Chapter XI

A Low Fertilizer Use Approach to Increasing Tropical Food Production

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Chapter Xl

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ABSTRACT

Low fertilizer use in the Tropics appears to be a desirable goal and it could involve several strategies aimed at increased crop production with minimal use of inputs.

According to the general response curve that shows the effects of added nutrients, the use of small amounts of an input may result in substantially increased production. The philosophy employed here is to use less than maximum inputs to achieve the highest output: input ratio or to make maximum use of inputs rather than to maximize yields. That often requires a much greater use of scarce inputs such as fertilizer, capital, etc.

Because they have inherent high fertility, limited inputs are needed on the "high base soils" (18 percent of tropical soils) when there is sufficient water, Small amounts of nitrogen, phosphorus, and/or micronutrients are sufficient. High yielding varieties should be used on these soils to take advantage of the naturally high soil fertility.

On the "low base soils" (51 percent of tropical soils), which have high soil acidity and aluminum and the associated phosphorus deficiency, the production package should be considerably different. Lime may be necessary to reduce the availability of toxic aluminum. This will also increase the availability of phosphorus. However, additional phosphorus and/or sulfur will probably be necessary to increase yields.

The use of crops that will tolerate adverse soil conditions should also be employed on these soils. This reverses the philosophy of changing the soil to fit the crop (an expensive procedure on these soils) to one that takes the soil as it is (or changes it minimally) and uses crops that grow well under existing conditions. Examples of such crops are upland rice, cassava, sweet potatoes, cowpeas, and some grass and legume pasture crops.

With both high and low base soils, nitrogen is probably the most limiting element. Low yields in many tropical areas reflect a low level of nitrogen availability. Low yields and the lack of nitrogen result in low levels of protein for local human consumption, causing malnutrition. An excellent source of protein and nitrogen are leguminous crops. These crops have the potential to biologically fix nitrogen from the atmosphere when growing in association with the correct bacteria. When these crops are used, the nitrogen input into the cropping system can be increased several fold. This technology is inexpensive, easy to use, and available. Most important, it can substantially increase the yield of crop plants as well as meat and milk production to the benefit of the smaII farmer and the landless poor.

THE TROPICS

The Tropics are that area of the world located between 23.50 north and south of the Equator. Thirty-eight percent of the Earth's land surface (about 5 billion hectares) and 45 percent of the world's population (about 1.8 billion people in 1975) live in this area. Most of the world's developing countries lie in the Tropics, although some areas in the Tropics are not considered developing and many developing countries are outside the zone.

Because of the proximity to the Equator, the Tropics experience little change in temperature during the year. Variation of daylength is also relatively small compared to temperate zones. Rainfall is the variable which differentiates tropical areas. About one-quarter of the Tropics, mostly those near the Equator, have a rainy climate. Seasonal climates—those with a distinct wet and dry period—cover about one-half of the Tropics. Dry climates, usually having a short wet season, cover 16 percent of the Tropics. Tropical deserts comprise the remaining area, about 11 percent.

In 1960, the world's population reached 3 billion; by 20006 billion will inhabit the Earth. Much of this population increase is taking place in the Tropics, primarily in Asia. This population explosion will place a much greater strain on the resources of the Tropics. Malnutrition, particularly protein deficiency, is widespread throughout the area. Protein deficiency, a lack of high protein food, is related to a lack of nitrogen in the soil-plant system.

Protein synthesis in the plant only occurs when there is sufficient nitrogen in the soils, therefore, a lack of soil nitrogen decreases the rate of protein production in plants and hence, in the food supply. Inexpensive and efficient means to increase nitrogen in the tropical system are known. Use of these simple technologies could increase protein production and eliminate much of the misery and suffering in the Tropics caused by poor nutrition.

LAND USE

About 10 percent of the tropics are cultivated for food production; pastures and meadows account for an additional 20 percent. The President's Science Advisory Committee estimated that only 500 million hectares were cropped in 1967 even though the potential for cultivation was 117 billion hectares. Grazing occupied 1 billion hectares, but the potential was 1.6 billion hectares. These figures indicate that there is much potential to expand in agricultural production in the Tropics.

The use of land will vary depending on soil factors, climate, economic, social, and political factors. In general, the farming systems are vastly different than those practiced in the United States.

FARMING SYSTEMS

Common farming systems in the Tropics are (56):

1. shifting cultivation, where the land is cropped and then abandoned when yields fall, covers 45 percent of the Tropics;
2. settled subsistence farming is practiced on 17 percent of the Tropics;
3. nomadic herding covers 14 percent of the area;
4. livestock ranching uses 11 percent; and
5. plantation systems, which cover 4 percent of the tropical area.

If food production is to be increased and the majority of people benefit, programs must be aimed at the small farm rural population since small farms are the most numerous. In tropical Asia, 75 percent of all farms are smaller than 2 hectares (5 acres) (36). Sixty-nine percent of Central American farms are smaller than 5 hectares (12 acres) (14). The average farm size of 20 tropical African countries reporting such data in the 1973 FAO Production Yearbook was 5.4 hectares. Studies by CATIE (14) and Pinchinat, et al. (53), showed that about 70 percent of the food consumed in Colombia and Central America is produced on small farms. Therefore, any strategy dealing with food production in the Tropics must deal with the small farmer.

