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The term "tropical soils" evokes widely different thoughts in specialists and scholars from several disciplines. Overgeneralizations about soils of tropical areas have led to many misconceptions about the potential of the tropics for food production. Much has been learned in the past two decades about the properties and management of such soils. Our purpose in this article is to outline the salient properties of soils in the tropics and the role of these soils in world food production.

Tropical soils can be quantitatively defined only as those soils which lack a significant summer to winter temperature variation; that is, the difference between the mean summer and mean winter temperature at a depth of 50 centimeters is less than 5°C (*1*, *2*). Aside from this, the range of conditions responsible for soil formation is as diverse in the tropics as in the temperate regions. Rocks, the parent material of soils, are the same in both regions. Erosional and depositional patterns are not markedly different between the two geographic regions. In both tropical and temperate regions, the time of soil formation on any geomorphic surface may range from yesterday on floodplains or fresh volcanic ashfalls to undetermined antiquity on more stable surfaces. Arid and humid, hot and cold climates exist in both zones. The term "tropical soils," therefore, is as meaningless in conveying most soil properties as its corollary, "temperate soils."

Although soil formation in tropical areas is not different in kind from soil formation in the temperate zone (*3*), the areal magnitude of certain soil-forming patterns is significantly different. Much of the northern temperate zone has had its surface reworked by Pleistocene glaciation and carpeted by thick loess mantles. These processes have influenced the age of the soils and added an influential silt-sized component (2 to 50 micrometers) to the parent material that is frequently absent in tropical areas. Many more soils in the tropics have been formed from material that has been reworked since the Precambrian by the processes of surface erosion and deposition, which intensively weather the material. Although the areal extent of recent volcanic ash deposits is greater in the tropics, there is a larger proportion of relatively younger soils in the temperate region.

Generalizations beyond these statements begin to lose accuracy. The statements that laterite and lateritic soils are prevalent in the tropics and that tropical soils have low organic matter contents are two generalizations that have tended to hinder understanding of tropical soil conditions.

The Laterite Exaggeration

Probably no greater misunderstanding about soils exists than the concept that there is a uniquely tropical soil-

P. A. Sanchez is associate professor and S. W. Buol is professor in the Department of Soil Science, North Carolina State University, Raleigh 27607.

forming process that leads ultimately to laterite. When European and American soil scientists traveled to the tropics during the 19th century, they were intrigued by the presence of laterite. Back home they wrote and lectured on this phenomenon. In the process, vast areas of the tropics with soils similar to those found in the temperate regions were essentially ignored. Thus, tropical soils came to mean those soils high in sesquioxides which harden irreversibly on exposure. Latosols and lateritic soils erroneously became known as soils in the process of developing into laterite. Even relatively recent publications in widely read journals (*4*) conclude that most tropical areas, when cleared of vegetation, will become worthless brick pavement in a few years. We have known natural scientists to observe slightly weathered soils in temperate desert areas and refer to them as laterites because of their reddish color. Many such erroneous conclusions are based on the assumption that Buchanan (*5*) adopted the word laterite because of the red color of the soil, whereas he actually intended to refer to its use as building material.

In 1933, Hardy (*6*) emphasized that laterites have a limited areal extent in the tropics. Reliable estimates of soils that will harden into laterite on exposure are not available for the entire tropics. Regional estimates by soil scientists and calculations based on maps provide the following estimates of the areal occurrence of laterites: 2 percent for tropical America (*7*), 5 percent for central Brazil (*8*), 7 percent for the tropical part of the Indian subcontinent (*3*), 11 percent of tropical Africa (*3*), and 15 percent for sub-Saharan West Africa (*9*). On the basis of these and other estimates, we venture that the total area of the tropics in which laterite may be found at or close to the soil surface is of the order of 7 percent. Furthermore, laterite or plinthite occurs in predictable positions in certain landscapes, not only in the tropics but in the southeastern United States as well (*10*), and is developed in the subsoil. Marbut (*11*) observed that "In no single case was the horizon of iron concentration found on the surface where the local situation was not such as to make it clear that it had been exposed by erosion." The vast majority of the tropics, therefore, is not affected by this problem, and it is not even a problem unless the iron-enriched plinthite layer is exposed by erosion.

