SOILS OF THE

HUMID TROPICS

NATIONAL ACADEMY OF SCIENCES

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Soils of the Humid Tropics

COMMITTEE ON TROPICAL SOILS
AGRICULTURAL BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C. 1972

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The members of the study committee were selected for their individual scholarly competence and judgment with due consideration for the balance and breadth of disciplines. Responsibility for all aspects of this report rests with the study committee, to whom we express our sincere appreciation.

Although the reports of our study committees are not submitted for approval to the Academy membership nor to the Council, each is reviewed according to procedures established and monitored by the Academy's Report Review Committee. Such reviews are intended to determine, inter alia, whether the major questions and relevant points of view have been addressed and whether the reported findings, conclusions and recommendations arose from the available data and information. Distribution of the report is approved, by the President, only after satisfactory completion of this review process.

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PREFACE

In the 1967 report of the President's Science Advisory Committee Panel on the World Food Problem, it was estimated that of the 13 billion ha of ice-free land in the world, more than 3 billion are potentially arable. Of this amount, more than half, or some 1.6 billion, are not now under cultivation. Half of this uncultivated land, or some 800 million ha, lies in the humid tropics between the Tropic of Cancer and the Tropic of Capricorn (23½° north and south of the equator), where the climatic environment offers a high potential for crop production. These 800 million ha represent a substantially greater area than is now being cultivated in the humid tropics. If only 2 percent of this area were put into cultivation with good management practices, enough food could be produced to feed the present population of Latin America.

If soil areas in the humid tropics that are most likely to respond to modern technology could be identified and if the most efficient uses of these soils were better understood, much more of the land could be successfully utilized. There is little doubt of the great need for more knowledge on how best to utilize this vast untapped resource effectively. Though there has been a considerable amount of research on tropical soils over the years, a much greater effort will be required

to solve the many technical problems involved in their efficient use.

Since it is urgent that expanding world food needs be met, and since there are limits on the scientific manpower that can realistically be brought to bear on these problems, there is a critical need to identify the tropical soils research that should receive first attention. In response to this need, the Agricultural Board of the National Research Council, with financial support from the Agency for International Development, established a Committee on Tropical Soils to assess present knowledge of the soils of the humid tropics and to establish the major research needs. The 12 members of the Committee, from the United States and abroad, have had extensive experience in the tropics and represent a wide range of experience in soil science (including soil classification, morphology, and genesis; soil fertility and management; soil physics, chemistry, and microbiology) and related disciplines (including agricultural climatology).

Because of the great range of soils in the humid tropics, the Committee limited its study for the most part to areas at the lower elevations, less than 1,000 m, and to the better-drained upland soils of favorable topography where the greatest agricultural potential exists. The humid tropics were considered to include areas that have substantial rainfall during most of the year but have a distinct dry season lasting perhaps 4 to 5 months. There is a substantial amount of literature and research in progress on the flooded rice soils and the Vertisols (dark clays); consequently, these soils were not given much attention in this study.

The Committee wishes to thank the Professional Associates who contributed so substantially to its work: J. Boyer, Office de la Recherche Scientifique et Technique, Outre-Mer (France); P. H. Le Mare, Rothamsted Experimental Station (England); A. R. Van Wambeke, Ghent State University (Belgium); and H. Vine, University of Leicester (England). Thanks also are due to Dr. E. J. Kamprath of North Carolina State University, who made an important contribution to this volume.

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INTRODUCTION

Throughout the world, the nature of soils and the uses that can be made of them are strongly influenced by climate. The climates of the tropics vary considerably, but they differ collectively from climates of temperate regions in certain respects that have profound consequences for vegetation, soils, and men.

The wet equatorial climate is confined largely to areas between 5° north and south of the equator where the well-distributed rainfall, with perhaps 2 or 3 months of lower rainfall, may exceed 250 cm per year. Such areas are extensive in South America, the Congo Basin, a narrow strip in West Africa, the Pacific Islands, and the Far East, mainly Indonesia. Generally, the soils are highly weathered and highly leached, and though large areas are topographically suitable for agriculture, they are not intensively used. Dense populations usually are found where the soils have been enriched by recent volcanic activity or by young alluvial deposits.

The alternating wet and dry tropical climate, e.g., the monsoon climate controlled by the movement of air masses, covers areas of great agricultural importance between 5° and 15° North and South latitudes in South America and Central and West Africa; they extend considerably farther north in South and East Asia. Areas with two

rainy seasons of varying length or with one rainy season also of varying length are located within this belt, e.g., Southern Ghana, Southern Nigeria, and parts of Uganda and Southeast Asia. A belt north of this, extending across Africa, has one short rainy season. Between these two extremes in this climatic zone are areas such as Malawi and Zambia, which have one long rainy season of up to 6 months. The soils within this belt are quite variable. On the old surface of Africa and South America, large areas of highly weathered and highly leached soils are thoroughly impoverished, whereas in South and East Asia, rich alluvial deposits support very dense populations.