TROPICAL FOOD CROPS

Common tropical crops are sugarcane, pineapple, bananas, coffee, and tea. These crops, however, contribute little to the nutrition of people in the Tropics because they are exported, largely to the temperate zone. The major food crops consumed by tropical people are rice, cassava (root crop), corn, sweet potatoes, yams, wheat, sorghum, peanuts, potatoes, and dry beans (in order of decreasing importance). The total area cultivated for these 12 crops is only 300 million hectares compared to 1 billion hectares of pasture and meadow.

The Tropics can be characterized as a region where population pressures are often highest and likely to remain that way in the near future. But on the positive side, the soils and climate provide a resource base that can expand production and help meet these food needs. The introduction of simple technologies could greatly increase food production, helping to stabilize these countries in many ways.

Much of this increase must come from a better use and understanding of the tropical soils' capacity to produce. Therefore, the bottom line question becomes a question of soil fertility.

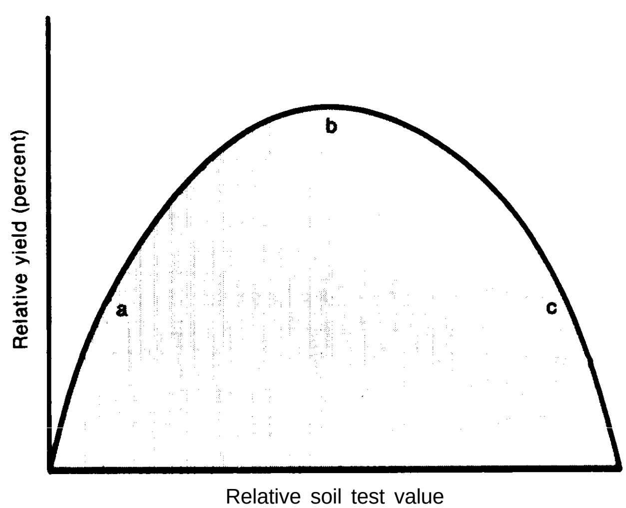
SOIL FERTILITY CONCEPTS-A GENERAL STATEMENT

A fertile soil has the capacity to produce a high yielding and high quality crop. More specifically, it is a soil that does not limit production because of physical, chemical, or biological constraints.

Numerous essential elements are required for crop production, including carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, copper, boron, zinc, manganese, and molybdenum. The first three are obtained from water and the carbon dioxide in the atmosphere. The rest must be taken up from the soil by the plant's root system. Another important element is aluminum. Although not considered essential to growth, if excessive, it is severely toxic to plants and can reduce plant growth and crop yield.

Soil tests attempt to predict crop yield for a number of elements. These tests determine as nearly as possible the soil's capacity to supply the elements necessary for plant growth. where the soil's supply is considered insufficient for a desired yield, additional amendments are supplied to the soil increasing its "fertility," or ability to produce.

A typical soil test crop response curve follows:



The response curve has three general areas. Area "a" is the part of the curve where small inputs of nutrients result in increasingly greater production, i.e., the output: input ratio is favorable. Area "b" is a relative plateau where increasing fertilizer inputs do not result in increasing yields and the output: input ratio is poor since yield can be maximized at a lessor input rate. Area "c" represents the portion of the curve where additional nutrients actually reduce yield because of excessive or toxic concentrations. Obviously this is a situation to be avoided. This is the situation with aluminum in many unlimed soils of the Tropics.

A few simple equations help to explain the relationship between the soil and plant nutrients. The general relationship between elements in the soil and plants maybe seen in the following, where E represents an element used in plant growth.

Soil solid phase$_{(E)}$ Soil solution phase$_{(E)}$
Plant root$_{(E)}$ Plant top$_{(E)}$

As the above equation indicates, an element is taken in by plant roots and moved to the plant top as a soluble element dissolved in the soil solution. Elements are generally considered to be available when they are in the solution phase of the soil. In many instances an element is unavailable to the plant because it is not in a form the plant can use, that is, not in solution. Another equation helps to explain the soil fertility-plant nutrition relationship. Again, E represents an element necessary for plant growth.

Unavailable$_{(E)}$ Available$_{(E)}$

This simple equation shows the equilibrium in the soil that determines if the nutrient can be used by a plant. This equilibrium is controlled by the soil environment: soil pH, micro-organisms, oxygen, water, temperature.

SOIL ACIDITY AND LIMING

Soil pH is a term used to delineate the relative acidity or alkalinity of soils. It is important because soil pH affects the availability of most nutrients. The soil pH scale follows:

1 2 3 4 5 6	7	8 9 10 11 12 13 14
More acid	Neutral	More alkaline or basic

Early in history, man learned to cultivate high base soils (soils high in calcium, magnesium, and potassium and low in aluminum) because they are naturally more productive. The majority of cultivated soils of the Tropics are not acid (56), although the majority of soils of the humid Tropics are acid. Soils of tropical America are more acid than those of tropical Africa and Asia.

Liming of acid soils has been a longstanding practice. For a long time, the practice involved adding sufficient lime to raise the soil pH to 7 (neutrality). However, in the early 1950s soil chemists showed that exchangeable aluminum, toxic to plants, was the predominate element in acid mineral soils as contrasted to organic soils (18). Exchangeable elements such as calcium, magnesium, and potassium are positively charged and are held in the soil by negatively charged sites. Strongly acid soils (pH less than 5.0) favor aluminum availability to plants, whereas above pH 5.5, calcium, magnesium and potassium prevail.

