relationship is again reversed and soil physical parameters become the major constraints. Nutrient deficiencies or imbalances can readily be corrected if soil physical properties are favourable. On the other hand, fertilizer will be rather ineffective if the physical properties of a soil are poor or are allowed to deteriorate by poor management.

Organic matter can play a central role in maintaining or increasing soil productivity by improving soil temperature, moisture and structure and by reducing the danger of erosion. Because Oxisols (Ferralsols) have inherently good physical properties, their productivity is less dependent on organic matter management than is that of Ultisols (Acrisols).

(i) Soil temperature. The roots of most crops are sensitive to temperatures above 34-42°C (Table 3). Exposed surface soils may reach temperatures of over 50°C, when root activity stops and fine roots may die. High soil temperature can therefore be a very serious constraint to food production in the tropics. Under forest cover, in contrast, soil temperature will rarely exceed 30°C. While maintenance of continuously low soil surface temperatures similar to those under forest cover is not possible if the land is in cultivation, good organic matter management (live or dead mulch) can greatly reduce soil temperature extremes (Figure 7).

(ii) Soil moisture. No single factor is as important as water in its effect on crop yields and yield fluctuations, even in the humid tropics. Good soil moisture management provides the key to high yield and good fertilizer response.

Because of their good structure, Oxisols have excellent internal drainage properties and are often too freely drained. Plants grown on Oxisols therefore frequently suffer from severe moisture stress, while excess water is rarely a problem. On Ultisols plants can easily suffer from both moisture excess because of poor drainage and moisture stress because rooting depth is often limited by Al toxicity.

Organic matter, especially as a mulch, can help to increase water infiltration and reduce evaporative moisture losses; it can also stimulate root growth and thus improve utilisation of soil water.

(iii) Runoff and erosion. Heavy tropical rainfall can cause serious problems through surface runoff and soil erosion, especially on Ultisols. Lal (1979) showed that removal of 2.5 cm of topsoil can result in yield losses of 40-50%.

Structural stability against raindrop impact is very low for most Ultisols and crusts therefore form easily reducing water infiltration and increasing runoff. A soil cover in the form of live or dead mulch can minimise the destruction of soil aggregates, the formation of crusts and runoff (Table 4).

Table 3 EFFECT OF HIGH SOIL TEMPERATURE ON NUTRIENT UPTAKE BY MAIZE SEEDLINGS (mg/g DM)

Soil temperature (°C)	N	P	K	Zn		B
	Shoot	Shoot	Shoot	Shoot	Root	Shoot
30	46.1	7.2	68.1	0.19	0.42	3.1
34	43.9	6.3	62.5	0.26	0.35	3.5
35	41.7	4.7	58.6	0.21	0.30	3.0
36	40.3	4.0	49.5	0.32	0.25	3.4
37	46.1	4.6	40.8	0.19	0.24	3.6
38	47.1	7.0	33.4	0.26	0.24	3.9
LSD (.05)	2.6	2.4	23.8	0.09	0.17	1.2

Source: Lal *et al*. (1975)

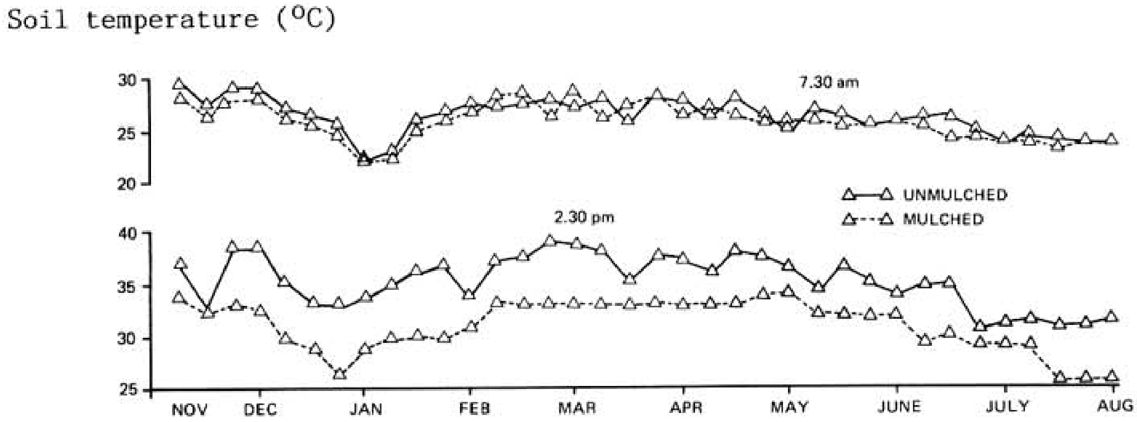

Figure 7 The effect of mulching on soil temperature. Source: adapted from Lal (1979)

Table 4 EFFECT OF MULCHING ON RUNOFF LOSSES (% OF RAINFALL LOST)

Slope (%)	Under maize		Forest cover
	Unmulched	Mulched	
1	6.4	2.0	1.7
5	40.3	7.7	1.3
10	42.7	5.7	1.7
15	17.6	1.9	2.0

Source: Lal *et al.* (1975).

4.3 LIME AND LIMING

4.3.1 Lime in acid tropical soils

In temperate regions liming is one of the oldest and best established agronomic practices for the improvement of acid soils. However, liming practices that work very well for temperate region soils, dominated by 2:1 silicate-layer clay minerals with permanent charge, often fail for tropical soils with low CEC, 1:1 silicate-layer clays and oxides of Fe and Al with very high surface charge densities. In such soils much of the lime can be consumed in the development of surface charge. While increased surface charge density (CEC) is highly desirable, the amounts of lime required to raise the pH of some clayey Oxisols (Ferralsols) and Ultisols (Acrisols) to a pH of 6.5-7.0 can be very large; not only is this expensive but it may also cause side effects including deficiencies of K, Mg, Zn, B, Fe and Mn, together with undesirable effects on soil structure.

In Oxisols and some Ultisols subsoil pH is often higher than that in the topsoil; yet even though no physical barrier is present the subsoil contains few roots. Such a condition is often associated with subsoils high in Al, low in Ca and having a pH near or below the ZPC (Uehara and Keng, 1975). Because of the low negative charge density, such a subsoil will adsorb (and thus be able to release) only traces of Ca, Mg and K. When lime is added to the topsoil, most of the lime is consumed in generating negative charge, which in turn attracts calcium ions. As a result, little Ca moves into the subsoil, unless very large amounts are used or anions are provided that help downward movement of Ca, e.g. by applying ammonium sulphate or potassium chloride. However, these applications could in turn induce nutritional imbalances or deficiencies of other elements in the topsoil. The effects and efficiency of lime could be improved if devices for subsoil application of lime were developed and brought into use.

Liming practices in the tropics have been reviewed in much detail by Kamprath (1973) and Pearson (1975). Early liming efforts aimed to raise the pH to 6.5 or 7, but since the 1960s agronomists have established that for many tropical soils and crops the pH does not have to be (and in most cases even should not be) raised above 5.5.

4.3.2 Effects of liming

The liming of acid tropical soils has the following effects:

(i) Reducing Al and Mn toxicity. Aluminium toxicity is a major constraint to food production on soils with a pH below 5.1 and Mn toxicity may be a problem below pH 5.6.

(ii) Increasing the number of crops that can be grown. At very low pH only a few Al tolerant crops and/or cultivars can be grown. Liming to an intermediate pH (5.2 to 5.8) greatly enlarges the range of crops and varieties that can be grown.

(iii) Improving P availability. The high concentrations of Fe and Al ions in very acid soils form insoluble or slowly soluble compounds with P, making this nutrient unavailable or poorly available to plants. Liming to a pH of 5.5 to 6.0 increases both soil P availability and the efficiency of uptake of water soluble fertilizer P, because Fe and Al precipitate with elements other than P. Over-liming to pH above 7.0 decreases P availability because P is precipitated or fixed in the form of Ca or Mg phosphates.

(iv) Stimulating nitrification. The activity of most micro-organisms involved in nitrification increases with pH.

(v) Promoting N fixation. Biological N fixation is promoted by liming, mainly because of the increased availability of P.

(vi) Changing the availability of micro-nutrients. The availability of Mn, Zn, B, Fe and Cu is decreased by increases in soil pH, whereas that of Mo is increased. For most tropical soils a pH between 5.2 and 5.8 is optimal, although some crops, e.g. soybeans, prefer slightly less acid conditions.

(vii) Increasing the CEC. Liming acid tropical soils, especially those with high contents of clay minerals with pH-dependent surface charge, increases the CEC and thus decreases leaching losses of the cations Ca^{++}, Mg^{++}, K^+, NH_4^+.

(viii) Decreasing the availability of K. Liming acid tropical soils usually depresses K availability (see section 4.5.1).

(ix) Changing soil structure. In temperate soils, Ca has a very favourable effect on soil structure, especially in fine-textured soils. In some acid tropical soils, however, liming can have the reverse effect. Application of lime to oxidic soils can result in flocculation or dispersion depending on whether liming changes "effective" surface charge from positive to zero values (flocculation) or from zero to negative values (dispersion) (Uehara and Keng, 1975).

4.3.3 Determining lime requirements

One approach to the measurement of lime requirement has been the use of buffer solutions to measure the amount of acidity that has to be neutralised in order to reach a desired soil pH. As the pH values of the commonly used buffer solutions are in the range 6.6 to 8 (Woodruff, 1948; Adams and Evans, 1962; Mehlich, 1976), they measure not only exchangeable Al but also H^+ associated with hydroxy-Al, hydrated oxides of Fe and Al and carboxyl groups (Kamprath, 1980). Liming acid tropical soils to neutrality on the basis of titratable acidity would often call for very large amounts of lime and cause severe yield depression by inducing deficiencies of K, P, Mg, B, Fe, Zn and Mn.

For soils with a low permanent charge and a relatively high pH-dependent charge, Kamprath (1967, 1970) suggested that lime recommendations should be based on the amount of exchangeable Al in the topsoil. Based on a depth of 15cm, 1.5 meq of Ca or 1.65 tons of $CaCO_3$ equivalent should be applied for every meq of exchangeable Al present. Exchangeable Al is responsible for buffering in the pH range of 4.0 to 5.6, while hydroxy Al and Al organo complexes control buffering in the pH range of 5.6 to 7.6 (Jackson, 1963).

Exchangeable Al extractable with N KCl is, according to Kamprath (1980), a valid criterion on which to base lime rates and has been used successfully in the tropics, eliminating the need for time-consuming neutralisation tests in the laboratory (Sanchez, 1976). The procedure gives considerably lower liming recommendations for most acid soils with low effective CEC (Table 5).

Table 5 FACTOR WHICH, WHEN MULTIPLIED BY EXCHANGEABLE Al (me /100g SOIL) GIVES THE CALCIUM CARBONATE EQUIVALENT REDUCING Al SATURATION TO LESS THAN 10%

Area	Soil (surface 15 cm)	pH	Al (me / 100g)	Al saturation (%)	Factor	Final pH
Brazil[a]	Red-Yellow Latosol	4.0	0.7	70	3	4.9
	Red-Yellow Latosol	4.4	0.9	75	2	5.5
	Dark Red Latosol	4.0	1.9	86	2	5.0
Colombia[b]	Oxisol	4.3	3.5	78	2	5.3
Panama[c]	Latosol	5.1	1.2	53	1.5	5.9
	Latosol	5.0	3.0	64	1.5	6.0
United States[d]	Ultisol	4.5	0.9	82	2.0	5.9
	Ultisol	4.7	1.0	78	2.0	6.0
	Ultisol	4.5	2.3	73	1.5	5.7
	Ultisol	4.7	4.2	54	1.5	5.6
India[e]		5.0	-	-	2.0	5.3
Natal[f]	Oxisol	5.0	-	-	3.3	

[a] Soares et al. 1975. [b] Spain et al. 1975. [c] Mendez and Maprath 1978. [d] Kamprath 1970. [e] Pradhan and Khera 1976. [f] Reeve and Sumner 1979.

Source: Kamprath (1980).

In some soils, especially Ultisols very high in exchangeable Al - which may be as high as 20 me /100g - Kamprath's formula sometimes still leads to liming rates in excess of agronomic need. Even relatively low rates of lime (1.5 -2 tonnes/ha) can depress yield of some crops when grown on soils low in K, B or Zn not supplemented by appropriate applications of these nutrients, or if the lime is not thoroughly and evenly incorporated into the soil.

Criteria for liming rates should therefore, in addition to measurements of exchangeable Al, take account of possible effects of lime on the availability of other elements.

Low rates of lime (supplying 100 to 150 kg/ha Ca) often increase yield and uptake of P, K, Zn, Cu and Mn, while higher rates depress yield, in association with lower uptake of these elements. An example of the relationship between liming rate, soil pH, Al saturation and growth of sugarcane is given in Figure 8. Plant species vary greatly in tolerance to acidity and their sensitivity to liming (Spain et al., 1975). Wright (1976) has reviewed plant tolerances to Al and Mn, which differ considerably.