The distribution and properties of the major soils of tropical areas are discussed in detail in subsequent chapters, but it is appropriate to note here how temperate-region soils and climates, from which many management concepts have been derived, differ from those in the tropics. Apart from the fact that the parent materials of many tropical soils are much older, so that the reserves of weatherable minerals are small, the leaching and weathering pattern is different. In temperate climates, summer, the time of greatest plant growth and of most intense chemical and biological activity, is also the period of least leaching, for much of the soil moisture is taken up by plants and lost by transpiration. In winter, the time of greatest moisture surplus, temperatures are low, so plant growth and rates of evaporation are small or negligible.

By contrast, high temperatures throughout the year in the tropics accelerate microbiological and chemical activities if there is sufficient moisture. Where rainfall is uniformly distributed, there is a surplus for leaching in most months. Where there is a distinct dry season, the vegetation removes all or most of the available water within root range during the growing season, and the next season starts with little or no reserve of moisture in the soil. Caught in this way between drought and leaching, with the added risks of seasonal waterlogging and erosion, the management of soils and crops in the tropics is profoundly different, and inherently very much more difficult, than in temperate regions.

The great difference between climates and soils of the tropics and temperate regions imposes important restraints on the transfer of farm technology from one region to the other. Though the broad and tested principles of pure and applied science may be universally valid, their application to agriculture in any particular place depends on the specific environmental circumstances of that place. A copper mine, a steel mill, or a textile plant may need no more than adaptive investi-

gation before it can utilize improved technology. But farm technology, like all technology for the use of biological natural resources, is locale dependent. Most tropical soil problems can be solved only where they exist; all imported assumptions, preconceptions, and prejudices must stand open to question. Consequently, in what follows, we have sought to distinguish the specific problems in the use of tropical soils from the guiding generalizations of soil science that have wide global applications.

RESEARCH NEEDS

The Committee was fully aware of the difficulties of listing research priorities that would have overall application to soils of the tropics. Any priority listing will need to be modified by social and economic factors as well as by the nature of the soils and other physical resources of any particular area. Bearing these limitations in mind, the Committee proposes the following priority research needs.

SOIL INVENTORY

Soil Survey

In developing countries, where needs are urgent and resources are limited, one of the first objectives should be a soil survey to develop a general inventory of the principal kinds of soil and to specify in broad outline the location and geological, geomorphological, ecological, and climatic relations of these soils. If maps based on such surveys are available, they should be published and should include essential descriptive material. A serious international effort should be made to expedite publication of the FAO-UNESCO World Soil Map

at the 1 : 5 million scale and the world soil map of the USDA Soil Conservation Service at a 1: 2.5 million scale. Larger-scale international maps for some regions will be needed in the near future (1 : 1 million). These maps will provide the basis for intermediate surveys for maps generally on a scale of 1 : 100,000 or 1 : 200,000. Intermediate surveys should be undertaken only for specific and clearly defined purposes, particularly those concerned with development, e.g., intensification of agriculture in existing farm settlements, colonization projects, construction of new roads or railways, and irrigation schemes.

Detailed surveys, mapped on scales of 1 : 20,000 or larger, will be needed for operational planning and development of particular localities. Detailed surveys with accompanying reports are highly desirable in densely populated areas; where such surveys exist, they should be made widely available. Also, special detailed surveys associated with soil management studies are recommended for areas that include relatively infertile soils with good potential for development, e.g., Terra Roxa Legitima (Acrorthox); soils of Northeast Brazil (mainly Ustalfs) and New Caledonia (mainly Ustults and Udults); Oxisols and Ultisols in the Central Plateau of Brazil; Sols Ferrallitiques fortement désaturés (Paleudults) in Upper Volta; Sandy Ferralsols (Orthox and Ustox) in the Republic of the Congo (Kinshasa); Gray Podzolic Soils (Paleustalfs and Paleustults) on old terraces in Southeast Asia; and Tropepts and Orthox in the Llanos of Colombia and Venezuela.*

In the special detailed surveys associated with soil management practices, attention should be given to irregular plant growth over very short distances. The causal factors of this microvariability, such as termite mounds and microrelief, merit detailed study in order to apply appropriate corrective measures.