High soil solution aluminum, the available form for plants, causes reduced plant growth because aluminum is toxic to plants. Evans and Kamprath (25) found that an exchangeable aluminum saturation of 60 percent was required before a large amount of aluminum was present in the soil solution. Work in Guyana showed that an aluminum saturation of less than 60 percent resulted in less than 1 ppm—1 part per million—in the soil solution (13). Increasing fertilizer results in an increase of aluminum in the soil solution (34). Therefore, use of high amounts of fertilizer could increase aluminum toxicity if the soil is sufficiently acid. Available aluminum in the soil solution decreases with increasing organic matter since aluminum forms very strong complexes, making it unavailable.

Research by Kamprath (42) showed that elimination of all the exchangeable aluminum was not necessary to obtain maximum yield in field and greenhouse studies. Maximum yields of corn, soybeans, and cotton were achieved with aluminum saturation values of less than 45, 20 and 10 percent respectively where soil pH was 10W. Growth of sugarcane was severely depressed on a soil with an exchangeable aluminum saturation of 70 percent. Addition of lime to reduce the aluminum saturation to 30 percent resulted in a four-fold increase in sugarcane growth (l).

FINDING THE CORRECT LIME LEVEL

The work cited above, plus other work, has shown that lime should be added to reduce the toxic levels of aluminum. This results in a much lower soil pH and the use of much less lime than the traditional approach of liming to neutrality. Liming beyond this point has resulted in reduced yields on soils of the Tropics because of deficiencies of manganese, zinc, and/or iron. Like aluminum, manganese becomes available as the soil becomes more acid (7). Some soils are low in aluminum but high in manganese. In either case, liming will reduce the availability of manganese. However, since manganese is an essential element, liming must not be so high as to make the element unavailable and reduce the soils productivity.

A wise liming philosophy, therefore, should be to add sufficient lime to decrease the availability of aluminum without limiting manganese to the point of deficiency. The factors to be considered are: 1) the amount of lime needed to decrease the percent of aluminum saturation to a level where the particular crop and variety will grow well, 2) the quality of lime, and 3) the placement method (56). Kamprath (42) suggests that lime recommendations be based on the amount of exchangeable aluminum and that lime rates be calculated by multiplying the milliequivalents (meq) of aluminum by 1.5, to find the meq of calcium needed as lime. Lime rates calculated by this method neutralize 85 to 90 percent of the exchangeable aluminum in soils with 2 to 7 percent organic matter, which includes the majority of soils.

This method has been successfully used in Brazil since 1965 and is employed in most American countries. The application of this formula has reduced rates of liming substantially, particularly in acid, highly leached soils low in cation exchange capacity (this term refers to the amount of negatively charged sites in the soil). In most cases where 1 to 3 meq of exchangeable aluminum is present, lime applications are now on the order of 1.6 to 5 tons per hectare. In the past, rates of 10 to 30 tons per hectare were frequently used with mixed results.

Different crops tolerate different levels of aluminum. Crops such as cotton, sorghum, and alfalfa are susceptible to levels of 10 to 20 percent aluminum saturation, therefore, liming should be aimed at zero aluminum for these crops. Corn is sensitive to 40 to 60 percent aluminum saturation, therefore, 20 percent aluminum saturation could be more economical for corn. Other crops such as rice and cowpeas are more tolerant than corn. Coffee, pineapple, and some pasture species seldom respond to lime, even in soils with high aluminum saturation.

Sources of lime are difficult to find in the Tropics. If possible, lime should contain both calcium and magnesium. The coarseness of the lime also affects its usefulness. Coarse lime, that which does not pass through a 20 mesh sieve, will have very little reactivity; lime that passes through a 60 mesh sieve will react very slowly. Fine lime, which passes a 100 mesh sieve, will react quickly. Generally, a good grade of fineness is more than 60 mesh; a better grade is 100 mesh. Lime is commonly mixed in the top 6 to 8 inches of soil. In Puerto Rico, Abruna, et al. (z), observed no differences in pasture yields between surface-applied and soil-incorporated lime.

When very acid leached soils are limed to pH 5.5, most of the root development occurs in the topsoil. The highly toxic aluminum in the subsoil prevents deeper root development. In such cases, plants suffer from water stress during short-term droughts even though the subsoil is still moist. Studies show that deep placement of lime resulted in deeper root development, diminished water stress during drought, and increased corn yield of 20 to 25 percent (56).

NITROGEN

Nitrogen, too, is very crucial to crop production and the availability of protein to tropical people. Acid soils contribute to that problem largely because soil acidity reduces nitrogen fixation by leguminous plants. In nitrogen fixation, the nitrogen of the atmosphere is made available to plants. Next to water, nitrogen is the most limiting factor in crop production in the Tropics. It is necessary for protein synthesis and production. Plant-available nitrogen is derived from organic matter, leguminous nitrogen fixation, fertilizers, and animal manure. The main source of nitrogen in the Tropics is the decomposition of organic matter. Therefore, practices that maintain organic matter in the soil are essential. Organic matter not only provides nitrogen, but it improves the soil's physical condition and water-holding capacity, increasing water to plants and decreasing the soil temperature.

NITROGEN SUPPLY PROCESS

Nature has provided the nitrogen for crop production since the beginning of time through natural processes. However, seldom has it provided an abundance of nitrogen for long and sustained periods of crop production on the same piece of land. Moreover, natural processes at their best have seldom provided enough plant-available nitrogen to achieve the level of food and fiber production needed to meet the demands of present day crop production. Natural nitrogen-supplying processes include: 1) mineralization of nitrogen from soil organic matter and from crop residues; 2) the reverse process of immobilization in the decomposition of plant and animal debris and soil organic matter; 3) fixation of nitrogen from the atmosphere, largely through biological processes; 4) addition of nitrogen through rain and other forms of precipitation (5).