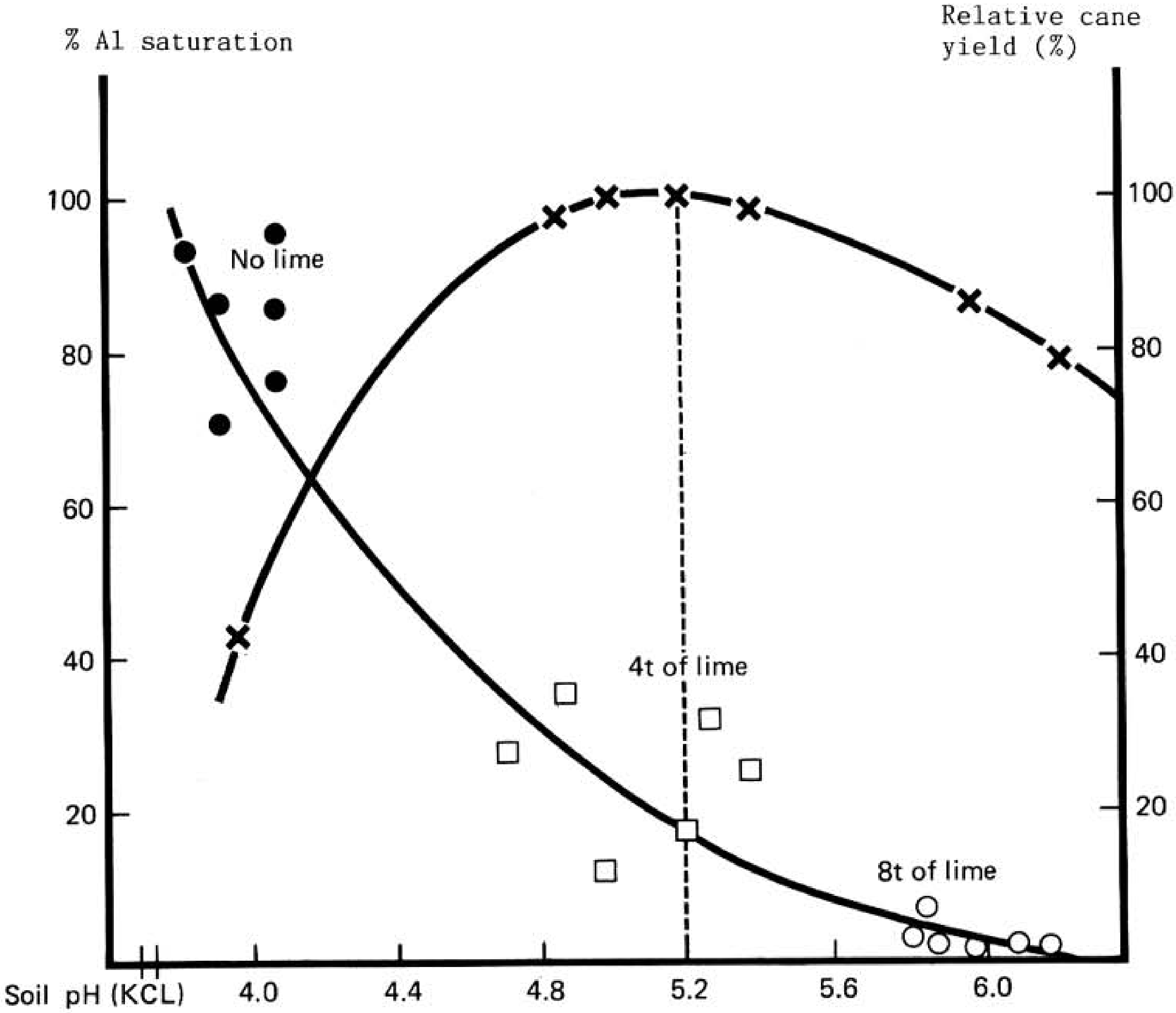

Figure 8 Relationship between rates of lime, pH, Al saturation and growth of sugarcane on an Ultisol (Acrisol) in Indonesia
Key: % Al saturation ● ◻ ○
Cane yield as % of maximum ×
Source: Von Uexkull, unpublished data.

4.3.4 Liming materials

The most commonly used liming materials are the oxides, carbonates, and silicates of Ca and Mg. To qualify as a liming material, the accompanying anion must be one that will reduce the activity of H^+ and Al^{3+} in the soil solution. For this reason, gypsum ($CaSO_4.2H_2O$) is not a liming agent, though it can be an effective source of Ca. The main liming materials are:

(i) Calcium oxide (CaO). Calcium oxide (quicklime, unslaked lime or burned lime) is obtained by roasting calcitic limestone in a furnace. It is highly caustic, reacting so quickly that proper mixing with the soil is difficult. On a weight basis, CaO is the most effective liming agent, having in its pure form a neutralising value or calcium carbonate equivalent of 179, but is too expensive and too difficult to handle in large scale improvement of acid soils.

(ii) Calcium hydroxide ($Ca(OH)_2$). Calcium hydroxide (slaked or builder's lime) is the second most reactive liming compound having in the pure form a calcium carbonate equivalent of 136 but suffers from the same cost and handling problems as calcium oxide.

(iii) Calcium carbonate ($CaCO_3$). Calcium carbonate, often occurring as a mixed compound with Mg, is the most common liming source. Pure crystalline $CaCO_3$ is called calcite or calcitic limestone and has a neutralising value of 100%.

Crystalline calcium magnesium carbonate [$CaMg(CO_3)_2$] can have various Ca:Mg ratios. Limestone with Ca and Mg in equimolar proportions is called dolomite while with other proportions it is referred to as dolomitic limestone. The neutralising value of dolomitic limestone can vary from less than 60% to over 100%.

(iv) Calcium metasilicate ($CaSiO_3$) (blast furnace slag). Finely ground $CaSiO_3$ can have a liming effect similar to that of $CaCO_3$ and has the additional benefit of supplying Si, which is in poor supply in many acid tropical soils. Application of $CaSiO_3$ may be desirable for upland rice or sugarcane. Most rice varieties that can be grown under upland conditions suffer, especially at high N rates, from blast disease *(Piricularia oryzae* Cav.) the incidence of which can be reduced by increasing the available Si in the soil.

4.3.5 Particle size

The speed with which liming materials (and other materials such as rock phosphate) react with soil is dependent on the surface area of the material that comes into contact with it. To be effective a liming material has to be finely ground and particularly fine grinding may be beneficial if rapid results are needed.

Calcium oxide and $Ca(OH_2)$ are very fine by nature. Furthermore, because they are also very reactive, they do not require the same degree of fineness as for $CaCO_3$, which is a much less reactive material. Coarse calcite or dolomite is cheap, but it reacts with the soil rather slowly. On the other hand, very finely ground material is difficult to apply and may easily be blown away by wind; if the application is not uniform, acute and harmful localised changes in pH may result; and if the material is too fine its residual effect may be short-lived. For clay soils with high buffer capacity a higher degree of fineness may be required than for coarse-textured soils but for most soils a fineness ranging from 30 to 60 mesh represents the best compromise among cost, speed of reaction, residual effect, and avoidance of localised over-liming effect. The influence of particle size of dolomitic limestone on pH over time is shown in Figure 9.

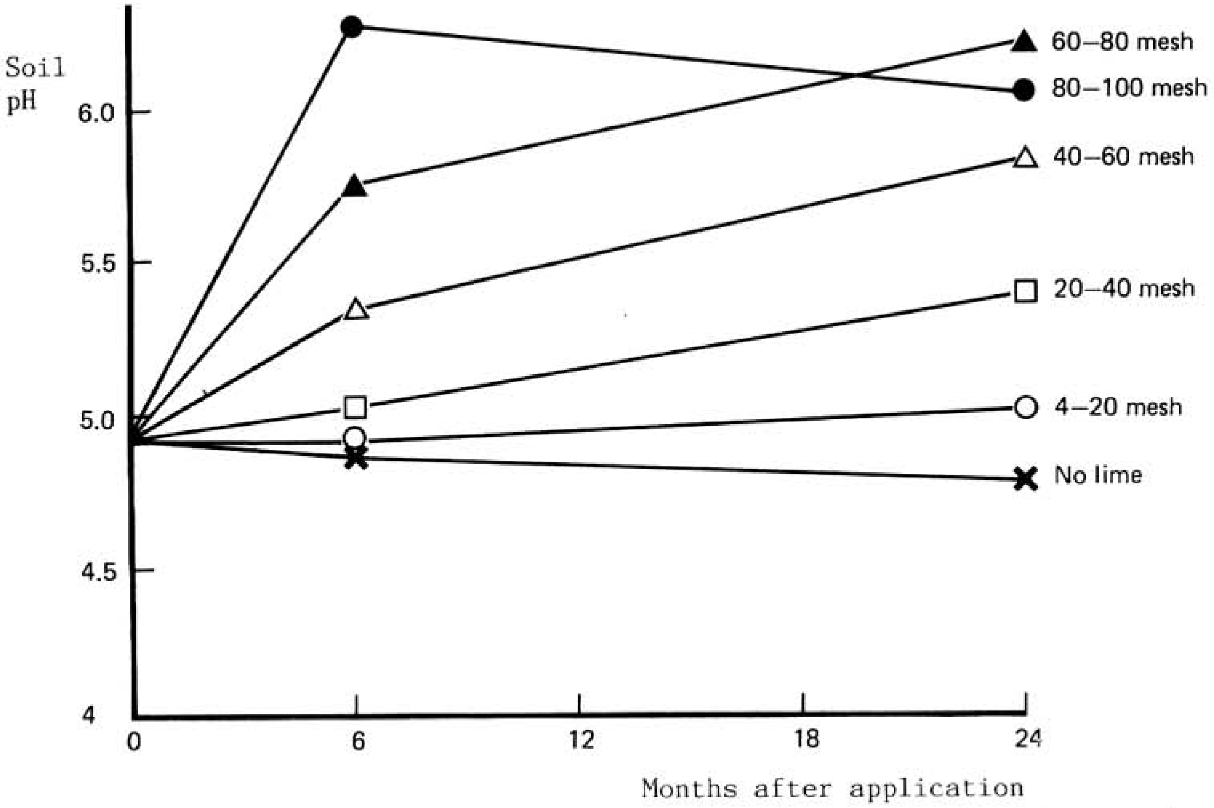

Figure 9 Effect of 4 t/ha of dolomitic limestone on an Ultisol (Acrisol) in the southern Philippines

4.3.6 Placement of lime and downward movement of cations

To be effective finely ground limestone has to be thoroughly mixed with the soil. A number of studies (Kamprath, 1973: Humbert, personal communication) have shown that deep incorporation of a given amount of lime is more effective than shallow incorporation. Though deep incorporation is undoubtedly beneficial, in practice it is often difficult to achieve because of lack of equipment and the high cost of the operation.

Raising the pH of the topsoil only in acid soils may restrict root growth to this zone, a situation in which plants will not fully utilize moisture and nutrients in the subsoil. Deficiencies of K, B and Zn may also be induced. When lime is applied to a soil with a high content of clay with pH-dependent charge much of the Ca may be retained close to the site of application because a large percentage of it is used for the creation of negative charge. While the resulting increase in topsoil CEC is often highly beneficial for sustained and stable improvement in soil productivity it is also necessary to raise the subsoil pH.

Spreading lime into the plough furrow or deep ploughing is one way of correcting subsoil acidity. Another is to promote downward movement of Ca^{++} and Mg^{++} from lime applications by providing suitable anions to accompany them, e.g. by applying ammonium sulphate and/or potassium chloride at the same time.

Increases in subsoil pH and CEC and decreases in Al saturation improve not only the environment for plant roots but also the retention of cations including K^+ and NH_4^+, thus reducing leaching losses. The overall effect is that plant use of soil moisture and nutrients is improved and the yield potential of the soil and its capacity to retain applied fertilizer and make it available to plants are increased.

4.4 PHOSPHORUS

4.4.1 General

It has already been pointed out (section 2.4) that most acid soils in the tropics have low contents of both total and plant-available P. A further important consideration is that many of them can convert large quantities of applied fertilizer P to non-available form. Phosphorus is therefore a key element in these soils and the amount available to plants has to be raised if their productivity is to be improved.

4.4.2 Phosphorus fixation

As soils weather their Ca contents tend to decrease while reactive Al and Fe contents increase. With increased weathering there is thus a shift in the control of phosphate solubility from Ca, which gives low phosphate ion concentrations in the soil solution, to Al and Fe which form complex phosphate compounds that are precipitated or strongly adsorbed on the clay lattice and amorphous sesquioxides; much of this loss of P availability is virtually permanent and is referred to as fixation. Fixation of P is initially rapid and then slows down; fixation capacity is greatest at pH levels below 5.5.

The largest amounts of P are fixed by amorphous hydrated oxides of Fe and Al and smaller amounts by crystalline and lattice minerals such as gibbsite, goethite, kaolinite, and montmorillonite (Kamprath, 1974); the more crystalline the material, the lower the reactivity and the smaller the fixation capacity. Phosphorus fixation by volcanic ash soils (Andepts) is usually greater in soils derived from recent deposits than where the soil material has undergone extensive ageing and weathering. This is because, contrary to the changes occurring in most soils the amorphous Al and Fe compounds in the volcanic ash tend to become more crystalline as they age.

According to Fox et al. (1971), the intensity of fixation by different types of mineral is ranked as follows:

Amorphous oxides > crystalline oxides > 1:1 clays > 2:1 clays

P fixing capacity is directly related to soil contents of Fe and Al oxides, so that in oxide or oxide-coated layer silicate systems P fixation increases with soil clay content.

Moisture regime plays an important role in P fixation; under wet conditions the more soluble Al phosphates tend to be important whereas under dry conditions it is the less soluble Fe phosphates which predominate.

Plants obtain their P by taking up phosphate ions from the soil solution. In acid tropical soils with high Fe and Al oxide contents, however, the P concentration in the soil solution is usually very low. Fortunately high temperatures accelerate both fixation and release reactions and thus help to maintain the P concentration in the soil solution, provided the buffer capacity of the soil is adequate. The buffer capacity of a soil is represented by the ratio of quantity to intensity; the higher the fixation capacity of a soil (low pH, high Fe, high Al) the larger the quantity factor has to be to ensure an adequate supply of plant available P (Fox et al. 1971).

The amount of P that soils can fix varies over a very wide range. The factors affecting it are the quantities of reactive Al and Fe present, the type and quantities of clay minerals and the nature and amount of organic matter in the soil.

4.4.3 Determining phosphorus requirements

In general terms, P requirements can be determined with greater accuracy than those for most other elements. There are many different methods of measuring available or labile P, but no single method gives good results for all soils. For tropical soils extraction of P with strong acids is commonly used, but acid extractants appear less effective for soils high in sesquioxides where the labile P is associated with Al and Fe. Van Raij (1978) and Roche et al. (1978) have recently reviewed and discussed most of the methods presently in use.

4.4.4. Sources of phosphorus

P fertilizers can be broadly divided into two groups - those in which the phosphate is insoluble in water and has to be dissolved by reaction with the acid soil solution; and those in which the phosphate has been converted to water soluble form and is thus immediately soluble in the soil solution, irrespective of pH. The characteristics and agronomic properties of the principal P fertilizers are described below, with particular reference to their suitability for use on acid tropical soils:

(i) Rock phosphate (ground mineral phosphate). Rock phosphate is the P source used in most phosphate fertilizer production but finely ground, reactive (or soft) rock phosphates can themselves be excellent sources of both P and Ca on all acid tropical soils.

The effectiveness of rock phosphate can vary according to origin from almost zero to equality with (or even greater effectiveness than) superphosphate, which contains water soluble phosphate. In addition to rock source, effectiveness is influenced by reactivity and particle size, soil pH, application method and period of reaction in the soil. Some experimental results showing the effect on maize growth of a number of rock phosphates relative to triple superphosphate are shown in Figure 10, while Figure 11 demonstrates the effects of reaction time, soil pH and particle size on the availability of P in North Carolina rock phosphate.

When suitable rock phosphate reacts with the soil, other soil properties as well as soil P status are influenced. Rock phosphate contains 30 to 50% CaO and thus increases available Ca in the soil, raises soil pH and lowers exchangeable Al content. Rock phosphate often also contains small amounts of trace elements such as Zn and Cu.