Soil Survey Report

The objectives, terminology, and methods, including the methods for physical, chemical, and mineralogical characterization of soils, must be clearly defined and recorded in all surveys. Descriptions of soils

*Oxisols, Ultisols, Orthox, Paleudults, Paleustalfs, Paleustults, and Tropepts are taxonomic classes in the new soil taxonomy of the National Cooperative Soil Survey of the United States. It is commonly known as the 7th Approximation, but in this publication it will be referred to as the new U.S. soil taxonomy. For brief descriptions of classes of importance in the tropics, see the chapter on Soil Survey by Aubert and Tavernier, p. 17.

should use internationally accepted and clearly defined terms at all levels of detail. The names of the soil units should be correlated with the terminology of one of the internationally recognized systems such as the new U.S. soil taxonomy or the FAO system.

Every soil map, at whatever level of detail, must be accompanied by an explanatory memorandum that follows the principles set out above and includes for each recognized soil unit at least the following information: (1) the general features of the location and environment; (2) a description of the soil, including physical, chemical, and mineralogical measurements; and (3) an interpretation of the data in relation to present and possible future uses and development of the area surveyed. All relevant agricultural data and farming experience should be utilized for this purpose.

SOIL MANAGEMENT SYSTEMS

The major objective of soil research programs should be to improve the current soil management practices within the social and economic conditions of any particular area. In large areas of traditional agriculture, fertilizers will replace natural fallows as a means not only of maintaining but also of increasing fertility and productivity. But fertilizers will be only one component of systems of higher productivity; manipulation of the physical properties of the soil to control erosion and improve water entry and of the biological properties to control soilborne pests and diseases—functions at present performed by the fallows—will need to be worked into the improved systems. Research on soil management will need to be designed, therefore, to fit these components into socially and economically acceptable systems. Natural fallows, however, are likely to remain the dominant form of agriculture over considerable areas for several decades. Their function in maintaining soil fertility thus should not be ignored, nor should opportunities for their improvement be missed.

Long-term experiments are essential for developing soil management systems, including multiple cropping and rotations that are an improvement over those currently used in traditional agriculture in the tropics. Such experiments need repetition at several sites on carefully characterized soils and climates that are representative of extensive areas. The priorities assigned to specific research problems in these experiments will be locale dependent; for example, in some

areas soil moisture or soil structure will be most important; in others, the nitrogen supply or soil acidity. Most probably a combination of two or more problems will be involved. The more important of these are outlined below.

Physical Properties

One of the basic soil physics problems in the humid tropics arises from the removal of the protective vegetative cover when the rain forest or savanna is cleared for cultivated crops. The natural source of organic matter is removed, and the soil is exposed to the impact of tropical rains and to the intense rays of the sun. These new environmental circumstances cause many physical changes in the soil that require evaluation and the development of appropriate management practices.

Evaluation of Changes That Occur in Soil Temperature, Soil Moisture, and Soil Structure Regimes

To evaluate changes that occur in soil temperature, complete climatological stations must be set up in areas selected for study to (1) measure both air and soil temperatures, (2) establish the pattern of rainfall characteristics, and (3) determine the necessary parameters to characterize energy and water balances.

Soil moisture measurements by appropriate instrumentation are essential for evaluating water infiltration, permeability, and water retention in relation to rainfall distribution and crop utilization.

Soil structure changes will require measurements of both aggregate stability and pore-space relationships. Pretreatment techniques with alcohol and benzene have proven valuable for determining aggregate stability for most tropical soils, other than sandy types. Rainfall-acceptance tests not only provide data on aggregate stability but also give an approximate measure of soil crusting. Soil aeration porosity is determined at a moisture tension of 1/10 to 1/3 bar. This value also gives a fairly reliable index of soil permeability. In some cases, it may be necessary to determine soil porosity at one or two other tensions on the wet end of the moisture-tension curve. Both the stability of soil aggregates and the soil porosity measurements are important to characterize certain groups of soils, such as Ultisols, Alfisols, and Inceptisols.

Development of Improved Practices for Soil Conservation and Soil Moisture Utilization

In changing from natural vegetation to cultivated crops, improved soil and crop management techniques are required to optimize soil moisture conditions and soil structure for optimum crop production and to minimize erosion losses. Such techniques will necessitate long-term field experiments on crop rotations, use of cover crops, intercropping, crop residue management including soil mulches, tillage practices, contour cultivation, and strip cropping.

Nitrogen and Organic Matter

Nitrogen is the nutrient element most likely to limit crop growth and yields under the leaching conditions of the humid tropical water regime. Increases in yield and profit are bound to require more available nitrogen for crops. The Committee, therefore, recommends that the nitrogen cycle be viewed as an integral research field that should include studies of gains, losses, movement, forms, and transformations of all kinds, as well as management of the processes involved.

Nitrogen-Supplying Capabilities of Tropical Soils, and Crop Needs for Nitrogen

Some soils in tropical regions supply important quantities of nitrogen to crops. There is need to identify these soils and to evaluate the methodology for assessing their nitrogen-supplying capacities by laboratory methods in order to minimize the more costly field and greenhouse techniques.