The nitrogen in soil organic matter is important for crop production, However, soil nitrogen is not inexhaustible; it declines in quantity in the soil as it is used by crops grown, harvested, and consumed. Nitrogen in soil is largely organic, replenished by periodic additions of fresh plant or animal residues.

Under normal conditions, nitrogen is added to the organic supply in soil each year through crop residues (immobilization), but it is unavailable to plants. Also through biological decomposition, organic nitrogen in the soil is continuously converted to the inorganic form (mineralization), which is available to plants. Under any sustained system of crop and soil management, these two processes tend to approach each other in magnitude so that mineralization balances immobilization (9). When this balance is attained, the system is considered to be in equilibrium.

The implications and consequences of an equilibrium in the soil's organic nitrogen need to be emphasized. At equilibrium, the amount added to the supply of organic nitrogen is essentially balanced by a like amount of decomposition. The total quantity of soil nitrogen remains unchanged and the net amount that can be and is supplied to a crop is zero (5). During periods of virgin or noncultivated conditions, such as a forest, certain soils tend to build up organic matter, accumulating as much as 10,000 kg/ha of nitrogen under virgin conditions. During the first years of cultivation, these same soils may supply as much as 400 kg/ha of available nitrogen per year to crops (59). As cultivation continues and the organic nitrogen declines, the quantity of nitrogen becoming available each year also declines. After long periods of cultivation, the soil's organic matter becomes exhausted unless legumes are grown or the soil fertilized with nitrogen. A minimal amount of nitrogen is supplied by rainwater and nonsymbiotic nitrogen fixation.

Many of the major land areas of the Tropics have now been cropped for extended periods and the organic matter stored under virgin conditions has been dissipated. With little or no use of nitrogen fertilizer, tropical crop yields reflect the paucity of the natural nitrogen supply from rainwater and nonsymbiotic nitrogen fixation.

Yields of corn of 600 to 1200 kg/ha and of wheat of 400 to 800 kg/ha require a nitrogen supply only a little larger than could be expected from rain and from nonsymbiotic fixation. Yields this poor remove no more than 15 kg/ha of nitrogen from the land in the harvested grain products. Such minimal yields can be sustained for a long period of time without fertilizer or legumes, but do little to sustain the protein needs of animals or humans.

However, with inclusion of legumes in the rotation either as a primary food crop or as a green manure, the nitrogen supply in the soil-plant system can be increased substantially. This will result in increased crop and protein production, helping to meet the primary malnutrition problem of the Tropics.

BIOLOGICAL NITROGEN FIXATION

Despite the great use of chemical fertilizer today, biological nitrogen fixation processes have been responsible for providing most of the nitrogen currently used by and tied up in plants and animals and in the decomposed residues found in soil. It supplies the major part of the nitrogen for crop production in world agriculture.

According to reviews by Henzell and Norris (37) and Jones (4)), *Rhizobium* bacteria fixation accounts for 100 to 300 kg of nitrogen per hectare and year. Whitney (67), however, reports an annual range of 47 to 905 kg of nitrogen per hectare for pure stands of an improved variety of *Leucaena leucocephala*.

Obviously, the potential to increase the nitrogen in a cropping system several fold (15 kg/ha v. several hundred kg) using legumes in crops or pastures is possible. Differences among adapted species within a specific environment seem to be closely related to dry matter production (total growth) (40). This suggests that there is little difference in the capacity of legumes to fix nitrogen as long as they are adapted to the environment. Factors affecting dry matter production, such as moisture or nutrient stress, solar radiation, diseases, and other factors will determine nitrogen fixation.

pastures and meadows make up the greatest portion of the land that is managed for food consumption, therefore, potential increases in food are large if this segment of tropical production could be increased. Another important factor to consider is that production from pastures and meadows results in increased meat and milk, both high in quality proteins.

Some individuals consider cattle to be a very inefficient source of protein for humans in the food chain. This is true when animals and humans compete for grain. It is not true when cattle convert forage from pasture and meadow lands into meat and milk. The determining factor will be how much and what kind of land is available for cultivation.

PRODUCTIVITY OF IMPROVED GRASS-LEGUME MIXTURES

Beef production will normally increase by a factor of 2 to 4 due to establishment of grass-legume mixtures (40). Few experiments provide long-term data. Sanchez (56) cites a study of a legume, *Stylosanthes humilis* introduced into a Queensland pasture and followed beef production for 7 years. The following table summarizes the results:

Beef Production Systems in the Tropics

Treatment	*Beef kg/ha*
Grass alone	24
Grass & fertilization*	62
Grass & legume	93
Grass & legume & fertilization*	148

● Annual application 10 kg P/ha as0O-20-0 and 40 kg K/ha plus Mo.

It is interesting to note that the grass-legume treatment produced more beef than did the fertilizer treatment. The grass-legume mixture plus fertilizer more than doubled the beef produced by grass alone plus fertilizer, demonstrating the effect of adding nitrogen to the system via the legume.

Another plant, a fern, Azolla, grows in association with rice, the major crop of Asia. Azolla does not fix nitrogen itself, however, it grows in symbiotic association with blue-green algae *Anabaena azollae* (16). About 10 percent of China's rice (3.2 million acres) are grown with Azolla. He states that yields of rice of 6 tons per acre have been reported along with 60 tons of Azolla. Rice with conventional fertilizers yields about 4 tons per acre. Preliminary experiments indicate that Azolla will produce so to 180 pounds of nitrogen per acre, making it highly attractive as a natural nitrogen source.