The benefits of reactive phosphate rocks for use on acid tropical soils are thus that they raise Ca status and pH and are often as effective sources of P as water soluble P fertilizers. Indeed, because their phosphate has first to be dissolved in the soil solution, the process of P fixation may be more prolonged, leading to a longer period of P availability. They are also usually cheaper per unit of P. To expedite dissolution of their phosphate in the soil solution (which is a prerequisite for plant availability) contact of the rock phosphate with the soil solution should be maximised, by uniform,

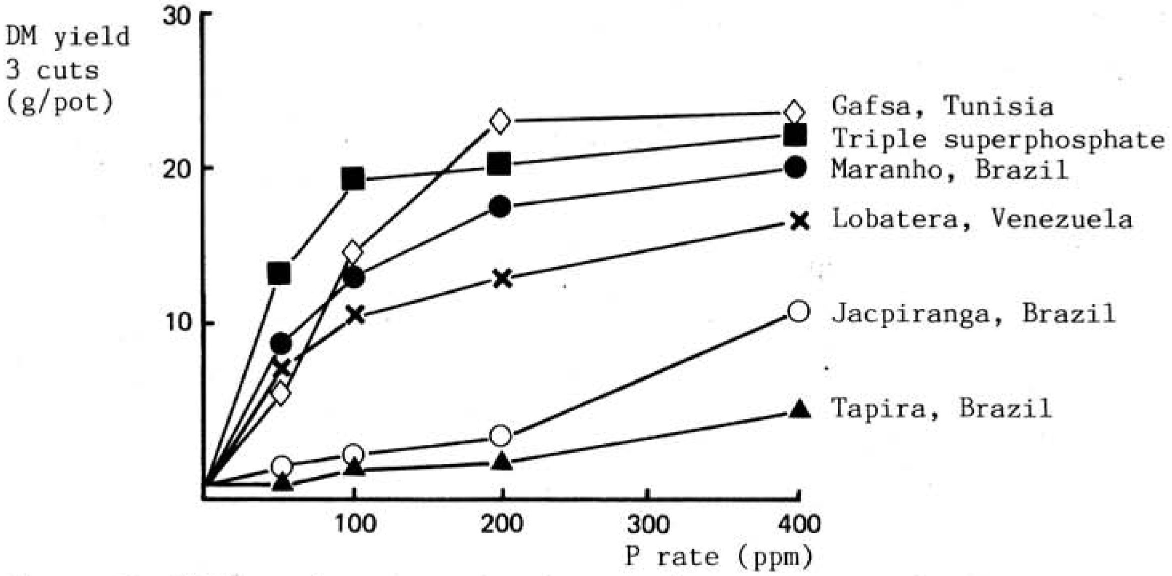

Figure 10 Effect of various phosphate rocks on maize production in a greenhouse experiment. Source: adapted from IFDC (1981)

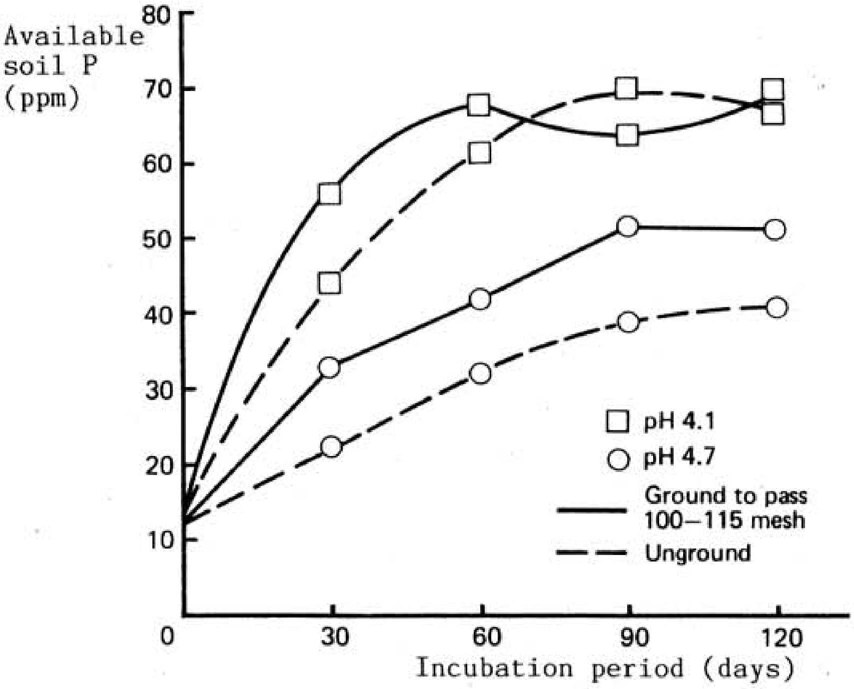

Figure 11 Effects of reaction time, soil pH and particle size on availability (Bray I extractable P) of North Carolina rock phosphate applied at a rate of 222 ppm to a Hyde soil. Source: Barnes and Kamprath (1975)

broadcast application as well as by fine grinding. The effectiveness of rock phosphate can also often be enhanced by application together with potassium chloride.

Because rock phosphates are slow acting sources of P, it is often advisable, especially for short growth period crops, to combine a broadcast, basal dressing of rock phosphate with a small "starter" application of quick acting, water soluble P placed in bands or pockets along the rows of plants.

(ii) Basic slag. Basic slag, also known as Thomas slag, is a by-product of steel making. Different basic slags contain 10 to 22% P_2O_5 in rather complex water insoluble form and 30 to 50% CaO. They also often contain trace elements such as Zn, Cu, Fe and Mn. Basic slag is an excellent P and Ca source for acid tropical soils but supplies are now very limited.

(iii) Fused magnesium phosphate. Fused magnesium phosphate is obtained by heating a mixture of rock phosphate with olivine or serpentine (magnesium silicate minerals) at a temperature of about 1550°C. The finely ground product contains 10 to 15% MgO and 22 to 26% P_2O_5 of which 90% is citric-acid soluble. As for rock phosphate and basic slag, optimum efficiency is obtained by application methods that maximise soil contact, i.e. uniform broadcast application and thoroug incorporation in the soil.

(iv) Water soluble P fertilizers. The main fertilizers containing water-soluble P are single and triple superphosphate and mono- and diammonium phosphates. In contrast to water insoluble sources of P the efficiency of water soluble P fertilizers is increased, especially in P fixing soils, by minimising soil contact, so reducing the rate of reaction of P with Fe and Al compounds. Presence of organic matter also helps to keep applied water soluble P in plant-available form.

If only small quantities of water soluble P fertilizer are available they should be placed in bands or pockets near the seeds or plants. On soils extremely low in available P, however, such application methods may restrict root development to the limited soil volume enriched with fresh P fertilizer, in turn restricting efficient utilisation of other soil nutrients and of water. In such cases a single large application (500 to 1000 kg/ha) of broadcast P fertilizer, preferably in the form of reactive rock phosphate, should be applied initially to improve overall soil P status.

4.5 POTASSIUM

4.5.1 Potassium and liming

Although most acid soils in the tropics have very low total and available K contents this nutrient rarely limits crop yields in virgin soils. K becomes a very important factor, however, once acid soils are improved by liming and P application and are used for intensive crop production.

Soil K status is influenced in several ways by liming and pH. Low soil pH enhances weathering and release of K from primary as well as secondary soil minerals and in the course of time results in loss of a large part of the original soil K by leaching. Leaching is promoted by the predominance in highly weathered, acid tropical soils of 1:1 layer silicate clays such as kaolinite which do not fix significant quantities of K. According to Mitra et al. (1958) pure bentonite (a member of the montmorillonitic group) can fix 10.0 me of K per 100g soil, illite can fix 10.9 me and kaolinite only 0.33 me. The increase in effective CEC brought about by liming many acid tropical soils helps to reduce leaching loss of K.

The effect of liming on K nutrition of plants is affected by rate of lime application. Small quantities of lime (100 to 300 kg/ha $CaCO_3$ equivalent) often stimulate root growth (especially where Ca is deficient) and thus increase K uptake. Larger quantities, however, often depress K uptake, for several reasons. Raising the pH by liming soils containing pH dependent surface charge minerals increases the CEC and thus increases the capacity of the soil to adsorb K^+; as a result, if no additional K is applied the K^+ concentration in the soil solution decreases. Since diffusion in the soil solution is the major mechanism by which K reaches plant roots the decrease in concentration adversely affects K uptake. Furthermore, liming increases the Ca^{++} concentration in the soil solution, which also depresses K uptake. Liming also increases the number of K selective sorption sites, which at lower pH would be occupied by Al hydroxy polymers (Kemmler, 1980). Liming to correct soil acidity can thus decrease availability and uptake of K, often to such an extent that unless extra K is applied the beneficial effects of liming are negated.

4.5.2 Measuring potassium availability

The most common way of assessing soil K availability is to measure exchangeable K plus the small amount in the soil solution. Many extractants have been used (Barber *et al*. 1971), but perhaps the most usual is N ammonium acetate adjusted to pH 7.0.

Soil solution K has been proposed as a measure of available K, since it is from this source that plants take up K. However, soil solution K is not a good guide without reference also to exchangeable K and the quantity/intensity relationship involved has been discussed by Koch *et al*. (1970).

For the intensive weathering conditions encountered in tropical soils a measure of 'reserve K' or 'slowly available K' can be very helpful. The most common extraction procedure is by boiling for 10 minutes in N nitric acid (Wood and de Turk, 1941). The amounts of K so extracted are comparable to the removal by 8 to 15 successive crops.

Electro-ultrafiltration (Nemeth, 1979, 1982) is so far the only method that may provide information on soil solution K, exchangeable K and reserve K, and on K fixation and buffering.

Measurements of exchangeable K alone, without information on the type and quantity of clay minerals and thus the soil's K buffering capacity (the amounts of K that the soil can adsorb and fix and that it can release into the soil solution), are of limited value (Mengel and Kirkby, 1982). The effect of clay mineral type on soil solution K concentrations at different exchangeable K levels is shown in Figure 12; K in the soil solution increased much more rapidly with increasing exchangeable K in the Oxisol (Ferralsol), in which the clay was mainly kaolinitic, than in the Alfisol in which K-fixing illitic clay predominated. The effect of clay content on the relation between exchangeable K and soil solution K is shown in Figure 13; the amount of K needed to raise K in the soil solution is much larger in the soil with the higher clay content and therefore the higher CEC.

A suggested classification of ammonium acetate extractable K values in Oxisols (Ferralsols) and Ultisols (Acrisols) of different texture classes is given in Table 6.

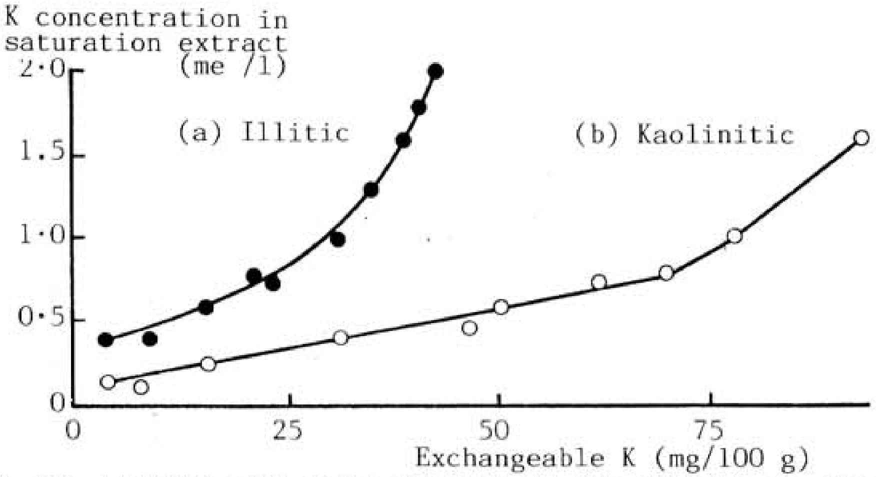

Figure 12 Changes in K concentration of the saturation extract with increasing exchangeable K in an Oxisol with 38% kaolinitic clay and an Alfisol with 39% illitic clay
Source: Nemeth (1971)

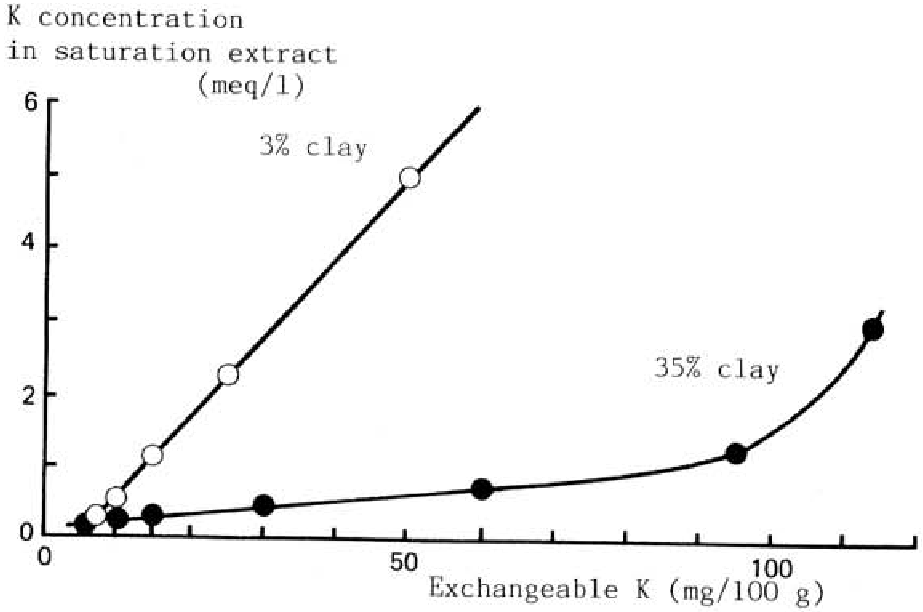

Figure 13 Effect of increasing exchangeable K on K concentration in the soil solution in two soils of contrasting clay content
Source: Grimme et al. (1971)

Table 6 SUGGESTED "CRITICAL" VALUES FOR N AMMONIUM ACETATE EXTRACTABLE K IN OXISOLS (FERRALSOLS) AND ULTISOLS (ACRISOLS) (me K PER 100 g SOIL)

K status	Soil Texture Sands and silty sands	 Loamy sands to sandy loams	 Clay loams
Deficient	0.08	0.08-0.15	<0.15
Low	0.08-0.15	0.16-0.25	<0.25
Adequate	0.15-0.25	0.25-0.35	<0.35
High	>0.25	>0.35	<0.5

Definition of K status:

Deficient: crop response to K very likely.
Low: response to K likely; K requirements increase with increasing yield.
Adequate: K application needed for maintenance only.
High: no K required for some years.

4.5.3 Application methods

Most acid soils have a very low effective CEC and their predominant clay minerals do not fix large amounts of K. The availability of applied K in such soils is therefore usually good, but it also follows that leaching losses can be high. Application techniques must take this into account; leaching losses can be minimised if K is broadcast over the entire cropped area, whereas banding of K or application in pockets can result in severe losses.