Nearly 20 years ago Carter and Pendleton (*12*) stated

> The concept of a tropical process came to be focused about the term "laterite." Laterite was and is a feature, a specific thing, and not a process. The process was invented by those who had never seen the feature and who, even worse, applied it to all sorts of phenomena supposedly, but not really like laterite as originally described.

In an attempt to confine laterite to its original definition the term plinthite, meaning iron-rich, humus-poor soil material which will harden on repeated wetting and drying, is now used in soil taxonomy (*13*).

Soil Organic Matter

The red color of soils in many tropical areas is in striking contrast to the color of soils in the cooler parts of the temperate zone. The immediate conclusion often made is that organic matter is lacking in tropical soils. However, comparing the organic carbon content of 16 randomly chosen, well-drained Mollisols, Aifisols, and Ultisols from the United States and the same number of similarly selected Oxisols, Alfisols, and Ultisols from Brazil and Zaïre, we found some major contradictions to common beliefs. The average organic carbon content in the top 1 meter was 1.11 percent for the black U.S. Mollisols and 1.05 percent for the red, highly weathered Oxisols. Mollisols and Oxisols are, respectively, the principal soils of temperate and tropical American grasslands. The gray-brown Alfisols from the United States contained 0.52 percent organic carbon, while the reddish tropical Alfisols contained 0.54 percent organic carbon. The reddish temperate Ultisols contained 0.40 percent organic carbon, and the reddish tropical Ultisols 0.66 percent (*14*). None of these differences in organic carbon content between tropical and temperate soils are agronomically or statistically significant. Although the organic matter content is low in many African soils, in general it is higher than that in soils of the southeastern United States or of U.S. desert areas of comparable mean annual temperature and rainfall.

This similarity between tropical and temperate soils can be understood in terms of the temperature and moisture regimes and the empirical rule that for every 10°C increase in temperature, the rate of biological activity doubles. In the temperate regions, low winter temperatures greatly reduce biological activity. In the 78 percent of the tropics that has a pronounced dry season of at least 90 days, the lack of moisture during this period has a similar effect. Topsoil and air temperatures during the tropical rainy seasons are similar to, but seldom as high as, the corresponding summer temperatures in the temperate regions. For the 22 percent of the tropical areas with heavy rainfall and no dry season, the explanation is somewhat different. Most of these areas are covered by tropical rain forests. Neither temperature nor moisture limits organic matter accumulation and decomposition at any time. These forests produce about five times as much biomass and soil organic matter per year as comparable temperate forests. The rate of organic matter decomposition, however, is also about five times greater than in temperate forests (*15*). Thus, the equilibrium contents are similar.

Soils of the Tropics

The tropics are by no means uniform climatically or in the distribution pattern of soils. Four major ecological zones can be distinguished: the savannas and associated grasslands, which cover approximately 49 percent of the land area; the evergreen forests, which cover 24 percent; and the desert and semidesert areas, which cover 16 and 11 percent, respectively (*16*). Approximately 23 percent of the tropics is more than 900 meters above sea level; these areas constitute the tropical highlands.

Within the confines of a single article, some generalization must accompany a discussion of a subject as broad as soils of the tropics. Assuming this risk, we will point out what we think are the major differences between soils in the tropical zone and then give some examples of the variations that are found within the major types.

Tropical savannas are a temptation to agronomic development because they can be easily cleared of vegetation and they are apparently underused at present. Extensive savanna areas occur in tropical America and Africa, with smaller areas in Asia and Australia, and a cursory overview indicates that similar soil-related problems would be encountered on all of them. A dry season of at least 3 months and annual burning are common in these savannas.

More detailed examination of the soils reveals that savannas in West and East Africa are generally well supplied with bases, while those of South America are generally almost devoid of bases. Variations in tropical America subsequently result in the presence of semi-deciduous forests interspersed with the savannas in areas where parent rock is of basic composition and abundant bases are present in the soil.

Supplemental calcium and phosphate are almost always needed for range cattle in tropical America to prevent the occurrence of broken bones, since calcium and phosphorus are deficient in the soil and consequently in pastures. While few large mammals evolved in tropical America, vast herds of large mammals have evolved in Africa and on the temperate prairies. This suggests that the evolution of large mammals was precluded in the savannas of tropical America by the calcium and phosphorus deficiency of the soil. Projected agricultural development of these savannas will require greater attention to supplying bases than will similar development in Africa.