Another nitrogen fixing system has been reported by Dobereiner and her associates in Brazil (20,22). Their work has focused on nitrogen fixation by nonleguminous plants. This work has a great potential if efficient strains of bacteria can be found. At present, this rate of asymbiotic fixation contributes only about 10 kg of nitrogen per hectare per year.

Recent evidence suggests that symbiotic nitrogen fixation takes place in some tropical grasses (22). The nitrogen fixation takes place in the rhizosphere (soil close to root), however, since this nitrogen is taken up directly by plants, it is considered symbiosis. Laboratory experiments suggest that the magnitude of this mechanism may be on the order of 1 kg of nitrogen per hectare per day. This system needs to be taken out into the field to determine nitrogen fixation under more realistic conditions.

Field beans, *Phaseolus vulgaris,* a staple in many Latin American countries, appear to fix little nitrogen (56). This is attributed to poor modulation characteristics that may be due to low phosphorus or high aluminum which inhibit *Rhizobium* activity. When these legumes are grown, they contribute nitrogen to the system. It eventually becomes available via mineralization or the breakdown of complex nitrogen compounds into simpler nitrogen compounds.

NITROGEN RELEASE FROM ORGANIC MATTER

Plant-available inorganic nitrogen in most tropical areas shows a marked seasonal fluctuation (56). This is characterized by a slow nitrate (available form to plants) buildup during dry season. There is a large, but short-lived, increase at the beginning of the rainy season, and a rapid decrease during the rest of the rainy season because of leaching.

Since the level of plant-available nitrogen in many tropical soils is low, the use of extra nitrogen (green manure, animal waste, or fertilizer) will almost always increase yields of crops if these crops can make use of the extra nitrogen. Therefore, if nitrogen fertilizer is to be added, it should be at rates that can be justified economically.

Since most nitrogen fertilizer is very transitory due to its soluble nature, the use of nitrogen should be timed to the needs of the plant, This will avoid excessive loss due to leaching rain or denitrification, the loss of nitrogen as a gas. Numerous experiments in both temperate and tropical climates have shown that the application of nitrogen soon after planting, when demand is highest, will result in higher yields and more efficient use of the applied nitrogen,

Nitrogen loss is not a serious problem with organic nitrogen from legumes or animal waste since these complex organic materials are not subject to leaching like the more soluble inorganic fertilizers. This suggests that organic forms of nitrogen have a greater efficiency in high rainfall areas. In some cases, nitrogen addition alone will not increase productivity substantially because other elements may be deficient or toxic. This is the case with acid soils, Lime will promote legume establishment and growth by reducing aluminum availability and increasing the availability of phosphorus. Phosphorus deficiency is a serious problem in many tropical soils and must be considered in the fertility regime,

PHOSPHORUS

Following water and nitrogen, phosphorus is probably the most limiting nutrient in the Tropics. This is particularly true in the acid soils of the humid tropics since the high aluminum and iron concentrations render phosphorus unavailable to plants. The term used to denote this is phosphorus fixation. When phosphorus is added as soluble monocalcium phosphate ($Ca(H_2C9PO_4)_2$) the soil pH is reduced to 1 to 1.5 (very acid). The acid dissolves aluminum, iron, potassium, and magnesium compounds and unsoluble phosphates of iron and aluminum are formed. The higher the phosphorus-fixing capacity of the soil, the higher the content of iron and aluminum oxides (56). Higher exchangeable aluminum also increases the soil's phosphorus fixation ability. Because of the fixation process, higher rates of phosphorus must be added to achieve the same level of plant-available phosphorus compared to a soil that does not fix phosphorus. The amount of phosphorus added to a soil to get 0,2 ppm phosphorus (adequate level) in the soil solution can vary from 20 to 30 pounds per acre to as much as 1,500 pounds per acre. A general recommendation for corn and rice in Latin America is 100 to 150 of kg P_2O_5 per hectare for corn and from O to 60 kg for upland rice. In many cases, soils respond only slightly to phosphorus unless they are first limed (15). In an experiment, limed corn plots showed a marked response to 50 kg P_2O_5 per hectare with a yield increase from 0.8 to 3.2 tons per hectare. In limed plots, rice did not respond to phosphorus.

MANAGEMENT OF PHOSPHORUS FERTILIZER

Phosphorus responses are common in many tropical soils. Well-calibrated soil tests can identify the soils with a high probability of phosphorus response. Phosphorus management in soils with moderate fixation capacity is usually a simple procedure: small annual rates of superphosphate can be broadcast (spread over top of soil) and incorporated or banded (placed in a band near the seed).

In soils with high phosphorus fixation capacity, economically sound phosphorus management involves several approaches (56). Two general approaches are used to deal with high phosphorus fixing soils. One is to apply small to moderate amounts in bands near the plant. The other is to apply a large amount at one time saturating the soil's fixation capacity, eliminating the problem right away. However, this has

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a disadvantage because it requires a high initial investment and adequate financing. In a high-fixing soil from North Carolina, Kamprath (41) studied the residual effect of massive initial applications versus small annual maintenance rates applied in bands. In that study, the small annual banded application is superior to the massive single dose.