4.5.4 Sources of potassium

In contrast to P there are very few widely used types of K fertilizer; indeed, except for chloride-sensitive crops such as tobacco, pineapples and tomatoes, potassium chloride (muriate of potash) is the only important source of K. Potassium sulphate is the usual choice for chloride-sensitive crops and may increasingly be used for areas found to be deficient in both K and S; it can also be a more effective source of K where there is risk of leaching losses (Uehara and Keng, 1975).

4.6 MAGNESIUM

Magnesium is readily leached, particularly from highly weathered acid soils such as Oxisols (Acrisols); these soils often have a very low available Mg content and respond well to application of Mg fertilizers (Mikkelsen *et al*., 1963). One facet of Al toxicity is that it can induce Mg deficiency (Plate 3) and in addition to its direct nutrient effect applying Mg can help to reduce Al toxicity (Grimme, 1983, 1984). Where dolomitic limestone is not available as an Mg source the incidence of Al toxicity can be reduced by applying Mg as kieserite (magnesium sulphate) together with P fertilizer.

Lombin and Fayemi (1975) suggested that a value below 10% for the Mg saturation of the effective CEC is a useful indicator of potential Mg deficiency. The incidence of Mg deficiency is, however, influenced by other

Plate 3 A maize plant growing on a very acid Ultisol (Acrisol) in West Sumatra, Indonesia and showing Al-induced symptoms of Mg deficiency

Plate 4 Zn deficiency in cassava as a consequence of heavy liming and phosphate fertilizer application to an Ultisol (Acrisol) in northeast Thailand

factors such as the application of ammonium N or K fertilizers, which can induce it on soils of marginal Mg status. Plant species also vary in their sensitivity to Mg deficiency; tree crops as a group are more sensitive than annual crops and annual dicotyledons more sensitive than annual monocotyledons. Cultivars or clones of the same species can differ widely in their ability to utilise both soil and fertilizer Mg.

4.7 SULPHUR

4.7.1 Sulphur deficiency

Sulphur deficiency is rarely a primary constraint in acid tropical soils but can readily become a problem once they are brought into intensive cropping systems. The increase in use of S in fertilizers in Indonesia in the period from 1967 to 1979 is shown, together with the increasing N consumption, in Figure 14. Similar trends can be observed in many tropical countries and S deficiency is now recognised to be widespread in intensive cropping systems (IFDC, 1980; Probert and Samosir, 1983).

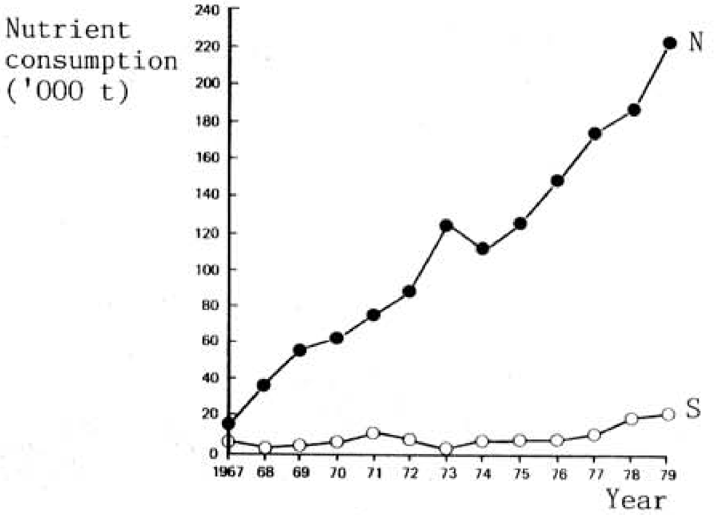

Figure 14 Fertilizer N and S consumption on food crops in Indonesia 1967-1979. Source: IFDC (1980)

Some of the reasons for the incidence of S deficiency in tropical soils are as follows:

(i) Many tropical soils have much lower total and available S contents than temperate soils (Neptune *et al*., 1975).

(ii) Burning the vegetation during land clearance depletes soil S reserves by releasing large amounts to the atmosphere.

(iii) Loss of organic matter as a result of cultivation is accompanied by volatile or leaching loss of S.

(iv) Acid soils containing large amounts of Al and Fe oxides adsorb much S (Fox *et al*., 1971), but this adsorption is pH dependent and the adsorbed S is also readily displaced by phosphate ions (Kamprath *et al*., 1956).

(v) SO_4^{2-} is readily lost from the Ap horizon of acid soils which have been limed and received dressings of P fertilizer (Kamprath _et al_., 1983).

(vi) The reduction in the use of S-containing fertilizers (ammonium sulphate, single superphosphate) in favour of more concentrated fertilizers containing little or no S (urea, triple superphosphate, diammonium phosphate) is likely eventually to lead to serious S depletion in many soils.

Sulphur deficiency is frequently encountered in areas with distinct seasonal rainfall distribution patterns (Fox _et al_., 1983). It is therefore more frequently observed in savanna zones, where the vegetation is frequently burned, than in soils under rain forest.

So far no soil test for plant-available S has gained wide acceptance (Asher et al., 1983) mainly because the chemistry of soil S is rather involved. Calcium phosphate solutions are the most commonly used extractants, P effectively displacing S from the exchange complex (Blair _et al_., 1980).

According to Kamprath and Till (1983) 5 to 7 ppm S is needed in the soil solution of highly weathered soils to enable most crops to make good growth. Crops differ widely, however, in their S requirements; oilseeds, grain legumes and cotton have high S requirements, whereas pineapples, cassava and sweet potato are relatively undemanding.

4.7.2 Sources of sulphur

Elemental S, gypsum and S-containing fertilizers are all effective S sources, though elemental S has a strong acidifying effect. Choice therefore depends mainly on price and availability, but the fact that elemental S (often the cheapest) frequently needs to be accompanied by liming should be taken into account.

4.8 TRACE ELEMENTS

The availability of most trace elements increases with falling pH and in their natural state few acid tropical soils suffer seriously from trace element deficiencies. For several trace elements (B and Zn in particular) total content is, however, often rather low and applications of lime and some fertilizers can reduce their availability and induce severe deficiencies (Plate 4). For example, Juo and Uzu (1977) showed that liming two Ultisols (Acrisols) in southern Nigeria to pH above 6.2 and 5.6 respectively reduced Mn and Zn uptake by maize and reduced yield considerably. Lopez (1980) reported that heavy liming of highly weathered low CEC soils reduced the availability of trace elements and K, and seemed to have more deleterious than beneficial effects. Careful use of lime and good organic matter management are the most important factors in avoiding or minimising trace element problems. The subject has been reviewed in detail by Drossdorf (1972).

4.9 NITROGEN

4.9.1 Soil nitrogen status

When first cultivated, most acid upland soils in the humid tropics are endowed with a large supply of nitrogen but a relatively low yield potential, set by low pH, toxicities and nutrient deficiencies. Good management in the first years of cropping, including liming, P application and the correction of other deficiencies, should overcome these constraints on yield but at the same time the supply of N from organic matter falls steadily. The inverse relationship between soil N supply and N requirement for maximum yield is shown in Figure 15. There is thus no need for supplementary N in the early years of cultivation, but response to an N input from fertilizer or other sources develops after two years or so.

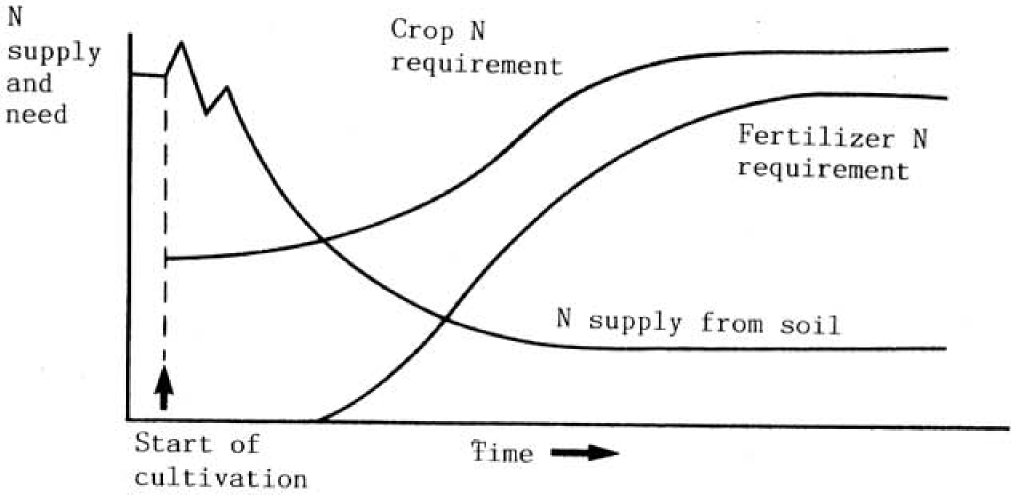

Figure 15 N supply and N requirements as functions of time after transition from forest to agriculture

Similar relationships have been found in land use systems based on shifting cultivation, where N supplies are often more than sufficient to meet crop yield potential (Bouldin et al., 1980). Nye and Greenland (1960) also found in Africa that total mineralisation of N in the first two years of cultivation after ten or more years fallow exceeded crop uptake of N by a considerable margin; N requirements increased with time as toxicities and deficiencies were overcome.

Fertilizer N is only one of the supplementary sources of this nutrient that can be used to provide an adequate N supply to acid soils after initial improvement. The N supply to crops can also be enhanced by effective recycling of N from soil organic matter and by encouraging biological N fixation; both these sources may provide N more cheaply than inorganic fertilizers.

4.9.2 Biological nitrogen fixation (BNF)

Traditional agriculture largely, if not entirely, depends on biological N fixation and globally more N is obtained from BNF than from synthetic fixation for fertilizer production. BNF has an important part to play in the successful development of agriculture on acid soils in the tropics for two reasons:

(i) The infrastructure in most newly developed areas is usually poor and N fertilizer may not be available in sufficient quantity and at the right time.

(ii) N fertilizer prices may be high in relation to the prices received by farmers for their products.

It is unlikely, however, that BNF as currently understood will ever supply sufficient N for the needs of high yielding crops, though it may enable worthwhile economies to be made in fertilizer use.

Nitrogen may be fixed symbiotically or by free-living soil bacteria. *Azotobacter* and other free-living species are present and fix nitrogen in many soils. Experience in temperate regions suggests that the amounts fixed may be 10 to 20 kg/ha N per annum. It is now suggested that non-symbiotic N fixation in tropical soils is greater than has previously been accepted (Neyra and Dobereiner, 1977; App et al., 1980) but few quantitative data are available on how much N can be fixed in different cropping systems and in different soils. It is known, however, that many acid soils do not have populations of N-fixing bacteria and it has been widely but not universally found that the use of bacterial inoculants, perhaps associated with liming, can increase yields.

Symbiotic N fixation in upland acid tropical soils is mainly due to legume/*rhizobium* associations. The benefit is therefore confined to leguminous crops and to following crops which may benefit from the enhancement of soil N status when legume and bacterial biomass is broken down. Estimates of the amount of N fixed range from less than 100 to over 600 kg/ha per annum (Graham and Hubbell, 1977).

There are a number of *Rhizobium* species and strains within species, and for symbiotic nitrogen fixation to take place the *Rhizobium* strain and the legume must be compatible. Some legume species, e.g. *Glycine max* and *Leucaena* spp, are highly strain-specific; others are less so e.g. *Desmodium*, *Centrosema* and *Stylosanthes* spp; and *Arachis*, *Cajanus*, *Crotalaria*, *Calopogonium*, *Mucuna*, *Pueraria* and *Vigna* are compatible with an even wider range of strains. Many soils contain *Rhizobium* inoculum but there are also many others in which the necessary *Rhizobium* species or strain is absent or ineffective. The practice of seed inoculation with suitable rhizobial strains shows much promise in ensuring that the potential for symbiotic N fixation is achieved.

As with higher plants, rhizobial strains differ in their tolerance to low soil pH. The critical soil pH range appears to be between 4.3 and 4.9 (Morales et al., 1973) and liming soils with pH below 5 enhances N fixation. Nutrient deficiencies can limit symbiotic N fixation, especially P and to a smaller extent K. Mo deficiency is often a problem in soils with pH below 5.5.

4.9.3 Nitrogen fertilizers

In terms of suitability for use on acid upland tropical soils, N fertilizers differ in the form of N present - NH_4, NO_3 or urea N - in the associated ions which may or may not provide other plant nutrients and in their effect on soil pH.

Ammonium nutrition results in plants taking up more cations than anions; they respond to this by excreting H^+ ions which lower the pH at the root surface. This fall can intensify the problems associated with low pH, so that nitrate N is often a better form than ammonium N on acid soils.

The N sources of practical significance are urea, ammonium sulphate, ammonium chloride, calcium ammonium nitrate and ammonium phosphates. Urea is the most widely used but requires care in application to minimise loss of N by volatilisation in the form of ammonia. Urea should be incorporated in the soil rather than left on the surface or should be applied at a time when subsequent rainfall will rapidly carry it into the soil.

Ammonium sulphate, although rather expensive and having a strongly acidifying effect, can have a specific role as a supplier of S. Also, its application shortly after liming can help to move Ca down the soil profile.

5 MANAGEMENT OF ACID TROPICAL SOILS

5.1 THE PROBLEMS

The productivity of acid upland soils in the humid tropics is limited by physical and chemical constraints, but climatic constraints are usually unimportant. Successful and permanent use of these soils for crop production largely depends on the identification and correction of the limiting soil factors.

Because of the widespread and multiple nature of the problems, these soils have so far been little used for agriculture. Only when most, if not all, of the constraints are alleviated at the same time and all factors are in proper balance can good and lasting results be expected. The high prevailing temperatures and the resulting rapid chemical, physical and biological processes mean that the penalties paid for imbalances in the solid, liquid and gaseous phases of the soil are much larger than in temperate regions. The problems in acid upland tropical soils can be solved and consistently high yields obtained only by the development and introduction of comprehensive management packages.

To obtain high yields, reduce climatic risks and use soil and fertilizer nutrients effectively the soil physical and chemical environment must be modified in a number of ways: extremes of soil temperature and moisture content must be avoided; subsoil conditions should be altered so as to encourage rooting therein, by correcting pH, providing adequate P and if necessary increasing subsoil CEC; improvements in surface and subsurface drainage may be necessary; organic matter must be conserved. The improvements needed will often only be possible over a period of years.

The management package adopted should have as objective the attainment of improved, non-limiting soil conditions and should enable these conditions to be fully exploited. It should therefore comprise land clearance, conservation of organic matter, drainage, liming, correct fertilizer application, choice of suitable crops and cultivars, and suitable cultivations and cultural operations.