Densely forested parts of the tropics are frequently viewed as potentially viable agricultural areas. Proponents point to adequate rainfall and temperature conditions or, more naively, to the volume of biomass present. The soils in such areas vary widely. The density of the humid forest tends to show little response to soil conditions, although compositional variation is often related to soil variation. Depending on the composition of the parent material, soil conditions are very much like those in the forested areas of the nonglaciated temperate zone. Where the parent materials are acidic, the soils closely correspond to those of the southeastern United States and have the same problems of low cation retention, high acidity, and high exchangeable aluminum content. Where soils are derived from basic materials they tend to be less acid and frequently neutral in reaction. In all the forested areas the bulk of the available nutrient elements are bound in the biomass and tightly conserved in a closed nutrient cycle. Recent floodplain areas which receive additions of fertile sediment abound but are seldom contiguous for sufficient distances to support more than subsistence exploitation.

Shifting cultivation is common in many of these areas. Farmers utilize the nutritional accumulation of several years of biomass in hardy noncommercial species to fertilize 1 to 3 years of cultivated agriculture. Fire, used to clear the land, hastens the release of the organically bound nutrients, thus providing for the farmers' needs in rapid crop production.

Tropical deserts and semiarid areas with low total annual rainfall exist at all altitudes and over a wide range of temperatures. The soils are often quite fertile, and their only outstanding need is for irrigation systems to transmit water. There may be some salinity and alkalinity problems. These areas are sparsely populated except for the irrigated valleys, many of which support modern intensive agriculture.

Recent volcanic areas and steep slopes are sites of intensive subsistence cultivation in the tropical highlands. Although the processes of soil formation and many of the soil properties differ greatly, one common pedogenic principle prevails: the soil materials have not been subjected to intensive weathering. Therefore, these soils provide enough nutrients so that when a crop seed is placed in the ground it will grow. Erosion, detrimental in most areas, is frequently the mechanism of removing the more weathered, base-depleted mineral material from the soil surface and exposing less weathered material.

A better understanding of the similarities and differences between soils of tropical and temperate areas is needed for appraising their properties and for extrapolating management practices. This task has been greatly helped by the development of a natural soil taxonomy system (*2, 13*) akin to the better known plant and animal taxonomies. Soils can now be grouped and named according to their measurable properties, instead of the older classifications based on various soil genesis theories.

In this system, many similar temperate and tropical soils fall into the same classes through the fifth hierarchical level (the soil family), where soil temperature criteria separate them. Early observations—such as those of Marbut and Manifold (*17*), who asserted that the predominant soils of the Amazon Basin are similar to those of southeastern United States—can now be quantitatively proved (*18*). A more abbreviated system has been developed by the Food and Agriculture Organization of the United Nations (*19*) in preparation for the U.N.-sponsored world soil map. The nomenclature is somewhat different to accommodate different national preferences, but the effect is similar. It is possible now to have a reasonably well quantified estimate of the geographical extent of the main soils of the tropics based on small-scale maps (*20, 21*).

High Base Status and Low Base Status Soils

Agriculture in the tropics first developed in areas of high base status soils. These soils—now called Alfisols, Vertisols, Mollisols, and certain Entisols and Inceptisols (*13*)—cover approximately 18 percent of the tropical land area (*16*). The centers of population in the tropics are in areas having these soils. The impact of the Green Revolution programs is very much limited to areas with high base status soils, particularly those that are irrigated. These soils have generally developed from alluvium, sediments, or volcanic ash rich in calcium, magnesium, and potassium. They present slight to no acidity problems and therefore require practically no investment in lime. Nitrogen is the most commonly limiting nutrient. Phosphorus deficiency, micronutrient disturbances, and moderate salinity problems occur, but these can be corrected at low cost. In other words, high base status soils are almost synonymous with high native soil fertility and a relatively low cost of supplying additional nutrients.