Applying phosphorus fertilizers in bands is a simple practice that satisfies the phosphorus fixation capacity of a small soil volume, making the fertilizer directly available to plants. In using a system of minimal inputs, banding is very appropriate since the goal is to increase crop production with minimal inputs without changing the inherent fertility of the entire soil volume. Sanchez (56) cites an example of banded versus broadcast applications in a high phosphorus-fixing soil in Brazil. The results showed that broadcast-incorporated applications were superior to banded applications in the first crop. Banded applications concentrated corn root development around the band. When a temporary drought struck, these plants suffered more than those of the broadcast plots because those had a more extensive root system. In time, however, the effectiveness of the banded treatments increased while the broadcast treatments decreased. Annually banded treatments began to approach the broadcast treatments as the phosphorus became mixed in the soil.

SOURCES OF PHOSPHORUS

Research in temperate regions indicates that phosphorus fertilizers should have at least 40 to 50 percent phosphorus in water-soluble form to ensure an adequate supply at early growth stages (23). Ordinary and triple superphosphate and monoammonium and diammonium phosphates meet this requirement and can be used effectively in soils with low to moderate fixation capacities.

In acid soils that fix large quantities of phosphorus, application of less soluble phosphorus sources such as rock phosphate may be more effective and economical than the slightly soluble forms. Rock phosphates are more reactive in acid soils and usually cost one-third to one-fifth as much as superphosphate per unit of phosphorus (56).

The literature on tropical agriculture is full of research indicating the desirability of high-quality rock phosphate sources over superphosphate in acid soils (46,4,23) and the poor performance of low-citrate-volubility rock phosphate sources in acid soils (3,50,66). Studies at TVA by Lehr and McClellan (45) indicate that when rock phosphate deposits (North Carolina and Tunisia) are given an index of 100, rock phosphates with a volubility index of 70 percent or greater can be recommended for direct application without testing. These are largely concentrated in North Africa, the Soviet ‘Union, and the Southeastern United States.

The effects of rock phosphates of varying citrate volubility on flooded rice yields in an acid sulfate soil from Thailand was studied by Englestad, et al. (24). The initial and residual effects of the rock phosphates were highly dependent on their absolute citrate solubilities. The yield responses of the North Carolina and Florida rocks approximated those of triple superphosphate.

In the Tropics, high-citrate volubility deposits are limited to relatively small areas in Peru and India (56). The majority of the deposits in most tropical areas, including significant ones in Brazil, Colombia, Venezuela, Togo, and India have relative solubilities lower than **40** percent. Most are unsuitable for direct applications, but their reactivity can be increased by fine grinding or by thermal alteration and fusion with silica sand, sodium, or magnesium carbonates. These silicophosphates, called “Rhenenia” or thermophosphates, appear to have promise for acid soils that fix large quantities of phosphorus because of the blocking effect of silicon on phosphorus fixation sites (52,27).

The potential effectiveness of these cheaper forms of phosphorus in acid soils is illustrated in the following table:

Behavior of Different Fertilizer Sources on Wheat Grown in Oxisols of Southern Brazil

Phosphorus source	Relative yield 5-year average
No phosphorus	100
Olinda rock phosphate*	179
Simple superphosphate	206
Thermophosphate.	218

‘Low citrate solubility.

SOURCE W.J. Goedert (personal communication) as cited by Sanchez (1976),

The low citrate volubility Olinda rock phosphate was inferior to ordinary superphosphate; but when thermally treated with silicates and carbonates to produce a thermophosphate, its effectiveness was superior to that of ordinary superphosphate. In view of the substantially lower costs of the rock phosphates and some thermophosphates, both seem desirable alternatives for soils with high fixation capacities.

An additional strategy, sometimes feasible for managing soils with high phosphorus fixation capacities, is to reduce their fixation through amendments that will block some of the fixing sites in the soil. This can be accomplished in some soils through liming or silicate additions (56).

Liming soils to pH 5.5 generally increases the availability of phosphorus by precipitating exchangeable aluminum and hydroxy aluminum. This has also been observed by Fox, et al. (29), in high fixing Hawaiian soils.

Applications of silicon or sand (an unessential element), usually as calcium silicate, sodium silicate, or basic slag, are known to decrease phosphorus fixation and increase phosphorus uptake by crops. In one study, grass yields increased from 2 to 7.6 tons per hectare and phosphorus uptake rose from 4 to 15 kg phosphorus per hectare when 1 ton of silicon per hectare was applied without added phosphorus (62),

Silicon is generally not considered to be essential to plant growth, however, positive yield responses have been achieved on highly leached soils of the Tropics under intense cultivation of sugarcane or rice. Soils having low contents of soluble silicon are most likely to show response to silicon applications. Fox, et al. (32), suggested that the critical level is 0.9 ppm silicon in water extracts. Responses have been obtained on the leached soils of Hawaii, Mauritius, and the rice soils in Japan, Korea, and Sri Lanka,

In these rice soils, silicon applications increased yields because of a more erect leaf habit, greater tolerance against insects and disease attacks, lower uptake of iron and manganese when present in toxic concentrations in the soil, and perhaps a rise in the oxidizing power of rice roots.