Systematic investigations need to be conducted under field conditions to ascertain the needs for nitrogen. These should include the use efficiency of different sources of nitrogen fertilizer and organic materials as well as application methods and time schedules. The movement and leaching patterns of nitrogen in the soil in relation to high rainfall regimes and to wet and dry season conditions need to be more thoroughly studied in order to formulate efficient practices for using nitrogen fertilizer.

The part that biological nitrogen fixation can and should play in improving tropical agriculture should be critically evaluated. Areas of applied research that require attention are (1) inoculation and nodulation of newly introduced legumes, (2) management and fertiliza-

tion of leguminous crops, (3) evaluation of nitrogen fixation by leguminous crops in tropical regions, and (4) evaluation of nonsymbiotic nitrogen fixation.

Organic Matter Problems

There is a great need for research on the impacts of (1) burning on soil organic matter and nutrient availability, (2) fallowing on changes in nitrogen and organic matter contents, and (3) crop residue management.

Phosphorus and Sulfur

Basically, research is needed to provide measures for increasing the availability of applied phosphorus and sulfur, both for the treated crop and residually for crops that follow. Increasing the efficiency of fertilizers would reduce a major input cost for the peasant farmer, which would make him more willing to accept fertilizers and other inputs needed to substantially increase his productivity. Specific areas in which research is recommended are outlined in the sections that follow.

Predicting the Need for and Crop Response to Applied Phosphorus and Sulfur

Reliable prescriptions of phosphorus and sulfur needs of crops grown on tropical soils are fundamental to economic fertilizer use by peasant farmers. Research is required to validate soil-testing methods for phosphorus and sulfur and to calibrate the tests with yield response data from field trials on the soils involved.

Improving the Efficiency of Phosphorus and Sulfur Fertilization

Standard Fertilizer Materials It is important to investigate the role of granulation *per se* and the combination of granulation with band or hill placement of phosphate in reducing fixation reactions and prolonging availability of applied increments.

Prilled sulfur products have not proved very effective as a fertilizer source in the cool temperate regions. However, an appropriate prill size could materially extend the release period of available sulfate

from an applied increment in the tropics and thus could eliminate the excessive leaching losses that occur when finely divided elemental sulfur and sulfate sources are used. A strongly granulated gypsum product might accomplish the same purpose with less acidifying action.

Thorough investigation would be desirable on all sources of rock phosphate and aluminum phosphate having economic potential, especially those closest at hand with minimum shipping requirement. Naturally, studies should be limited to acid soils. Certain rock phosphate sources have been shown to be almost as effective as acidulated materials for paddy rice. If such materials can be obtained cheaply, a substantial savings in foreign exchange might be possible, compared with importing factory formulations.

Modifying Standard Fertilizer Materials There is need to investigate the feasibility of coating important high-analysis phosphorus fertilizers like the ammonium phosphates and concentrated superphospate with some material that might minimize the phosphorus-fixing capacity of the soil in the zone of fertilizer placement. Much of the fertilizer evaluation work of the past was done in temperate regions with soils of little or no fixing capacity. Conceivably, coating each phosphate fertilizer granule with an appropriate material might protect it for at least several weeks against fixation by iron and aluminum hydrous oxides.

Determining Interactions of Applied Phosphorus and Sulfur with Other Nutrients

The influence of applied phosphorus and sulfur on uptake and utilization of other nutrients by crops should be studied in order to forecast the complementary or depressive action of the applied phosphorus and sulfur on the other soil nutrients (e.g., manganese, zinc, copper) and on each other.

Similarly, the impact of liming and of applied nitrogen fertilizers on the efficiency of crop utilization of fertilizer phosphorus and sulfur carriers should be investigated. Such studies would logically include long-term evaluation of residual accumulations in the soil of available phosphorus and sulfur.

Improving the Residual Effects of Applied Phosphorus

Feasibility studies are needed with chemical carriers of low water solubility that have a comparatively high dissolution rate in the soil,

such as anhydrous dicalcium phosphate, for minimizing the effects of the high phosphorus fixation potential of some tropical soils.

Phosphorus carriers should be studied in soils where fixation is a problem, including not only all the common carriers but also less common carriers like polyphosphates, which have not been evaluated in the tropics.

The influence on fixation reactions of organic substances that are applied with phosphorus fertilizers should be studied in important Oxisols and Ultisols.

The phosphorus fertilizer rate and conventional carrier studies should be planned with a major objective of evaluating the residual availability of phosphorus to help determine the full economic value of any applied increment.