A larger group of soils in the tropics are of low base status and are highly leached. They are now classified mainly as Oxisols, Ultisols, some Inceptisols, and sandy Entisols. They cover approximately 51 percent of the tropics (*16*) in vast areas in the interior of South America and Central Africa and smaller areas of the hill country of Southeast Asia. These soils are commonly deficient in bases and often present aluminum toxicity problems. Deficiency of phosphorus is often difficult to correct because phosphorus fertilizers react with iron and aluminum oxides and are fixed in slightly soluble forms. Micronutrient and sulfur problems are common. Correcting these nutritional problems usually involves substantial investments in fertilizer and lime. On the positive side, many of these low base status soils, especially the Oxisols, possess excellent physical properties which facilitate tillage and reduce erosion hazards. The fact that no great centers of population are found in these areas can be related to the infertility of such soils, as well as other factors. Similar soils, mainly the Ultisols, are found in the temperate region in areas such as southeastern United States and southeastern China, where they support large populations. They were intensively cropped after correction of their low fertility with manures, fertilizer, and lime.

A third major grouping consists of high base status soils called Aridisols, which occur in tropical deserts and occupy about 14 percent of the tropics. The availability of irrigation and nitrogen are the principle limiting factors. When properly irrigated, and thus free of salinity problems, these soils can become extremely productive.

A fourth group consists of shallow soils and dry sands, which occupy the remaining 17 percent of the tropical land mass.

Our discussion will be limited to the first two groups only, the third being the domain of irrigation specialists and the potential of the fourth being severely restricted.

There is no need to remind the reader of the dismal statistics on the subject of world food shortages. Massive food exports from the developed countries into famine areas should only be considered as short-run measures. In the long run, political and practical considerations dictate that developing countries must feed themselves. Is this likely to happen in the remainder of this century? Assuming significant gains in birth control, there is increasing evidence that, in certain tropical countries blessed with some high base status soils and cursed with vast areas of low base status soils, this is agronomically possible.

We submit two fundamentally different strategies to achieve this goal: intensive agriculture in high base status soils and extensive agriculture in low base status soils.

Intensive Production in High Base Status Soils

The productivity of high base status soils has been proved; for centuries they have supported dense human populations and large animals. Application of a technological package consisting of new high-yield varieties of wheat and rice, nitrogen fertilization, chemical weed and pest control, and very often irrigation has provided dramatic sustained increases in production (*22*).

The spread of the Green Revolution is very much limited to high base status areas of tropical Asia and tropical America. Further progress can be expected when high-yielding varieties of other cereals, grain legumes, and particularly root crops are developed. Soil management adaptations to future varietal breakthroughs are bound to be relatively straightforward. The value of the crops and land will probably justify substantial investments in fertilizer, in spite of the current high prices.

Research on more efficient use of nitrogen fertilizers, through either slow-release sources or improved manipulation of rates, placement, and timing of applications, is of high priority and has already produced significant results (*23*).

An intriguing possibility is to improve the intercropping systems practiced for centuries by subsistence farmers, in which a number of crops are grown at the same time in the same field. Such practices were regarded as primitive by agronomists and soil scientists until original research by Bradfield and associates (*24*) attracted international attention. The shift of the soil scientist's focus from supplying nutrients to a single crop to supporting two or more interacting root systems and harvesting two or sometimes four crops a year will require a major effort in fundamental and practical research. The first results of this effort show that certain intercropped systems use fertilizers much more efficiently and economically than would the separate crops grown on an equivalent area (*25*).

The food production increases in high base status soils will be limited by their relatively small area and already intensive exploitation. It is doubtful whether the world food crisis can be solved if development is limited to these soils.

Extensive Production in Low Base Status Soils

An appraisal by Kellogg and Orvedal (*26*) indicates that the vast tropical jungles and savannas constitute the largest block of potentially arable soils in the world. What has been done about them? The first research efforts, by European colonial governments in Africa, attempted to replace the seemingly primitive system of shifting cultivation by intensive mechanized farming similar to that of Europe. These efforts failed because of inadequate knowledge of both the physical and the social environment. Later efforts in Zaïre concentrated on rationalizing the pattern of land clearing, using corridors to preserve the ratio of years in crops and years in fallow essential for the maintenance of shifting cultivation (*27*). In sharp contrast, the state of São Paulo in Brazil has developed modern agricultural practices on low base status soils basically no different from the soils of Zaïre. Research in São Paulo (*28*) led to fertilizer, lime, and energy inputs similar to those used in the southeastern United States. These dramatically different approaches deserve some examination. The low base status soils of Zaïre, São Paulo, and the southeastern United States have similar limitations of high exchangeable aluminum contents, low phosphorus contents, and associated problems. Direct transfer of U.S. or European principles and practices to Zaïre and São Paulo was possible at experiment stations, where crop production exceeded that in the United States because of the year-round warm climate. In Zaïre, lack of transportation, industry and market infrastructure, and century-old social customs prevented their adoption. In São Paulo, adequate transportation, industry (including fertilizer production), markets, and sparse population permitted their adoption. The high levels of investments in fertilizer and lime paid handsomely in São Paulo.