5.2 LAND CLEARING

5.2.1 Effects of forest clearing

A high proportion of the acid soils in the tropics are still under forest cover. The method of land clearing has a strong influence on initial crop performance, subsequent management needs and crop response to management inputs.

Effective root growth in most plants in natural rain forest is limited to the topsoil. There can be considerable root growth in the A_1 horizon and as the ground surface remains shaded, moist, and cool most of the time roots may well grow actively in the organic horizons above the mineral soil. Large amounts of nutrients are rapidly cycled around the plant/soil system and a high proportion of them may be taken up again by the vegetation without coming into close contact with the mineral soil. As most nutrients are taken up directly in this way from decomposing organic matter, the forest vegetation depends very little on the subsoil as a source of nutrients, provided conditions favourable for root growth are maintained in the topsoil. It is therefore important to provide soil cover to keep the topsoil as cool and moist as possible and to avoid soil compaction.

Plate 5 Loss of topsoil where an Ultisol (Acrisol) in West Sumatra, Indonesia, has been mechanically cleared and burned. Without lime, fertilizer and protective mulch crop growth is very poor

Plate 6 Exposed topsoil of an Ultisol (Acrisol) in Sumatra, Indonesia, after mechanical clearance and burning. The very infertile soil is directly exposed to solar radiation and to rainfall

When forest is cleared by cutting and burning many soil properties are adversely affected (Table 7). The immediate results of the operations associated with clearing are an increase in soil pH, base saturation and soil nutrient status by the transfer of nutrients from forest vegetation to soil; a very irregular spatial distribution of nutrients as a result of burning, stacking and reburning the biomass; localised irreversible dehydration of soil colloids where the soil surface is exposed to high temperatures during burning; and a rapid decrease in microbial acitivity due to partial sterilisation by burning, followed by a short flush of activity and then a gradual decline in microbial populations.

Table 7 SOIL CHANGES CAUSED BY CUTTING AND BURNING FOREST

Soil property	Before clearing	After clearing
Surface temperature	Uniform, 24-28°C	Large variation, 23-52°C
Surface moisture	Uniformly moist	Extreme variation
Leaching and surface erosion potential	Minimal	High to severe
Microbiological activity	High	Low--very high-- very low
Soil structure	Stable	Variable
Nutrient cycle	Closed	Broken
Organic matter cycle	Closed	Broken
Organic matter content	Constant	Declining
CO_2 production and release from soil surface	High and uniform	Low and irregular

Source: von Uexkull (1982)

Sanchez (1980) pointed out that biomass production by rain forests was related more to soil physical properties than to chemical and plant nutrient aspects. When the forest is cleared, crop productivity is initially and temporarily related more to chemical than physical parameters, but under continuous intensive cropping the relationship is again reversed and soil physical parameters become the main constraints.

Organic matter, more than any other single factor, is responsible for the good physical soil conditions that prevail under a rain forest and that are seriously at risk when it is cleared.

5.2.2 Clearing methods

There is much evidence to show that manual clearing gives better results than mechanical clearing (North Carolina State University, 1973, 1974, 1976/7). This is particularly true for Ultisols (Acrisols) which are prone to compaction by vehicular traffic. The use of bulldozers for land clearing can be justified only in areas where labour is scarce or expensive and on soils where destruction or disturbance of the topsoil and compaction of the subsoil are of minor concern.

The standard practice for land clearing is to slash the undergrowth, fell the large trees, burn, cut, stack and reburn. Burning has the advantages of being fast and of returning most of the nutrients contained in the burned biomass immediately to the soil. N and S are the exceptions. In Alfisols (Luvisols) in Ghana ash from the burned forest vegetation contributed 1.5 to 3 t/ha of Ca, 180 kg/ha of Mg and 600 to 800 kg/ha of K (Nye and Greenland, 1964), but forests grown on low base status, acid Oxisols (Ferralsols) and Ultisols (Acrisols) contain much smaller quantities of nutrients. According to Sanchez (1976) burning forest biomass on Ultisols and Oxisols contributed 275 to 600 kg/ha Ca, 30 to 80 kg/ha Mg and 90 to 240 kg/ha of K, enough to change the topsoil from Al-toxic to non-toxic and nutrient sufficient. On Oxisols and Ultisols, however, this effect is usually very short lived. Within one or two years the soil nutrient concentrations revert to pre-burning levels with the significant difference that most of the fertility contained in the original above-ground forest biomass has been lost (Sanchez, 1976).

Burning removes the soil cover and exposes the soil for some time to solar heat and to raindrops. Heavy rainfall after burning but before a new canopy has been formed by newly planted crops can result in very severe erosion and irreparable loss of soil and soil fertility (Plates 5 and 6). Burning also gives a very uneven spatial distribution of ash and nutrients with consequent uneven crop growth (Plate 7).

In the process of burning most of the foliage and branches of the trees and much of the mulch layer on top of the soil are destroyed, leaving the exposed mineral soil and the charred, carbonised, and sterilised trunks of the large trees. The process of burning usually results in the loss of the parts of the forest biomass which might usefully be retained. the only parts which are not destroyed being the larger tree trunks, whose presence is often an embarrassment. Compaction by bulldozers used to remove the stumps and tree trunks adds to the damage. The resulting soil has many chemical and physical defects limiting crop yield and response to fertilizer.

5.2.3 Zero-burn techniques

Zero-burn techniques are currently used in oil palm development projects in high rainfall areas of Papua New Guinea where burning is difficult (Bruere, 1982, personal communication). Von Uexkull (1984) suggested land clearing techniques aimed at minimum disturbance of the soil and a smooth transition from forest to agricultural use with maximum preservation of organic matter. The following sequence for zero-burn land clearing is suggested:

(i) Cut the underbrush at the start of the rainy season, so that it remains moist.

(ii) Stack the cut underbrush to allow access to the land.

(iii) Plant cover crops while the large trees are still standing. Large seeded legumes such as *Mucuna utilis* or *Phosphocarpus palustris* are most suitable, but cuttings of *Pueraria triloba* or *Calopogonium caeruleum* can also give good results. The winged bean *(Psophocarpus teragonolobus* L.) is a good cover crop which also provides food.

(iv) Spread 100 to 200 kg/ha of rock phosphate along the rows where the cover crop is being planted or sown.

(v) Ring-bark (girdle) and poison the large trees. Poisoning traps the moisture in the tree trunks and thus promotes rapid decomposition. The herbicide 2,4,5-T has been widely used as an arboricide in the past, but Triclopyr (DOWCO 233) is now considered safer.

Plate 7 Poor growth of sugarcane where the topsoil has been lost from an Ultisol (Acrisol) in Sumatra, Indonesia. The crop in the foreground received the same fertilizer (160-210-180 kg/ha N-P_2O_5-K_2O) as that in the background

Plate 8 Slash and burn farming by an experienced farmer on an Ultisol (Acrisol) in eastern Kalimantan, Indonesia. Not all trees have been felled and tree stumps are high to encourage regrowth of forest

(vi) Fell the trees when the canopy starts to die, without waiting too long, since if the trees are left standing the dead branches rapidly become very brittle and whole trees may collapse.

(vii) Before the large trees are poisoned and felled, the cover crop must be well established so that it rapidly covers the felled tree trunks and branches.

After about two years under the cover crop, all wood except the trunks of some hardwood trees will have decayed, and the soil will be covered by a thick layer of organic mulch. The cover crop, planted before the large trees are removed, takes over the following fertility-maintaining functions of the rain forest:

(i) Shading the soil and keeping it cool and protected.

(ii) Fixing up to 350 kg/ha per year of atmospheric N, which is needed for rapid microbial decompositon of the dead wood. Zero burning works best when the cover crop is vigorous and productive.

(iii) Covering the logs and thereby preventing them from becoming a breeding ground for black beetles *(Oryctes* spp.).

(iv) Preventing weed infestation, especially by grasses such as *Imperata cylindrica*.

(v) Stimulating the activity of various soil organisms including earthworms, so improving the chemical and physical properties of the subsoil.

(vi) Helping to maintain soil CEC and reduce leaching losses of nutrients.

Zero-burning is presently recommended for Ultisols (Acrisols). Oxisols (Ferralsols) and Andosols have excellent physical properties and the conservation of organic matter is less essential than in Ultisols but burning is nevertheless the preferred technique.

5.3 ORGANIC MATTER MANAGEMENT

The organic matter content of most acid tropical soils under forest vegetation is low and concentrated in and on top of the soil; the cycle of organic matter formation and decomposition is rapid. When these soils are brought into cultivation it is important to retain as much organic matter as possible and usually best to simulate forest conditions by forming a surface mulch.

5.3.1 Mulching

A good surface mulch protects the soil against the direct impact of raindrops and lowers the potential for erosion and surface crust formation, at the same time reducing evaporation losses and increasing water infiltration rate. A mulch layer reduces the impact of drought but during wet periods it may depress crop yields by increasing disease incidence because of high humidity at the base of the plant. In wet locations or during wet seasons strips 10 to 20 cm wide along the rows of crop plants may give better disease control.

Mulching protects the soil from direct solar radiation, thus preventing high soil surface temperatures, provides a source of nutrients which pass into the topsoil and minimises tillage needs.

Plate 9 A heavy application of organic manure in the People's Republic of China

Plate 10 A vigorous 7 year old stand of rubber on an Ultisol (Acrisol) in Sumatra, Indonesia, with a healthy inter-row cover crop of *Calopogonium caeruleum*

5.3.2 Incorporation of organic matter

Although the incorporation of compost or organic manure is standard practice in temperate agriculture, this procedure is only recommended in the humid tropics if the mineral component of the organic material is large enough to significantly raise soil pH. For example, incorporating filter mud from sugarcane mills, which has a high Ca content, can be effective in improving the soil environment and promoting root development.

5.4 TILLAGE, SUBSOILING, AND DRAINAGE

The purpose of tillage is normally to control weeds and create desirable physical soil conditions for crop growth. It may also, however, increase soil susceptibility to compaction. Because of the structural instability of Ultisols (Acrisols) zero tillage and controlled traffic are recommended for these soils, especially on steep slopes and in areas with periods of intense rainfall.

Subsoiling can be beneficial for Ultisols (Acrisols), especially after some years of continued cultivation but usually brings few benefits to Oxisols (Ferralsols) unless they have been compacted by heavy equipment. Deep tillage can have a pronounced effect when lime, fertilizer and organic matter are incorporated into the subsoil.

Surface drainage can be beneficial for Ultisols (Acrisols) in high rainfall areas to minimise problems during periods of high rainfall, when their topsoils may remain water-saturated for long periods, weakening or killing roots, causing loss of nitrogen by denitrification and impairing K uptake.

5.5 TOLERANCE OF SPECIES AND CULTIVARS TO LOW pH

Plant species and even different cultivars of the same species differ considerably in their tolerance to excess Al and Mn and to low levels of available P and other elements. One reason for the differences between cultivars in response to Al is the varying ability of plants to modify the pH of the soil-root interface (Mengel and Kirkby, 1982). Al tolerance can also depend on an Al exclusion mechanism. They cite evidence that the Al-tolerant wheat cultivar Atlas required 100 to 200 times more Al in the medium than the Al-sensitive cultivar Brenor before Al penetrated the plasmalemma of the meristematic root cells.

Crop species highly tolerant of low pH include pineapples, cassava and many graminaceous crops especially rice and sugarcane - though maize is an exception, all cultivars being sensitive to low pH. Many tropical legumes including *Calopogonium*, *Centrosema*, *Desmodium*, *Psophocarpus*, *Pueraria* and *Stylosanthes* species are very acid tolerant. Soybeans *(Glycine max)* are generally sensitive to low pH, but an increasing number of tolerant cultivars are available.

Some cultivars of crops that evolved in acid tropical soils are extremely sensitive to over-liming. Figure 16 illustrates differences in the reaction of two cassava cultivars to acid soil conditions and in their response to applied lime. Both cultivars responded well to a small dressing of lime, but while cultivar C 169 responded to increasing lime rates up to 6 t/ha cultivar C 87 gave virtually no yield where this rate of lime was applied.

In practice, therefore, it is always advisable to start with low rates of lime (0.3 to 1.0 t/ha) and relatively Al-tolerant crops and to increase the frequency and rates of lime as more demanding crops are grown and higher rates of fertilizer are introduced.

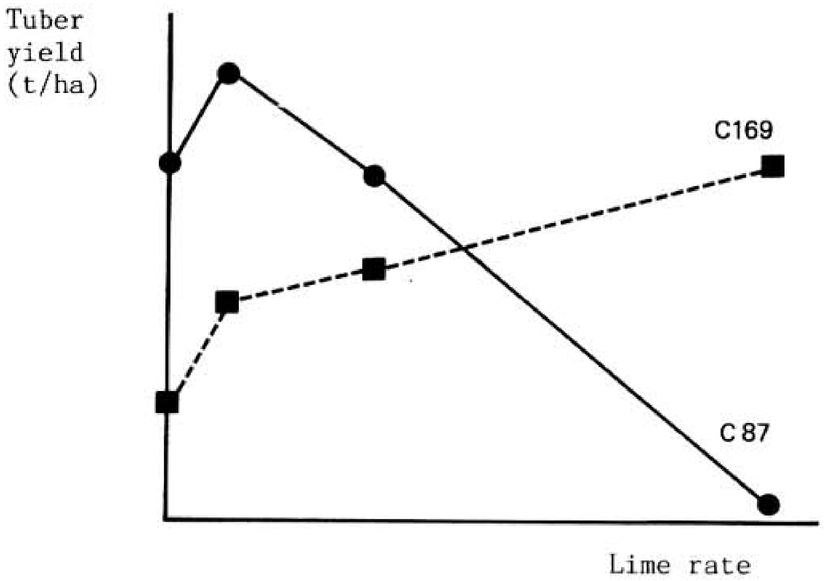

Figure 16 Differences in tolerance to low soil pH and in response to lime between two cassava cultivars. Source: Spain *et al*. (1975)

6 SOIL, CROP AND FERTILIZER MANAGEMENT SYSTEMS

6.1 CROPPING INTENSITY

In contrast to soils with high base saturation (mostly alluvial or young volcanic soils), acid upland tropical soils cannot sustain crop production for more than a few years without a continuous input of fertilizer. Fertilizers are used on high base status soils to supplement natural soil fertility, whereas on acid soils they quickly become the main support for crop production.

To maintain the productivity of acid tropical soils the amounts of nutrients supplied must exceed the removal of nutrients in successive crops. There is therefore no real 'low-cost' technology available for continuous cropping of these soils, though short term cropping (shifting cultivation) is possible, as described in section 6.2. Continuous cropping systems in which fertilizer use is integrated with biological nitrogen fixation or is used at high rates as the principal support for high yield levels are discussed in sections 6.3 and 6.4.