SULFUR Deficiency

An element with plant requirements very similar to phosphorus is sulfur. Sulfur deficiency results in a reduction of growth and protein deficiency, often resembling nitrogen deficiency. widespread sulfur deficiencies and responses have been reported all over the Tropics. McClung, et al. (48), observed sulfur responses in the Brazilian Cerrado in both savannas and recently cleared forests. In Central America, sulfur deficiencies are also widespread (5 I ,28), Sulfur deficiency has also been found in sub-Saharan Africa and the sandy soils of central Africa (8). They have been reported in Asia (52) and in Australia and Hawaii (68,30). Sulfur-deficient soils are generally high in allophane or oxides, low in organic matter, and often sandy. Soils subject to repeated annual burning are often sulfur deficient since about 74 percent of the sulfur is volatilized (goes off as a gas) by fire. Sulfur-deficient soils occur in unpolluted, inland areas where the atmosphere is low in sulfur.

Sulfur requirements are similar to phosphorus in tropical conditions ranging from 0.1 to 0.3 percent of plant tissue. A sulfur deficiency at early growth stages may disappear later when the roots come in contact with the sulfur-bearing subsoil.

In general, small rates of sulfur (10 to 40 kg/ha) will overcome sulfur deficiencies. Sulfur as part of either nitrogen or phosphorus fertilizer is usually sufficient to take care of sulfur problems. If not, any soluble source containing sulfate will work.

POTASSIUM DEFICIENCY

The last major element to be considered, of less importance than the other nutrients considered here, is potassium. Potassium deficiencies do occur in the Tropics, however, lack of potassium is not nearly as widespread as nitrogen and phosphorus deficiencies. Boyer (10) in a review article suggests that the absolute minimum requirement of exchangeable potassium—the amount considered to be available to the plant—is close to 0.10 meq/100 g of soil but that this may vary between 0.07 and 0.20 meq/l00 g depending on the kind of crops grown and the soils.

In Africa, the most severe potassium deficiency appears in the savanna on sandy soils. In the lower Ivory Coast, potassium application resulted in very substantial yield increase with oil palm (9). Potassium deficiencies have occurred in the southwestern Cameroon (64) in Madagascar (65) and in Brazil on sandy soils. Laudelot (45) in the Congo (Zaire) showed that the exchangeable potassium increased from 0.067 meq/100 g to 0.325 meq/100 after burning a forest. Thus, clearing a forest by burning substantially increases the potassium content of soils. Busch (12) found that the increases in bases (calcium, magnesium, and potassium) persists for a number of years after burning.

When soils are potassium deficient, fertilization with moderate amounts of potassium usually corrects the problem. High yield crops that contain high carbohydrates such as potatoes have a higher potassium requirement than a grain crop such as wheat or rice.

RICE

Since rice culture differs from other crops because it demands flooding, it must be considered separately. Regardless of their original pH values, most rice soils reach a pH of 6.5 to 7.2 within a month after flooding and remain at that level until dried (56). This increase in soil pH is a result of the release of OH. (base) ion when $Fe(OH)_3$ is reduced. Consequently, liming is of little value in flooded rice production. If low pH is a problem, flooding 2 to 3 weeks prior to transplanting may eliminate this danger.

Oxygen is consumed in flooded soils; therefore, nitrates will be lost via denitrification. Since ammonium is already reduced, it is stable in flooded environments. Organic matter decomposition proceeds at a slower rate without oxygen, however, materials such as rice straw (which has a high carbon to nitrogen ratio) may mineralize more rapidly under these anaerobic conditions, thus providing a source of plant-available nitrogen. Soil solution phosphorus increases upon flooding, explaining why additional phosphorus in flooded conditions is rarely needed.

Nitrogen use in rice is very critical. An ammonium source is generally used when fertilizer is used. It is incorporated in the soil before seeding or transplanting, or broadcast at different stages of growth. Incorporations of 2 inches are usually sufficient for constant flooding conditions. This places the nitrogen below the oxidized layer, a necessary condition to prevent denitrifiction (49). Nitrogen uptake proceeds throughout the growth cycle of the rice plant but it is particularly critical during two physiological stages: at the beginning of tillering and at the panicle (grain head) initiation stage (47). Adequate nitrogen at tillering increases tillers, which is closely correlated with yield in short varieties. However, excessive nitrogen after maximum tillering and before panicle initiation may result in a large proportion of unproductive tillers and premature lodging in tall varieties. Excessive nitrogen after flowering may extend growth duration and increase susceptibility to some diseases.

The efficient use of nitrogen is very important economically. Scientists at the International Rice Research Institute (38) have almost doubled the efficiency of nitrogen fertilizer by either mixing it in mudballs or making urea briquettes. Fifty pounds of nitrogen per acre in this fashion was equal to 100 pounds per acre applied on the surface.

Rice rarely responds to phosphorus fertilizer except in highly weathered leached soils (57). Traditional soil tests for phosphorus do a poor job in predicting the need for phosphorus under flooded conditions.

Zinc deficiency is probably the most widespread micronutrient disorder in tropical rice, occurring in parts of India, Pakistan, the Philippines, and Colombia under low lowland conditions (63,69,15,39). It also occurs throughout the Cerrado of Brazil under upland conditions (19). In lowland rice, zinc deficiency is associated with calcareous (high base) soils and is accentuated by prolonged flooding. Deficiency can be corrected by applications of 5 to 15 kg of zinc per hectare as the sulfate or oxide incorporated into soil before seeding (35). An alternative is dipping the transplant seedlings in a 1 percent zinc oxide suspension before transplanting and mixing zinc oxide with pre-soaked rice seeds before direct seeding (69,15). Yield increase of 2 to 3 tons/ha have been achieved with 1 to 2 kg of zinc oxide per hectare (11). This again is an example of fertilizing the plant and not the soil, a much more economical and easy approach than treating the whole soil.