With the advent of the protracted energy shortages and the continued high cost of petroleum and fertilizers, some modifications of the method applied successfully in São Paulo are needed. A strategy based on minimum inputs is gradually taking form within the tropical agronomy research community.

The first consideration is an awareness that shifting cultivation is an efficient soil management system, considering the resources farmers have at their disposal in sparsely populated forested areas (*29*). However, population pressures are reducing ratios of crop years to fallow years to the point where shifting cultivation is degenerating into a downward fertility spiral in many areas. The need for continuous cropping is acute and systematic research efforts are required. In the vast savannas of South America, where extensive cattle grazing is virtually the only form of agriculture, the opening of new roads and markets carries with it an infusion of new settlers. For example, within 10 years after the 1500-kilometer road between Belém and Brasília was constructed, 2 million people have settled along it. They are, however, dependent to a large extent on food transported from other areas.

A second consideration is that, instead of manipulating the soil to meet plant demands, the opposite strategy should be favored, that is, adapting plants to low base status soil conditions (*30*). Certain crop and pasture species are more tolerant than others to high levels of exchangeable aluminum, low levels of available phosphorus, and other soil problems. Examples of the more tolerant species are upland rice, cassava, sweet potatoes, cowpeas, and several grass and pasture legumes (*31, 32*). Significant differences in tolerance to these limitations are also known to exist between varieties of rice, wheat, dry beans, and soybeans (*30, 33*). Tolerant species and varieties evolved in low base status soils and thus are a result of natural adaptation to such conditions. These differences have been traced to specific genes in certain crops (*33*). Tolerance to exchangeable aluminum and low available soil phosphorus can become a major component of breeding programs. The nutritive value of these varieties, however, should be considered. Plant breeders and soil scientists working together on these problems should be able to produce more tolerant species with other desirable properties such as high yield potential and grain quality. As Jennings (*22*) commented, it is necessary to stop selecting future varieties under optimal soil, water, and pest control conditions.

There is increasing evidence for a quasi-symbiotic nitrogen fixation between bacteria that thrive in acid soils and certain varieties and species of tropical grasses. Döbereiner and Day (*34*) indicate that selection of species and varieties of such grasses could add a significant amount of nitrogen, when the conditions on which these organisms thrive are better understood.

Adaptation of crops to low base status soils cannot be viewed as a substitute for fertilizer applications. However, it would significantly decrease the quantity of fertilizer and lime needed to obtain optimum yields. The question that should be considered is what are optimum yields under these conditions. Economists and soil scientists are trained to consider an optimum yield as the point in the fertilizer response curve where the marginal revenue from an added yield equals the marginal cost of the last input of fertilizer. This concept may prove to be another casualty of the energy crisis.

In the areas we are considering land is relatively cheap, while the cost of fertilizer and its transportation from the factory to the farm are expensive. Optimum yields should be considered those which optimize the use of the scarce resources: fertilizers and other energy-based inputs. Maximum fertilizer efficiency is reached in the steep initial part of the fertilizer response curve. Marginal analysis, however, recommends fertilizer rates in the relatively flat later part of the curve. When the fertilizer response curve is represented by two straight lines, in the linear response and plateau model (*35*), the recommended rate is that at which maximum yield is attained at the point of maximum fertilizer efficiency. The rates recommended by the linear response and plateau model are usually lower than those recommended by marginal analysis. Considering the residual effect of many inputs, particularly lime, phosphorus, and some micronutrients, and the possibility of obtaining two or three crops a year in many of these areas, the use of lower fertilizer rates is not bound to decrease food production. Together with the use of adapted species and varieties, it represents an adjustment to the new economic realities and, in the long run, a means for conserving resources such as phosphates.

A third consideration is devising a means for increasing the efficiency of the fertilizer and lime that are applied. The use of methods for evaluating soil fertility, including soil tests, plant analysis, correlation studies, and interpretation, has substantially increased the efficiency of fertilization and liming in tropical America (*36*).