The importance of fertilizer and the costs involved in continuous cropping systems on acid soils requires that it should be used with maximum efficiency.

6.2 NO FERTILIZER INPUT: SHIFTING CULTIVATION

Shifting cultivation has been defined by Sanchez (1977) as a continuing agricultural system in which temporary clearings are cropped for shorter periods of years than the intervening periods of fallow. It is the predominant practice on almost half the potential arable land in the tropics and is at present the most frequently used management system for tropical acid soils. According to recent estimates (Dove, 1983), shifting cultivation is practiced by 240 to 300 million people.

Shifting cultivation makes use of the fertility accumulated in the primary or secondary forest vegetation and released after burning. According to Sanchez (1977) the large amounts of N and probably S still left in the topsoil of most acid tropical soils after burning, plus the large quantities of P, K, Ca, Mg and micronutrients added in the ash, are adequate for the first crop grown. The pH of the topsoil is temporarily raised and Al saturation is decreased.

Depending on the amount of nutrients released when the vegetation is burned and the quality of the soil, one to four crops may be obtained before the soil fails to support a reasonable yield. Generally, the yield of the second crop is about half that of the first. Application of fertilizer can prevent the rapid decline in yield (Figure 17), but shifting cultivation is usually practiced in areas with poor economies where fertilizer is expensive and often not readily available. Also, most farmers will avoid the use of costly fertilizer as long as sufficient new forest land is available as a relatively cheap source of short-term soil fertility.

Shifting cultivation can provide an efficient soil management system in subsistence agriculture, as long as population pressure is low and the people practicing it have sufficient experience of the system.

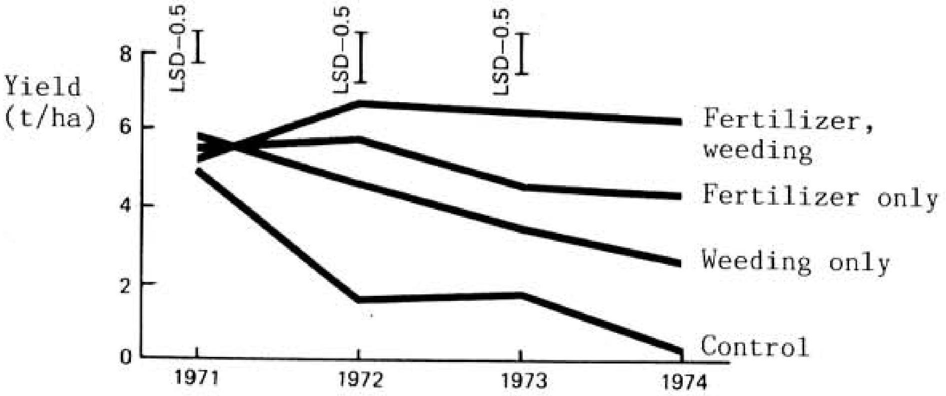

Figure 17 Effect of fertilizers and weeding on maize yield in southern Nigeria. Source: Moormann and Greenland (1980)

6.3 LOW FERTILIZER INPUT WITH LEGUME COVER CROPS

To maintain and improve soil fertility in the acid, low base status soils of the humid tropics at low levels of fertilizer and other input, the topsoil must be kept cool, moist, and shaded by mulching or by the leaf canopy of a crop. Von Uexkull (1982, 1984) suggested a low-cost management system based on the establishment of a leguminous cover crop and the adoption of a variant of shifting cultivation within the cover crop area. A good leguminous cover crop can contain 130 to 180 kg/ha N, 20 to 35 kg P_2O_5, 90 to 140 kg K_2O, 20 to 30 kg MgO and 50 to 90 kg CaO and is thus a valuable source of nutrients. The system is as follows:

(i) A suitable leguminous cover crop is established with the help of 500 to 1000 kg/ha of dolomitic limestone and 100 to 200 kg/ha of soft rock phosphate or triple superphosphate.

(ii) The soil is left under the cover crop for one or two years.

(iii) Strips of the cover crop are then killed by herbicide or by manual means and the dead plant material is left on the soil surface as mulch.

(iv) Under the mulch food crops such as maize,upland rice, cassava, soybean, peanut, and mung bean are planted, with zero or minimal tillage.

(v) To prevent damping off when the crop is sown during the wet season, the mulch close to the crop rows may be removed.

(vi) Fertilizer is limited to small maintenance applications of P, K and dolomitic limestone, N needs being met from biological fixation in the cover crop.

(vii) Weeding is confined to preventing the cover crop from spreading back into the cropped strips until about two weeks before harvest.

(viii) Once the cover crop has re-established itself in the strips from which the food crops have been harvested other strips are killed off and used for further cropping.

In such a system of 'shifting cultivation' or strip cropping up to 50% of the land area can be under food crops at any given time, with at least 50% under a recuperative cover crop (Figure 18).

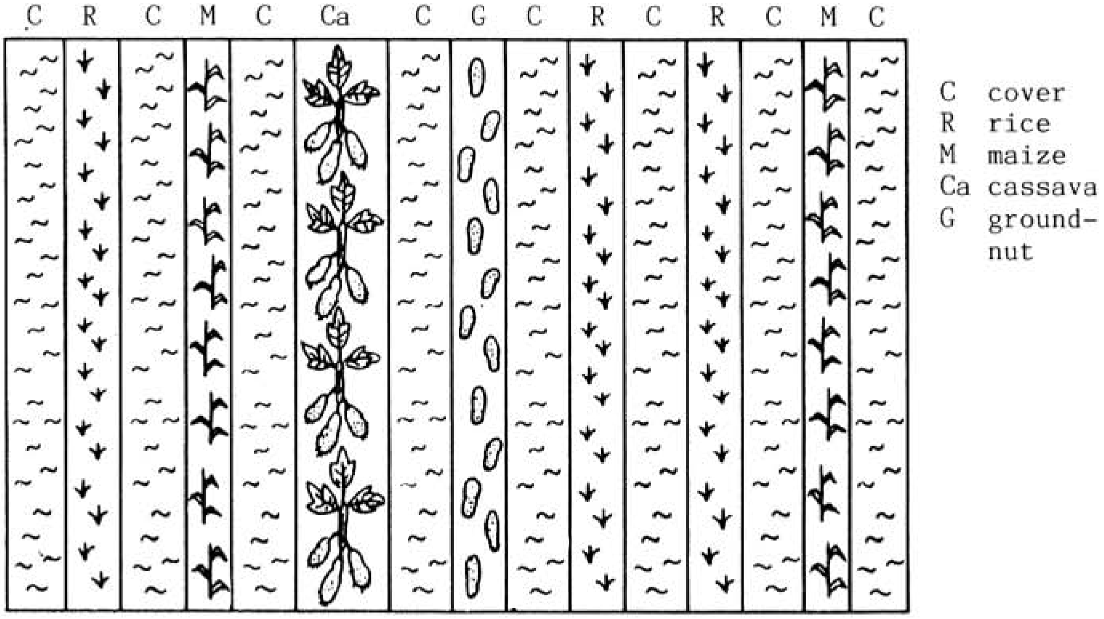

Figure 18 Suggested cropping system based on the alternation of food crops and cover crops. Source: von Uexkull (1984)

Strip cropping can make effective use of very low rates of fertilizer. For most food crops, 20 to 30 kg/ha of triple superphosphate, 20 to 30 kg of potassium chloride and 50 to 100 kg/ha of dolomitic limestone per crop are sufficient to give reasonable yields and maintain or improve soil fertility. N fertilizer is not usually required if the leguminous cover crop establishes well and has been growing for more than ten months.

Greater land use intensity than the strip cropping described above is possible where agronomic and economic factors favour it. However, most acid soils have very limited nutrient reserves so that any intensification of cropping immediately requires higher fertilizer inputs. Other fertility regenerating systems rely on low-growing and non-climbing legumes such as *Arachis prostrata* or *Desmodium* spp. as live mulch.

The agro-forestry technique known as alley cropping combines the soil restorative attributes of the bush fallow with arable cropping by growing arable crops and fast-growing perennial trees or shrubs side by side (Wijewardene and Waidyanatha, 1984). Leguminous trees or shrubs are established in rows 3 to 4 metres apart and at the time of seedbed preparation the trees are lopped. After removal of the woody material for use as fuel the green materials from the loppings are used in situ as a mulch and a source of nutrients (Figures 19, 20, 21).

Among the many tropical leguminous tree and shrub species, *Leucaena leucocephala*, *Gliricidia maculata*, *G. sepium*, *Cajanas cajan*, *Crotalaria lanceolata* and *Thephrosia candida* have been widely used. *L. leucocephala* has shown the most promise because of its fast growth, deep rooting, and high leaf N content. It has, however, the disadvantage of being sensitive to acid soil conditions and for quick establishment requires rather heavy liming. *Gliricidia* grows well on acid soils and can readily be established from cuttings but has the disadvantage of a shallow root system which competes with the interplanted food crops. It does, however, support the fixation of large amounts of N (Table 8).

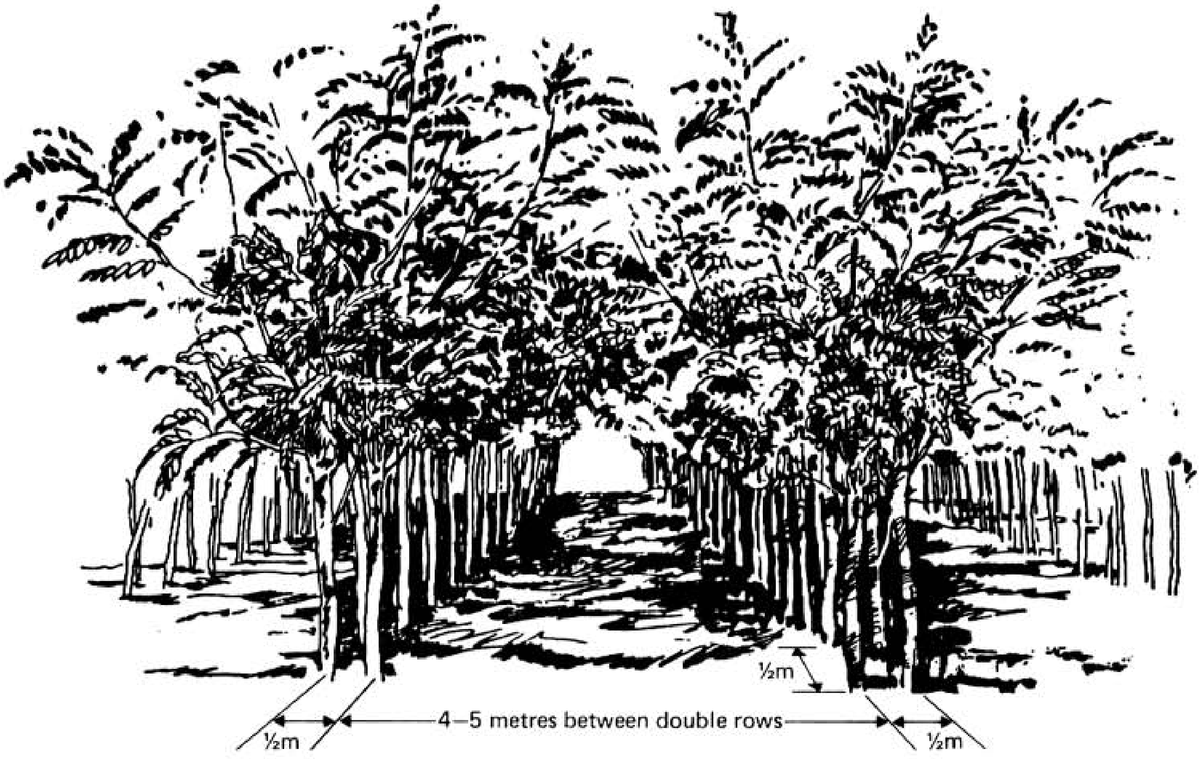

Figure 19 Double hedges of *Gliricidia* or *Leucaena* forming dense shade over the alleys during the dry (non-cropping) season. Source: IITA (1979–81)

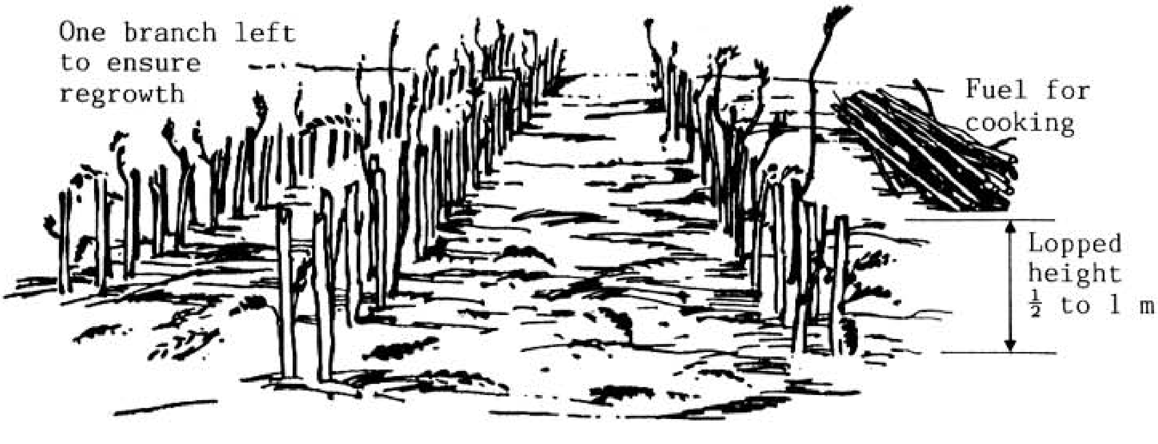

Figure 20 Hedgerows lopped and mulch laid in the alleys. Source: IITA (1979–81)

Figure 21 Crops growing in the alleys in light shade from the hedgerows which are lopped periodically during the growing season to provide further mulch and optimum light for the maturing crop. Source: IITA (1979-81)

Table 8 LEAF YIELDS AND ESTIMATED N CONTRIBUTIONS OF SHRUB LEGUMES AT CUTTING BACK AND FIRST PRUNING

Legume	Total dry weight (kg/ha)	N in dry matter %	N in dry matter kg/ha
Tephrosia candida	3453	3.8	131
Cajanus cajan	2312	3.6	83
Leucaena leucocephala	5595	4.2	234
Gliricidia sepium	6286	3.7	233

Source: adapted from IITA (1981)

The long-term effects of three different land management systems at three levels of N fertilizer are compared in Figure 22. Under live mulch yields were maintained at the original levels so that when maize was planted as the sixth consecutive crop, it yielded as much with no applied N fertilizer as under conventional tillage with 120 kg/ha N.