Potassium

Lack of potassium is rarely a limiting factor for crop production under conditions of traditional tropical agriculture. However, potassium deficiency may occur rapidly under intensive cultivation after land clearing in strongly leached Oxisols and Ultisols; deficiencies on most other soils develop only after several years of intensive cultivation. Based on these considerations, the following priority research studies are recommended:

Loss of Potassium by Leaching

In view of the low buffering capacity of many soils with a high content of free aluminum and iron oxides, e.g., Oxisols, it is important to determine leaching losses of potassium under various fertilizer and soil management practices. Attention should be given to the influence of phosphate, sulfate, and chloride ions on the retention and movement of potassium in the soil.

Methods of Determining Potassium Available to Plants

Studies on the release of nonexchangeable forms of soil potassium and the development and testing of analytical methods for determining both the readily and slowly available forms of soil potassium are needed. Once adequate procedures have been developed, it should be possible to identify areas deficient in potassium through routine testing of soil samples.

Soil Acidity, Liming, and Ion Exchange

Liming highly acid soils of the humid tropics according to the standards and procedures used in the temperate zone has often done more harm than good. A better understanding of the importance of exchangeable aluminum in soil acidity has evolved in recent years. The newer concepts help provide a better basis for determining response to lime of the various kinds of acid soils in the humid tropics, but much more research is required to resolve the many problems involved in the efficient use of liming materials.

Characterization of Soil Acidity

Available evidence indicates that many soils in the humid tropics have a high percentage of exchangeable aluminum saturation when the pH is less than 5, are very low in exchangeable calcium and magnesium, and have a low effective cation exchange capacity. Research is needed to provide information on the major acid soils relating (1) the amount of exchangeable aluminum to the exchangeable bases, and (2) the concentration of aluminum and other cations in the soil solution to the exchange properties of the soil.

Liming Studies

Field and greenhouse studies are needed on major acid soils of the humid tropics for establishing the rates of lime needed for most effective crop growth, including long-term studies to determine the frequency of lime application required for maintaining adequate base saturation. Where magnesium is limiting, dolomitic sources of lime should be included in the studies.

Particular attention should be given to the effects of subsoil acidity on root growth and methods of correction.

Soil tests should be developed for estimating the lime requirement. Logically, these should be based on neutralization of exchangeable aluminum and the amount required to eliminate manganese toxicity.

Experiments should be conducted to determine the aluminum tolerance of crop species and varieties commonly grown in the tropics.

Micronutrients

Micronutrient deficiencies will likely occur in many areas of the humid tropics with the intensification of cultivation that involves a

substantial use of fertilizers and lime and improved cultural practices. Some soils, such as those formed from quartz sands and very old sediments, may be so deficient in micronutrients when first cultivated as to seriously limit productivity. Therefore, the following priorities for research are recommended for areas where micronutrient problems are suspect:

Effect of Fertilization and Liming on Micronutrient Deficiencies and Toxicities

More information is needed on the effect of the source and amounts of nitrogen fertilizer on availability of micronutrients. Uptake of zinc and other micronutrients as influenced by applications of phosphate has been little studied in tropical soils. Liming to correct aluminum or manganese toxicity may seriously limit the availability of other micronutrients such as zinc and boron but may increase the availability of molybdenum. These interrelationships merit investigation on soils in the humid tropics where micronutrient problems might be anticipated.

Identification of Soil Properties Related to Micronutrient Problems

In areas where micronutrient deficiencies are likely to occur—e.g., soils formed from quartz sands or very old sediments—methods of characterizing more accurately the soil properties related to deficiencies of micronutrients need to be developed. Information on the distribution of the total amounts of the more important micronutrients in the profile may be helpful for predicting deficiencies as well as toxicities. Where a crop is grown, foliar analysis can be used as a diagnostic tool.

Availability to Plants of Micronutrients in the Soil

The use of extracting solutions and greenhouse studies to measure micronutrient availability must be accompanied by field experimentation. This is especially important for the micronutrients not only because they are required in such small amounts but also because they are especially sensitive to the soil, plant, and climatic factors that may influence their availability.

Silicate

Soils Responsive to Applications of Silicates

A better definition of the soils that are most likely to be responsive to silicate is needed. Broadly, these appear to be (1) soils derived from volcanic materials in high rainfall areas that are highly leached and highly weathered and (2) soils of the old terraces of South and East Asia and South America. Investigations are needed on crops such as sorghum and maize that might respond to applied silicate on deficient soils. Better definitions of responsive soils could be obtained if laboratory determinations of soluble silica were made during soil surveys.

Interaction of Silicate and Phosphate

The interaction between silicate and phosphate should be thoroughly studied. Although the use of silicates in relation to phosphate utilization has received considerable attention in temperate regions, it has had only limited attention in tropical areas, and work already in progress in certain institutions should be strengthened.