Many low base status soils have an extremely high capability to "fix" phosphorus in relatively insoluble forms. The quantities of water-soluble superphosphates needed to provide adequate yields are often uneconomical, unless ample credit is available to depreciate the cost as a capital investment for several years (*37*). Attention has recently been directed by the Tennessee Valley Authority and its cooperators toward direct application of water-insoluble rock phosphates (*23*). Many rock phosphates of high reactivity are soluble in acid soils, and are cheaper than superphosphates, because they are the raw materials from which the latter are produced.

In certain low base status Oxisols, silicates are applied commercially as fertilizer (*38*). The silicate anion reacts similarly to the phosphate anion in these soils, and thus silicates can also be fixed by iron and aluminum oxides. Although silicon is not officially accepted as an essential element for crops, favorable agronomic responses to silicon applications are known to occur in crops like sugar cane and rice (*38*). A further combination is also possible. Rock phosphates of low reactivity can be thermally fused with inexpensive magnesium silicate to provide a source of more soluble phosphorus with silica and other elements in it. These products were studied in the 1930's and 1940's in Europe and the United States, but were abandoned when they could not compete with superphosphates. The old literature is literally being pulled from the shelves and the findings adapted to these tropical soils. Research on these and other unconventional fertilizer sources, such as slow-release nitrogen products, is an exciting activity at many experiment stations in the tropics.

The concept of maximizing the efficiency of energy-related inputs in tropical areas is not necessarily limited to fertilizers. For example, research on land-clearing methods in the Amazon jungle indicates that the traditional slash-and-burn method with hand labor produced higher yields at a lower cost than does mechanized clearing with bulldozers (*39*). The main factors are the high cost of operating and maintaining machines in tropical rain forests and the free fertilizer obtained from the ash. Also, with smaller clearings the transition from shifting to continuous cultivation can be made gradually. Clearings of several hundred hectares, although attractive to development officials, create havoc for farmers when they have to cope with vigorous jungle regrowth, fertilizer shipments, and other severe management problems on a large scale. Very often such areas are eventually abandoned.

Prognosis for Increasing Food Production in the Tropics

We are cautiously optimistic that soils of the tropics can make a major and sustained contribution toward world food production when they are well characterized and understood and economically realistic management systems are used. Most of the improvements in the near future can be expected from increasing yields in the high base status soils, but in the long run the conquest of the low base status soils is the larger issue. Ongoing research projects in various regions of the tropics support these statements. Unlike classic plant breeding problems, many problems concerning soils are site-specific, and recommendations have to be compatible with practices at the local levels. Therefore, more sites are needed for practical soil management research. This was demonstrated at a recent seminar on soil management in Colombia (*40*), when a delegate from Nigeria recommended that burning should be eliminated in clearing tropical forests, while work in Peru demonstrated the dramatic fertilizing benefits derived from burning. This apparent discrepancy was explained by the fact that the ash raised the soil *p*H from 6 to 8 in Nigeria, causing iron deficiency, while in Peru the ash raised the soil *p*H from 4 to 4.5, supplying needed bases to the soil.

Pronouncements concerning the effectiveness of soil-related practices have to be carefully evaluated according to soil properties. A single tropical soil elixir is not available.

Summary

The properties and potential of soils of the tropics are poorly understood. The old idea that laterite is formed when tropical soils are cleared is true of only a small proportion of the area. In most features soils in the tropics are similar or equivalent to soils in the temperate regions. Specifically, soil organic matter contents, commonly believed to be low in the tropics, are essentially similar to those of the temperate regions. While the basic concepts about physical and chemical behavior developed in the nonglaciated temperate regions are directly applicable to the tropics, the development of soil management practices for sustained food production involves different strategies because of environmental and economic constraints. A major distinction is made between the development of high base status and low base status soils. With the former, soil management practices should be aimed at maximizing the potential of high-yielding varieties and improving intercropping systems with relatively intensive fertilizer inputs. With the low base status soils of the vast savanna and jungle areas energy-related inputs should be optimized by (i) selecting of crop varieties and species more tolerant to nutritional deficiencies or toxicities, (ii) applying fertilizers at lower rates than those recommended by classic marginal analysis, and (iii) increasing the efficiency of applied fertilizers in such soils.

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