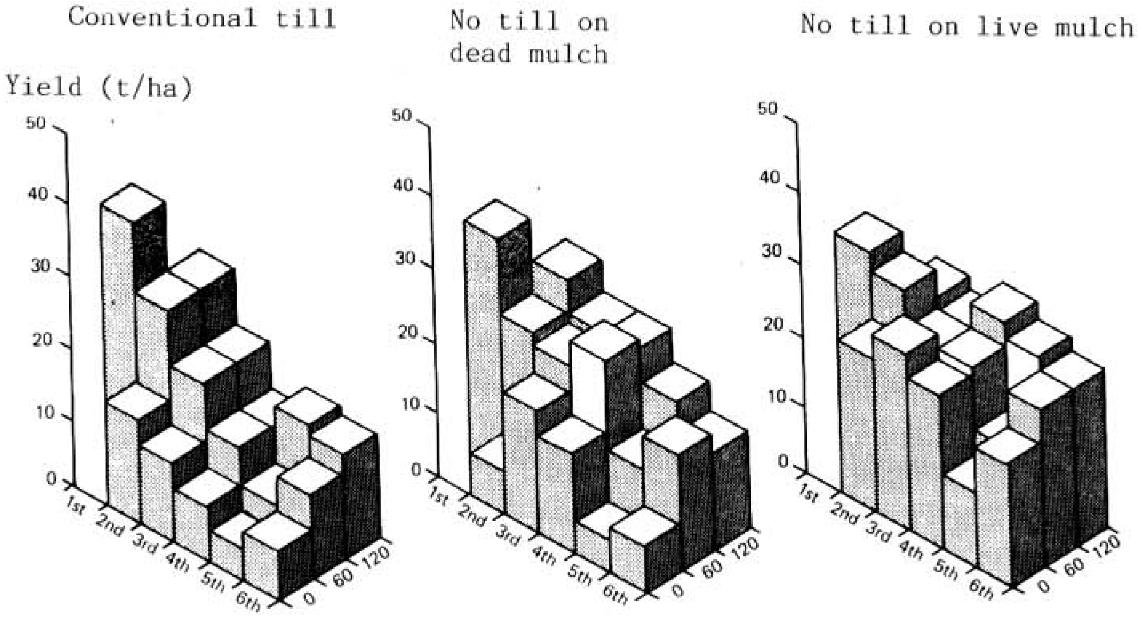

Figure 22 Effect on maize yields over six successive cropping seasons of three land management systems at 0, 60 and 120 kg/ha fertilizer N. Source: IITA (1979-81)

The effect of "simulated forest" (mulch from *Gliricidia* hedges) and fertilizer is shown in Table 9. With the shade and mulch from *Gliricidia*, the yield with NPK fertilizer was twice as high as the yield for the same treatment without shade and mulch. Equally remarkably, the yield under "simulated forest" conditions without fertilizer was higher than with NPK under conventional tillage.

6.4 CROPPING SYSTEMS WITH MEDIUM TO HIGH FERTILIZER INPUT

It is widely believed that continued cultivation degrades acid soils in the humid tropics, sometimes to such an extent that the degradation becomes irreversible (Friedman, 1977; Goodland and Irvin, 1975; Sioli, 1980). This is true for exploitive management systems without inputs, where the soil is frequently left for considerable periods without a protective crop canopy. Where sound soil management and fertilizer use are practiced, however, continuous cropping is entirely compatible with soil improvement (North Carolina State University, 1974, 1975, 1978, 1980, 1981; Sanchez et al., 1982; Sanchez et al., 1983; Villachia, 1978). Crop yields as a function of time, nutrient balance and changes in topsoil properties after eight years of continuous cultivation are shown in Tables 10 and 11.

Table 9 EFFECT OF "SIMULATED FOREST" AND FERTILIZER ON MAIZE YIELDS (KG/HA) OVER TWO YEARS IN SRI LANKA

Treatment	Loppings added	Grain yield	Loppings added	Grain yield
	1980		1981	
Simulated forest*				
No fertilizer	561	1373	2811	1561
60 N	-	-	3129	1921
60 N, 60 P, 60 K	579	3002	2963	2728
Without simulated forest				
No fertilizer	-	1163	-	680
60 N	-	-	-	1385
60 N, 60 P, 60 K	-	-	-	1354

* *Gliricidia* planted 5 m x 3 m, and maize grown in alleys between.
Source: Handewela (1983)

Table 10 BALANCE BETWEEN FERTILIZER ADDITIONS AND CROP UPTAKE OF NUTRIENTS OVER EIGHT YEARS (19 CROPS)

	N	P	K	Ca	Mg	Zn	Cu
				kg/ha			
Fertilizer additions	1480	850	1740	5235	289	11.0	15.0
Crop uptake	1916	279	1837	360	222	2.8	0.4
Balance	-436	571	- 97	4875	67	8.2	14.6

Source: Sanchez et al. (1983)

Reporting on changes in soil fertility after clearance of a tropical rain forest, over a period of eight years during which 37 crops of upland rice, 17 crops of maize, 24 crops of soybean and 10 crops of peanuts were monitored, Sanchez et al. (1983) concluded that ".... the long-term average annual grain production after the K-Mg imbalance and acidity constraints were overcome was 9.4 t/ha for the rice-soybean-peanut rotation. This compares well with annual grain yields of 1 to 2 t/ha, which farmers in the region normally obtain under shifting cultivation.

"Changes in topsoil chemical properties from prior to clearing to after eight years of continuous cultivation indicate a more favourable chemical environment in terms of soil acidity, base status, availability of most nutrients, and effective CEC. This is a direct consequence of the fertilizer and lime additions. The only negative aspects are a decrease in organic matter to an equilibrium level of 73% of the original and lack of an increase in exchangeable K.

"When continuous cultivation is attempted without complete fertilization, the absence of a vigorous crop canopy results in surface soil compaction and, thus, exposure to erosion. Continuous cultivation without proper fertilization and other appropriate agronomic practices is, therefore, likely to cause a deterioration of soil physical properties resulting in exceedingly low yields. Continuous cultivation with proper fertilization and other agronomic practices produces just the opposite results, improving chemical soil properties."

Similar results have been observed in the province of Lampung, Sumatra (Indonesia), where the P.T. Gunung Madu Sugar Plantation was established on an acid Ultisol (Acrisol) of very low fertility. As a result of continued heavy fertilizer application (138 to 160 kg/ha N, 210 to 270 kg/ha P_2O_5 and 180 to 240 kg/ha K_2O) the rooting depth of sugarcane increased from 15-25 cm initially to over 1.4 m after 10 years of cropping. Where cane yields originally ranged from 50-55 t/ha they now average over 80 t/ha with some fields yielding as much as 140 t/ha. Largely as a result of continued heavy P application combined with deep tillage there have been increases in subsoil pH, effective CEC and available P, whereas exchangeable Al has decreased. As a result of the above changes, rooting depth has increased, the cane has made more efficient use of soil moisture and has an increased capacity to use larger quantities of N and K fertilizer effectively.

Table 11 CHANGES IN TOPSOIL (0-15 CM) PROPERTIES AFTER EIGHT YEARS OF CONTINUOUS CROPPING AND 20 HARVESTS OF UPLAND RICE-CORN-SOYBEAN ROTATION WITH COMPLETE FERTILIZATION

Soil property (0-15 cm)	Before clearing (September 1972)	94 months after clearing (May 1980)	Significance
pH (1:1 water)	4.0	5.7	*
Organic matter, %	2.13	1.55	*
Exchangeable Al, cmol(+)/kg	2.27	0.06	*
Exchangeable Ca, cmol(+)/kg	0.26	4.98	*
Exchangeable Mg, cmol(+)/kg	0.15	0.35	*
Exchangeable K, cmol(+)/kg	0.10	0.11	NS
ECEC, cmol(+)/kg	2.78	5.51	*
Al saturation, %	82	1	*
Available P, mg/kg	5	39	*
Available Zn, mg/kg	1.5[a]	3.5	NS
Available Cu, mg/kg	0.9[a]	5.2	*
Available Fe, mg/kg	650	398	*
Available Mn, mg/kg	5.3[a]	1.5	*

* Significant at the 0.05 level or less.

[a] 30 months after clearing.

Source: Sanchez _et_ _al_. (1983).

7 CONCLUSION

Without doubt the acid soils of the humid tropics represent the largest land reserve available for meeting mankind's future needs for food, fibres and other plant products. A large proportion of these soils are at present still under virgin rain forest, but an increasing area is being used for shifting cultivation or has been abandoned to anthropic savanna. Low fertility and management problems associated with soil maintenance and improvement are the major obstacles to the efficient use of acid tropical soils for crop production. Climate and topography are generally favourable and seldom limit crop yields.

When cropped without proper management, most acid soils of the humid tropics deteriorate, chemically and physically, so quickly after clearing that after a few years no crop can be grown on them. However, with adequate inputs and proper care, the annual productivity of these soils can far exceed the productivity of most fertile soils in temperate regions, where insufficient rainfall or low temperatures limit production during parts of the year. Contrary to common belief, the productivity of these soils can be improved and continuous crop production is possible, provided they are managed correctly.

Any improvement in the fertility and productivity of these inherently poor acid soils is costly, because low or minimum input technology will not keep them permanently productive. Where population pressure is low, shifting cultivation is often still the most appropriate land use system. It is, however, an option that will not remain open for long, as increasing population pressure increases the demand for more effective use of the available land. The most promising approach is to develop and improve soil productivity in three stages:

(i) As much as possible of the original topsoil and biomass fertility should be retained through maximum conservation of organic matter.

(ii) Topsoil fertility should be maintained and improved by using regenerative systems depending on a fallow crop combined with small applications of lime and P. Organic matter is the mainstay of soil fertility in both these stages.

(iii) Subsoil problems - low pH, Al toxicity, P deficiency - should be dealt with by liming and P application. Furrow application of lime or the simultaneous application of lime with ammonium sulphate or potassium chloride promotes leaching of some of the Ca and Mg into the subsoil. Liming rates should be in the range 1 to 1.5 t/ha $CaCO_3$ and P application 40 to 80 kg/ha P_2O_5 per annum. Higher P rates, up to 400 to 600 kg/ha of P_2O_5, can be used to accelerate soil improvement where economic conditions are favourable.

Once subsoil properties have been improved and root systems are able to exploit the full depth of the soil profile, intensive year-round crop production becomes possible at little risk. As yields increase, K increases in importance as a potential yield-limiting factor.

With good management once infertile acid tropical soils can produce annually the equivalent of 15 to 20 t/ha of grain. The availability of high yielding and disease resistant cultivars means that maize yields in excess of 10 t/ha per crop are now obtainable, while acid tolerant and disease resistant soybean cultivars can yield 2.5 to 3 t/ha per crop; though it will usually take several years of good management to achieve these yield levels.

To maintain production when three crops are taken per annum total annual lime and fertilizer rates may need to be as follows, supplemented for some soils and some crops by trace element applications:

		Rate (kg/ha per annum)
Lime		1000 - 1500
Fertilizer:	N	250 - 400
	P_2O_5	220 - 300
	K_2O	450 - 600
	MgO*	60 - 120

* Including that in dolomitic limestone, if applied.

These rates of application may at first sight seem excessive, but they are in fact very similar to the rates used by many temperate region farmers aiming for comparable yields.

It is a common misconception to assume that agriculture in the tropics can prosper with minimal inputs. Nevertheless, when high inputs are used the risks involved must be minimised. For acid upland soils this can only be done by conserving organic matter, thereby avoiding moisture and temperature extremes and topsoil erosion, and by changing the properties of the subsoil so as to stimulate active root development therein. Organic matter, lime, and P are the three main pillars on which a successful soil management and crop productivity programme for acid tropical soils can be built.

To optimise fertilizer use efficiency, good seed of well-adapted, high yielding strains must be available and properly used. The agronomic practices adopted must supply a correct balance of primary, secondary and trace elements while planting and harvesting times, fertilizer application times and methods, drainage, irrigation, tillage and traffic on the land must be controlled by individual farmers in such a way as to optimise returns from each input, including fertilizer.

REFERENCES

Abruna F, Pearson R W, Perez-Escolar R. Lime responses of corn and beans
1975 grown on typical Ultisols and Oxisols of Puerto Rico. In: Bonemisza E and Alvarado A (eds) Soil management in tropical America. North Carolina State University, Raleigh, USA.

Adams F, Evans C E. A rapid method for measuring lime requirements of red-
1962 yellow podzolic soils. Soil Sci. Soc. Am. Proc. 26: 355-357.

App A, Bouldin D R, Dart P J, Watanabe I. Constraints to biological nitrogen
1980 fixation in soils of the tropics. In: Soil-related constraints to food production in the tropics. International Rice Research Institute, Los Banos, Philippines.

Asher C J, Blaney F P C, Mamaril C P. Sulphur nutrition of tropical annual
1983 crops. In: Blair G J and Till A R (eds) Sulphur in South-East Asian and South Pacific agriculture. Commonwealth of Australia, pp 54-64.

Barber S A, Munson R D, Dancy W B. Production, marketing and use of potassium
1971 fertilizers. In: Olson R A et al (eds) Fertilizer technology and use. Soil Science Society of America,Madison, USA.

Barnes J S, Kamprath E J. Availability of North Carolina rock phosphate
1975 applied to soils. N. Carolina agric. exp. Sta. Techn. Bull. 229.

Black C A. Soil plant relationships, 2nd ed. Wiley, New York.
1967

Blair G J, Mamaril C P, Ismunadji M. In: Soil-related constraints to food
1980 production in the tropics. International Rice Research Institute, Los Banos, Philippines, pp 233-251.

Bouldin D R, Reid R S, Stangel P J. Nitrogen as a constraint to non-legume
1980 food crop production in the tropics. International Rice Research Institute, Los Banos, Philippines, pp 299-318.

Bussler W. [Manganese toxicity in higher plants]. Z. Pflanzenern. Dung.
1958 Bodenk. 81: 256-265

Cabala P, Fassbender H W. Formas de fosforo en la region Cacaotera del
1970 Brazil. Turrialba 20: 439-444.

Chenery M. A preliminary study of aluminium and the tea bush. Pl. Soil
1955 6: 174-200.

Coleman N T, Kamprath E J, Weed S B. Liming. Adv. Agron. 10: 475-522.
1958

Coleman N T, Weed S B, McCraken R J. Cation exchange capacities and exchange-
1959 able cations in Piedmont soils of North Carolina. Soil Sci. Soc. Am. Proc. 23: 146-149.

Coleman N T, Thorup J T, Jackson W A. Phosphorus sorption reactions that
1960 involve exchangeable aluminium. Soil Sci. 90: 1-7.

Coleman N T, Thomas G W. The basic chemistry of soil acidity. In:
1967 Pearson R W, Adams F (eds) Soil acidity and liming. American Society of Agronomy, Madison, USA.