SUMMARY

Research priorities on soil chemical and physical properties are noted in the appropriate sections, but these priorities must be regarded as components of the total system. In broad outline, investigations of these chemical and physical properties would measure the changes in the soil and crop yields in long-term experiments. These experiments would compare farming systems of the area with those having resting periods of differing lengths of natural or planted fallows and those with continuous cultivation. Control of pests and diseases, used of improved adapted varieties, adequate moisture, and other management factors are essential components in the development of an appropriate system within the political, social, and economic framework of a country or region.

Summary of Present Knowledge

G. AUBERT AND R. TAVERNIER

Soil Survey

MAJOR PROPERTIES OF THE SOILS

Soil scientists traditionally have recognized the importance of climatic factors in the formation of soils. Although the soils of the equatorial regions vary greatly, climate indeed controls most of their key properties. These properties relate not only to pedogenetic processes but also to the actual potential of land to produce crops.

At low and intermediate elevations within the tropics, temperatures are high throughout the year, and there are no substantial seasonal variations. In these high isothermic regimes, soil-forming processes occur faster than in temperate regions, particularly the processes leading to advanced weathering stages of the parent materials. The products of this rapid decomposition have been studied in numerous investigations.

High temperatures also accelerate the turnover of organic matter in tropical soils; this process builds up humic complexes, the composition of which largely depends on the intensity of the dry season. At high elevations, where the mean annual temperature drops below 22°C, considerable organic matter may accumulate within the solum.

Less attention has been paid to the fact that in tropical and equa-

torial climates plant growth is never halted by low temperature. So long as water is available, growth continues. During the cold wet season in temperate climates, evaporation rates are small, and soils store water so that the season of crop growth starts with the soil fully charged with moisture. In the tropics a main factor restricting crop growth is drought—the growing season coincides largely with the rainy season, and it starts with the soil profile partly or wholly devoid of available water. Hence, one of the most striking unifying and distinguishing characteristics of tropical soils is the seasonal distribution of water availability, and its parameters constitute a very important criterion for the classification and utilization of tropical soils.

Other properties are important for understanding the behavior of tropical soils. As already mentioned, most parent materials have reached advanced stages of weathering. This is partly due to rapid rates of decomposition for long periods (Sieffermann and Millot, 1969). Age is a significant variable that determines many attributes of soils in the tropics and generally sets them apart from temperate soils. The largest land areas of the tropics belong to continental shields and tableland, which have not been subjected to recent folding. Rather, they have been subjected to gentle upwarping into continental swells and broad downwarping into large basins. This is particularly true for much of Africa, the Brazilian and Guinean shields in South America, and the Gondwana part of the Indian peninsula.

Since erosion has not been strong enough to remove the products of weathering on these relatively smooth, stable areas, and no icecaps have scraped the waste mantles away, almost all soils have developed from deeply weathered materials. They possess a very low mineral reserve for supplying nutrients to plants, are largely dominated by kaolinite in the clay fraction, and have retained much free iron oxides in the parent material. Low cation absorption capacities have made them particularly susceptible to leaching. Most of these soils contain some free aluminum oxides. In general, they have a deep acid solum that is poor in both major nutrients and micronutrients. Generally, they are well drained and their structure provides good aeration. However, as a result of their evolution during millions of years and under varying conditions, they often show, particularly in Africa, an altered upper layer in which gravels and even stones play an important role. Soil scientists of different countries have called the deep well-drained soils by various names: Latosols, Sols Ferrallitiques, Kaolisols, or Oxisols.

The recycling of the bases by the forest vegetation is an important

characteristic of soils in the humid tropics. Under natural forest vegetation and with a relatively low precipitation, less than 1,700 mm, the surface horizons are relatively enriched with bases as a result of the biotic cycles. With increasing rainfall, this enrichment becomes less pronounced. However, with the clearing of the forest under traditional farming systems, the natural forest fertility is gradually exhausted by leaching, and the surface soil becomes depleted of bases, even to levels below the subsoil. The natural forest fallow in the shifting cultivation system is a traditional means of remedying this depletion and rejuvenating the topsoil.

Not all soils within the tropics are developed on old landscapes; highly productive soils may occur in the low equatorial regions. Recent mountain building in the alpine orogenic belts has exposed fresh rock to erosion and provided a source of mineral nutrients to crops. Tropical Asia is a good example. Depressions and valleys are filled with detrital materials that react to management differently from the soils of the continental shields. A greater variability occurs within the profile characteristics of these soils, and no longer is the low mineral supply a major limiting factor for plant growth. During a long dry season, however, these soils may develop a structure unfavorable to rainwater penetration and root development, which may increase the erosion hazard. Soil scientists of different countries have called these soils Sols Ferrugineux Tropicaux, Sols Ferrallitiques Lessivés, Red Yellow Podzolics, Ultisols, or Gray Podzolics. The younger or rejuvenated soils that have developed from various parent materials have been called Sols Bruns, Tropepts, Ferrisols, or Alluvial Soil; those from basic volcanic rocks such as basalts, Reddish Brown Lateritic or Terra Roxa Estruturada; and those from volcanic ash, Andosols or Andepts. The most productive soils among them are tentatively called Nitosols in the latest legend for the FAO–UNESCO World Soil Map (Food and Agriculture Organization of the United Nations, 1968).