Potassium deficiency is rare in lowland rice as these soils are usually adequate in exchangeable potassium and receive potassium in the irrigation water when flooded. Soil tests are good for estimating potassium-deficient soils (56).

PLANTS THAT TOLERATE ADVERSE CONDITIONS

Up to this point this paper has concentrated on soil modification as a way to increase crop production. Another approach is to select or breed crops that will tolerate and produce well under natural, though sometimes hostile, conditions,

Certain crops grown exclusively in the Tropics normally grow at pH levels that would kill corn or soybeans (56). Pineapple is perhaps the best known example, but coffee, tea, rubber, and cassava also tolerate very high levels of exchangeable aluminum. Among the pasture species, several grasses and legumes are apparently very well adapted to acid soil conditions, Tropical grasses such as guinea grass, *Panicum maximum;* jaragua, *Hyparrhanea rufa;* molasses grass, *Melinia multiflora,* and several species of the genera *Paspalum* and *Brachiaria* grow well in very acid soils.

Legumes are considered very susceptible to soil acidity because of their high calcium requirements for modulation. However, several tropical pasture legumes are strikingly well adapted to acid conditions. *Stylosanthes* spp., *Desmodium* spp., *Centrosema* spp., *Calopogonium* spp., and tropical Kudzu, *Pueraria phaseoloides* are the principal ones (56), Among the grain legumes, cowpeas and pigeon peas are more tolerant of acidity than field beans and soybeans. Many of these species have evolved in acid soils and have genetic properties that tolerate conditions associated with high aluminum levels.

On the basis of research, Spain, et al. (61), have produced a list of species adapted to high soil acidity and aluminum:

Crops and Pasture Species Suitable for Acid Soils With Minimum Lime Requirements

Lime requirement (tons/ha)	*Al saturation (percent)*	*pH*	*Crops (using tolerant varieties*
0.25 to 0.5	68 to 75	4.5 to 4.7	Upland rice, cassava, mango, cashew, citrus, pineapple, Stylosanthes, Desmodium, kudzu, Centrosema, molasses, grass, jaragua, Brichiaria decumbens, Paspalum plicatulum
0.5 to 1.0	45 to 58	4.7 to 5.0	Cowpeas, plantains
1.0 to 2.0	31 to 45	5.0 to 5.3	Corn, black beans

In a review of tolerance to aluminum, Foy (1974) concluded:

1. Some aluminum-tolerant varieties keep developing and are not injured.
2. Some aluminum-tolerant varieties increase the pH of growth medium which reduces the availability of aluminum; sensitive ones decrease soil pH, compounding the problem.
3. Some tolerant species accumulate aluminum in their roots or translocate (transport) aluminum at a slower rate to the top.
4. Aluminum in roots does not inhibit the uptake and translocation of calcium, magnesium, and potassium in tolerant varieties, whereas it does so in sensitive varieties.
5. High plant silicon is associated with aluminum tolerance in certain rice varieties.
6. Aluminum tolerant varieties do not inhibit phosphorus uptake and translocation as much as susceptible varieties or species. Also, many aluminum-tolerant species or varieties are very tolerant of low phosphorus levels.

Cassava Manihot spp., a tropical root crop growing widely on infertile soils that are frequently acid, has acquired the reputation for being a crop that yields well under very low fertility conditions (17). Cassava tolerates low soil pH and high levels of aluminum and manganese as well as low levels of soil calcium, nitrogen, and potassium better than many other species. While it has a high phosphorus requirement for maximum growth, it can use phosphorus sources that are relatively unavailable to other plants. It is highly tolerant of uncertain rainfall patterns and is an extremely efficient carbohydrate source on low fertility, acid soils with low levels of fertilizer applications. Cassava yields of 36 metric tons per hectare per year have been obtained under conditions that are suboptimal for many crops.

An estimated 1.57 million people live in the Tropics and this number is likely to expand to 5 billion in 50 years (55). This rapidly growing population will have to rely increasingly on plants as sources of both energy and protein. In the semiarid to subhumid climates, two-thirds of dietary calories come from cereals, while in the humid tropics the bulk of dietary carbohydrate comes from roots and tubers. The production of starchy root and tuber crops is inherently more efficient than the production of cereals, especially on marginal lands and/or land with minimal external inputs. It is estimated that with roots and tubers, at least two to three times more caloric energy can be produced per unit of land and time and with only one-third to one-half the production cost of cereals. It is, therefore, suggested that an increasing proportion of human energy needs will be derived from starch roots and tubers. The Tropics have a large amount of infertile lands, ill-suited for many crops with moderate to high nutrient requirements. One of the most serious problems of some tropical soils is phosphorus deficiency that seriously limits crop production.

Sweet potatoes *(Ipomoea batatas* (L.) Lam.), long associated with poor people and less productive soils, may be one solution (54). There is good reason that the sweet potato is grown so widely under such difficult conditions. Sweet potato had one of the lowest phosphorus requirements of the crops studied (Lettuce, *Lactuca sativa;* corn, *Zea mays;* and Chinese cabbage, *Brassica pekinesis)* (31).

The International Rice Research Institute (39), classified varieties of rice that are tolerant or sensitive to low phosphorus. They are also selecting varieties for tolerance to iron deficiency or toxicity and the presence of toxic soil reduction products.

In summary, it is apparent that high production can be achieved on rather hostile soils as long as tolerant species or varieties of plants are selected, This would be a strategy that relies on no or minimal inputs and yet can increase food production substantially,

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