Date R A. Nitrogen, a major limitation in the productivity of natural com-
1973 munities, crops and pasture in the Pacific area. Soil Biol. Biochem. 5: 5-18.

Dove M R. Theories of swidden agriculture and the political economy of
1983 ignorance. Agroforestry Systems 1: 85-99.

Driessen P M, Burman P, Permadhy. The influence of shifting cultivation on
1976 a podzolic soil from Central Kalimantan. In: Peat and podzolic soils and their potential in Indonesia. Soil Research Institute, Bogor, Indonesia, pp 95-114.

Drosdoff M. Soil micronutrients. In: Soils of the humid tropics. National
1972 Academy of Sciences, Washington, USA, pp 150-162.

FAO-Unesco. Soil map of the world, Vols 2-10. Unesco, Paris.
1971-81

FAO-Unesco. Soil map of the world, Vol. 1, Legend. Unesco, Paris.
1974.

Fox R L, Hasan S M, Jones R C. Phosphate and sulphate sorption by latosols.
1971 Int. Symp. Soil Fert. Eval. Proc., New Delhi, India 1: 857-864.

Fox R L, Asghor M, Cable W J. Sulphate accretions in soils of the tropics.
1983 In: Blair G J, Till A R (eds) Sulphur in South-East Asian and South Pacific agriculture. Commonwealth of Australia, pp 39-53.

Foy C D, Chaney R L, White M C. The physiology of metal toxicity in plants.
1978 Ann. Rev. Pl. Physiol. 29: 511-566.

Friedman I. The Amazon basin, another Sahel? Science, Washington DC 197: 7.
1977

Goodland R J A, Irwin H S. Amazon jungle: green hell or red desert? Elsevier,
1975 Amsterdam, Netherlands.

Graham P, Hubbell D H. Soil-plant-rhizobium interaction in tropical agri-
1977 culture. In: Bornemisza E, Alvarado A (eds) Soil management in tropical America. North Carolina State University, Raleigh, USA, pp 211-227.

Greenland D J, Dart P J. Biological and organic aspects of plant nutrition
1972 in relation to needed research in tropical soils. Trop. Soils Res. Sem., Ibadan, Nigeria.

Grimme H, Nemeth K, Braunschweig L C. Some factors controlling potassium
1971 availability in soils. Int. Symp. Soil Fert. Eval. Proc. New Delhi 1: 33-43.

Grimme H. Aluminium-induced magnesium deficiency in oats. Z Pflanzenern.
1983 Bodenk. 146: 666-676.

Grimme H. Aluminium tolerance of soybean plants as related to magnesium
1984 nutrition. In: Proc. 6th Int. Coll. Optimisation Pl. Nutr. P Martin-Prevel (ed), Montpellier, France.

Handawela J. Significance of the catenary soil sequence in Sri Lanka.
1983 Doctoral thesis, University of Tokyo.

IFDC. Sulphur in the tropics. International Fertilizer Development Center
1979 Techn. Bull. T12.

IFDC. Kujang II pre-feasibility study. Vol. 2. International Fertilizer
1980 Development Center, Muscle Shoals, USA.

IFDC. World fertilizer progress into the 1980s. International Fertilizer
1981 Development Center Techn. Bull. T22.

IITA. International Institute of Tropical Agriculture. Ann. Rep. for 1974.
1974

IITA. International Institute of Tropical Agriculture. Ann. Rep. for 1979,
1979-81 1980, 1981.

Jackson M L. Aluminium bonding in soils: a unifying principle in soil
1963 science. Soil Sci. Soc. Am. Proc. 27: 1-10.

Juo A S R, Uzu F O. Liming and nutrient interactions in two Ultisols from
1977 southern Nigeria. Pl. Soil. 47: 419-430.

Juo A S R, Kamprath E J. Copper chloride as an extractant for estimating
1979 the potentially reactive aluminium pool in acid soils. Soil Sci. Soc. Am. J. 43: 35-38.

Kamprath E J, Nelson W L, Fitts J W. Effect of pH, sulphate, and phosphate
1956 concentration on the absorption of sulphate by soils. Soil Sci. Soc. Am. Proc. 20: 463-466.

Kamprath E J. Soil acidity and response to liming. Int. Soil Testing
1967 Techn. Bull. North Carolina State University, Raleigh, USA.

Kamprath E J. Exchangeable aluminium as a criterion for liming leached
1970 mineral soils. Soil Sci. Soc. Amer. Proc. 24: 252-254.

Kamprath E J. Soil acidity and liming. In: Sanchez, P A (ed) A review
1973 of soils research in tropical Latin America. North Carolina agric. exper. Sta. Techn. Bull. 219, 126-137.

Kamprath E J. Aspectos quimicos y formas minerales del fosforo del suelo
1974 en regiones tropicales. Suelos Equatoriales 4: 1-18.

Kamprath E J. Soil acidity in well-drained soils of the tropics as a con-
1980 straint to food production. In: Priorities for alleviating soil related constraints to food production in the tropics. International Rice Research Institute, Los Banos, Philippines.

Kamprath E J, Till A R. Sulphur cycling in the tropics. In: Blair G J,
1983 Till A R (eds) Sulphur in South-East Asian and South Pacific agriculture. Commonwealth of Australia, pp 1-14.

Kellog C E, Orvedal A C. Potentially arable soils in the world and critical
1969 measures for their use. Adv. Agron. 21: 109-170.

Kemmler G. Potassium deficiency in the tropics as a constraint to food production. In: Soil-related constraints to food production in the
1980 tropics. International Rice Research Institute, Los Banos, Philippines, pp 253-276,

Koch J T, Orchard E R, Summer M E. Leaf composition and yield response of
1970 corn in relation to quantity and intensity parameters for potassium. Soil Sci. Soc. Am. Proc. 34: 94-97.

Lal R. Effects of constant and fluctuating soil temperatures on growth,
1974 development and nutrient uptake of maize seedlings. Pl. Soil. 40: 589-606.

Lal R, Kang B T, Moorman F R, Juo A S R, Moomaw J C. Soil management and
1975 possible solutions in Western Nigeria. In: Bornemisza E, Alvarado A (eds) Soil management in tropical America. North Carolina State University, Raleigh, USA, pp 372-408.

Lal R. Management of soils for continuous production: controlling erosion
1979 and maintaining physical conditions. In: Greenland D J (ed) Characterisation of soils in relation to their classification and management: examples from some of the humid tropics. Oxford University Press, London.

Lal R, Greenland D J (eds). Soil physical properties and crop production
1979 in the tropics. Wiley, New York, 566pp.

Lathwell D J, Peech M. Interpretation of chemical soil tests 1964.
1964 Cornell Univ. agric. exper. Sta. Bull. 995.

Lin C, Coleman N T. The measurement of exchangeable aluminium in soil and
1960 clays. Soil Sci. Soc. Am. Proc. 23: 12-18.

Lombin L G, Fayemi A A. Critical level of Mg in western Nigeria soils as
1975 estimated under greenhouse conditions. Agron. J. 67: 272-275.

Lopez A S. Micronutrients in soils of the tropics as constraints to food
1980 production. In: Soil-related constraints to food production in the tropics. International Rice Research Institute, Los Banos, Philippines, pp 277-3298.

Mehlich A. New buffer pH method for rapid estimation of exchangeable acidity
1976 and lime requirement of soils. Comm. Soil Sci. Pl. Anal. 7: 637-652.

Mengel K, Busch R. The importance of the potassium buffer power on the
1982 critical potassium level in soils. Soil Sci. 133: 27-32.

Mengel K, Kirkby E A. Principles of plant nutrition. 3rd ed. International
1982 Potash Institute, Bern, Switzerland, 655 pp.

Mikkelsen D S, de Dreitas L M M, McClung A C. Effects of liming and fertilizing cotton, corn and soybeans on Campo Cerrado soils, State
1963 of Sao Paulo, Brazil. IRI Research Institute Bull. 29.

Mitra G N, Sharma V A K, Ramamoorthy B. Comparative studies on the potassium
1958 fixation capacities of Indian soils. J. Indian Soc. Soil Sci. 6: 1-6.

Moormann F R, Greenland D J. Major production systems related to soil
1980 properties in humid tropical Africa. In: Soil-related constraints to food production in the tropics. International Rice Research Institute, Los Banos, Philippines.

Morales V M, Graham H P, Cavallo R. Influencia del metodo de inoculacion y
1973 el encalamiento del suelo de Carimagna (Llanos Orientales, Colombia) en la nodulacion de leguminosas. Turrialba 23: 52-55.

Morgan P W, Johan H E, Amin J V. Effect of manganese toxicity on the indole
1966 acetic acid oxidase system in cotton. Pl. Physiol. 41: 718-724.

Morimura S, Takahashi E, Matsumoto H. Association of aluminium with nuclei
1978 and inhibition of cell division in onion *(Allium cepa)* roots. Z. Pflanzenphysiologie 88: 395-401.

Nemeth K. Die charakterisierung des K-haushaltes von böden mittels K-
1971 desorptionskurven. Geoderma 5: 99-109.

Nemeth K. The availability of nutrients in the soil as determined by
1979 electo-ultrafiltration (EUF). Adv. Agron. 31: 155-187.

Nemeth K. Electro-ultrafiltration of aqueous soil suspension with simultaneously
1982 varying temperature and voltage. In: Nemeth K (ed) Application of electro-ultrafiltration (EUF) in agricultural production. Martinus Nijhoff/Dr W Junk, The Hague.

Neptune A M L, Tabatabai M A, Hanway J J. Sulphur fraction and carbon-
1975 nitrogen-phosphorus-sulphur relationships in some Brazilian and Iowa soils. Soil Sci. Soc. Am. Proc. 39: 51-55.

Neyra C A, Dobereiner J. Nitrogen fixation in grasses. Adv. Agron. 29: 1-38.
1977

North Carolina State University. Agronomic-economic research on soils in
1973-81 the tropics. In: Ann. Reps, Department of Soil Science, North Carolina State University, Raleigh, USA, 1973 to 1981.

Nye P H, Bertheux M H. The distribution of phosphorus in forest and savanna
1957 soils of the Gold Coast and its agricultural significance. J. agric. Sci. Camb. 49: 141-149.

Nye P H, Greenland D J. The soil under shifting cultivation. Techn. Comm. 51,
1960 Commonwealth Bureau of Soils, Harpenden, England.

Nye P H. Organic nutrient cycles under a moist tropical forest. Pl. Soil
1961 13: 333-346.

Nye P H, Greenland D J. Changes in the soil after clearing a tropical forest.
1964 Pl. Soil 21: 101-112.

Pearson R W. Soil acidity and liming in the humid tropics. Cornell Int.
1975 Agric. Bull. 30, Ithaca, USA.

Pratt P F, Peterson F F, Holzley C S. Qualitative mineralogy and chemical
1969 properties of a few soils from Sao Paulo,Brazil. Turrialba 19: 491-496.

Probert M E, Samosir S S R. Sulphur in non-flooded tropical soils. In:
1983 Blair G J, Till A R (eds) Sulphur in South-East Asian and South Pacific agriculture. Commonwealth of Australia, pp 15-27.

Roche P, Gariere L, Barbe D, Calaba H, Fallavier P. La carence en phosphore
1978 des sols tropicaux et ses méthodes d'appreciation. Proc. Congr. Int. Soc. Soil Sci., Edmonton, Canada.

Sanchez P A. Properties and management of soils in the tropics. Wiley,
1976 New York.

Sanchez P A. Soil management under shifting cultivation. In: A review of
1977 soils research in tropical Latin America. North Carolina State University, Raleigh, Techn. Bull. 219, pp 46-60.

Sanchez P A. Productivity of soils in rain-fed farming systems - examples
1981 of long-term results. In: Symposium on potential productivity of field crops under different environments. International Rice Research Institute, Los Banos, Philippines.

Sanchez P A, Bandy D E, Villachia J H, Nicolaides J J. Amazon Basin soils;
1982 Management for continuous crop production. Science, Washington DC 216: 821-827.

Sanchez P A, Villachia J H, Bandy D E. Soil fertility dynamics after clearing
1983 a tropical rain forest in Peru. Soil Sci. Soc. Am. J. 47: 1171-1178.

Sioli H. Foreseeable consequences of actual development schemes and alterna-
1980 tive ideas. In: Barbira-Scazzocehio (ed) Land, people and planning in contemporary Amazonia. University of Cambridge, England, pp 257-268.

Spain J M, Francis C A, Howler R H, Calvo F. Differential species and varietal
1975 tolerance to soil acidity in tropical crops and pastures. In: Bornemisza E, Alvarado A (eds) Soil management in tropical America. North Carolina State University, Raleigh, USA, pp 308-329.

Uehara G, Keng J. Management implications of soil management in Latin America.
1975 In: Bornemisza E, Alvarado A (eds) Soil management in tropical America. North Carolina State University, Raleigh, USA, pp 351-363.

USDA. Soil taxonomy. Agric. Handbook 436, Soil Conservation Service, USDA
1975 Washington.

Van Raij B, Peech M. Electrochemical properties of some Oxisols and Alfisols
1972 of the tropics. Soil Sci. Soc. Am. Proc. 36: 587-593.

Van Raij B. Selecao de metodas de laboratorio para avaliar a disponibilidade
1978 de fosforo em solos. Rev. Bras. Ciencia Solo 2: 1-9.

Villachia J H. Maintenance of soil fertility under continuous cropping in an
1978 Ultisol of the Amazon Jungle in Peru. Doctoral thesis, North Carolina State University, Raleigh, USA.

Von Uexkull H R. Prblems in development of modern tropical agriculture.
1966 Japanese Potassium Symposium, Sapporo,Japan, pp 26-40.

Von Uexkull H R. Problem soils for food crops in the humid tropics. Int.
1982 Symp.Distribution Characteristics and Utilization of problem Soils, Proc. p 139-152. Trop. agric. res. Centre, Min. Agric. For. Fish., Tsukuba, Japan. Trop. agric. Res. Series no 15.

Von Uexkull H R. Managing Acrisols in the humid tropics. In: Ecology and
1984 management of problem soils in Asia. Food and Fertilizer Technology Centre, Taiwan, Book Series no 27: pp 382-396.

Wijewardene, R, Waidyanatha P. Conservation farming. Department of Agric-
1984 ulture, Sri Lanka and Commonwealth Consultative Group on Agriculture for the Asia Pacific Region.

Wood L K,de Turk E E. The adsorption of potassium in soils in nonreplaceable
1941 forms. Soil Sci. Soc. Am. Proc. 5: 152.

Woodruff C M. Testing soils for lime requirement by means of a buffered
1948 solution and the glass electrode. Soil Sci. 66: 53-63.

Wright M J: Proceedings of workshop on plant adaption to mineral stress in
1976 problem soils. Cornell University, Ithaca, USA.

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