This brief review of soil characteristics in tropical areas, which are discussed at length in the following chapters, would not be complete without mentioning laterization, the formation of the soft plinthite and its hardening into ironstone. Iron oxide accumulates in flat lowland soils in the tropics at the level where the water table fluctuates in the profiles of the soils. It can also occur in poorly drained parts of level plateaus or at the lower end of long pediments. Huge subsiding zones that border the orogenic belts—for example, at the eastern foot of the Andes in South America—are being affected by the

formation of the soft plinthite or groundwater laterite, which may indurate when the water table is permanently lowered after wetting and drying cycles. It is felt that human activity has very little influence on these phenomena and that only under certain circumstances would agricultural practices modify the processes responsible for the formation of plinthite. For example, changes in vegetation (clearing of the forest) and artificial drainage favor the induration of plinthite. Extensive areas of ironstone formations are often found at the edge of tablelands (Maignien, 1958). These are probably relict features of a former landscape.

Soil moisture regimes, weatherable minerals, organic matter and nitrogen cycles, cation and anion exchange, clay minerals and soil structure are the properties that require most attention for adequate use of land resources in the tropics. It is essential to know the geographic distribution of these properties; soil survey and interpretation for agricultural utilization can provide suitable means to achieve this purpose.

DISTRIBUTION OF MAJOR SOILS

Many data on the geographic distribution of soils in the tropics have been collected during recent years. To get an overall picture of the soil distribution in the tropics that can be reasonably grasped, simplification of the data is a first necessity. During this process, important soil properties are selected as differentiating characteristics, and a classification is built on the basis of these criteria. This has been done in various ways, resulting in several world classification systems.

For the sake of clarity, one system was selected for use in this publication. The Comprehensive System (7th Approximation) of the U.S. Department of Agriculture (Soil Survey Staff, 1960) was selected as a central reference system.* Selection of this system does not mean that it is necessarily the most useful one in all situations or that it is endorsed in all its subdivisions by the contributors to this report. The color insert between pages 24 and 25 shows the distribution of soil orders and suborders according to this system. Tables 1 and 2 provide correlation with other systems.

*An updated version of this classification system is being prepared for publication under the title "Soil Taxonomy of the National Cooperative Soil Survey of the United States."

TABLE 1 Approximate Correlation between the French Soil Classification System and the New Soil Taxonomy of the United States, with Special Reference to the Tropics[a]

French Classification	U.S. Taxonomy (Orders, Suborders, or Great Groups)
I. Sols Minéraux Bruts (as far as recognized as soil)	Orthents, Psamments, and Fluvents
II. Sols Peu Evolués	
S.p.é. humifères	Orthents, p.p. Humitropepts, p.p.
S.p.é. à allophanes	Andepts, Eutrandepts, Vitrandepts
S.p.é. non climatiques	
d'érosion	Orthents, p.p., Tropepts, p.p.
d' apport alluvial } d'apport colluvial }	Fluvents
d'apport éolien	Psamments
IV. Andosols	Andepts
Sols saturés	Eutrandepts
Sols désaturés	Hydrandepts, Dystrandepts
VII. Sols Brunifiés des Pays Tropicaux	
Sols Bruns eutrophes tropicaux	Eutropepts, Tropudalfs
IX. Sols à Sesquioxydes de Fer	
Sols Ferrugineux (tropicaux)	
S.f.t. peu lessivés	Ustropepts
S.f.t. lessivés	Haplustalfs
	Paleustalfs
	Plinthustalfs
S.f.t. appauvris à pseudogley	Tropaqualfs (p.p.)
X. Sols Ferrallitiques	
Sols Ferrallitiques faiblement désaturés en (B)	
typiques	Eutrorthox, Eutrustox
appauvris, remaniés	Alfic Eutrustox
rajeunis	Ustropepts, Eutropepts
Sols Ferrallitiques moyennement désaturés en (B)	
typiques	Haplorthox, Haplustox
humifères	Haplohumox, Sombrihumox
appauvris	Ultic and Alfic Haplorthox
remaniés	Oxic suborders of Udults, Haplorthox, Haplustox
rajeunis	Typic Dystropepts and Oxic Dystropepts

TABLE 1 (Continued)

French Classification	U.S. Taxonomy (Orders, Suborders, or Great Groups)
Sols Ferrallitiques fortement désaturés en (B)	
typiques	Haplorthox, Acrorthox, Oxic Psammentic Dystropepts
humifères	Haplohumox, Acrohumox, Sombrihumox
appauvris	Ultic subgroups of Haplorthox
remaniés	Haplorthox, Acrorthox
rajeunis	Oxic Dystropepts
lessivés	Paleudults, Oxic Tropudults, Oxic Rhodudults
XI. Sols Hydromorphes (with the exception of the Sols Hydromorphes Organiques et Moyennement Organiques)	
Sols Hydromorphes minéraux ou peu humifères	
S.h.p.h. à gley	Tropaquents, Tropaquepts
S.h.p.h. lessivés	Tropaqualfs, Tropaquults
S.h.p.h. à pseudogley	Aquic Subgroups of Tropudalfs and Tropudults
S.h.p.h. à accumulation de fer en carapace ou cuirasse	Petroferric subgroups of Aquox, Aquults and Aquepts

[a] In some cases there is no good correlation between the classes and subclasses of the French system and the orders and suborders of the soil taxonomy of the United States.

Most of the soils of the humid tropics belong to the following orders, listed according to a genetic sequence beginning with the most recent: Entisols, Inceptisols, Alfisols, Ultisols, and Oxisols.

Entisols

Entisols are recent deposits that have not been altered or have been only slightly altered by soil-forming processes. On small-scale maps of the low humid tropics, they would hardly be represented, since rock outcrops are rare, recent sand dunes are not extensive, and young alluvial sediments (Fluvents) occupy only a narrow strip bordering the waterways. Quartz sands (Psamments) may be extensive in some areas, for instance in the south of the Congo basin. The value of Entisols depends on many properties: shallowness of the stony soils, which limits the soil volume; sand dunes, which usually restrict

TABLE 2 Approximate Correlation of the Food and Agriculture Organization of the United Nations, New Soil Taxonomy of the United States, and French Soil Classification Systems

FAO[a]	New U.S. Soil Taxonomy	French Classification
FLUVISOLS	Fluvents	Sols minéraux bruts et sols peu évolués d'apport alluvial et colluvial
REGOSOLS	Psamments Orthents	Sols minéraux bruts et sols peu évolués d'apport éolien
ARENOSOLS		
Ferralic A.	Oxic Quartzipsamments	Sols ferrallitiques moyennement ou fortement désaturés (à texture sableuse)
GLEYSOLS		
Eutric G.	Tropaquepts	Sols hydromorphes peu humifères à gley
Dystric G.		
Humic G.	Humaquepts	Sols humiques à gley
Plinthic G.	Plinthaquepts	Sols hydromorphes à accumulation de fer en carapace ou cuirasse
ANDOSOLS	Andepts	Andosols
PLANOSOLS		
Eutric P.	Paleudalfs	Sols ferrugineux tropicaux lessivés (pro parte)
Dystric P.	Paleustalfs	
CAMBISOLS		
Dystric C.	Dystropepts	Sols ferrallitiques fortement et moyennement désaturés, rajeunis (pro parte)
Eutric C.	Eutropepts	Sols ferrugineux tropicaux (non lessivés); Sols ferrallitiques faiblement désaturés, rajeunis
Humic C.	Humitropepts	Sols ferrallitiques fortement et moyennement désaturés, humifères, rajeunis
LUVISOLS	Tropudalfs Paleudalfs Paleustalfs	Sols Ferrugineux tropicaux lessivés
ACRISOLS		Sols ferrallitiques fortement désaturés
Rhodic A.	Rhodudults	Sols ferallitiques désaturés lessivés

TABLE 2 (Continued)

FAO[a]	New U.S. Soil Taxonomy	French Classification
	Rhodustults	Sols ferrallitiquement désaturés lessivés
FERRALSOLS	Oxisols	Sols ferrallitiques
LITHOSOLS	Lithic subgroups	Lithosols et Sols lithiques

[a] Adapted from FAO World Soil Resources Report No. 33 (1968), September 1970 revision, with special reference to the tropics.

water storage capacity; and alluvial sediments, which may suffer from periodic flooding. On the other hand, these soils often have not undergone the adverse action of tropical weathering and leaching and, when all other factors are favorable, they may be among the most productive soils of the world.

Inceptisols

The term "Inceptisols" was coined for the class of soils that show some profile development but are relatively immature. They may show strong gleying as a result of reduction by water, release of free iron oxides as a result of weathering, or the formation of soil structure under conditions of wetting and drying. Within the Inceptisols, one suborder of soils, Andepts, deserves special attention. Andepts have been used intensively in the tropics, especially in areas affected by volcanic activity. They are derived from volcanic ash, which weathers rapidly and produces a peculiar kind of amorphous clay, allophane. In combination with organic matter, allophane gives the soil its most striking characteristics, namely high water-holding capacity and incomplete dispersibility. Allophane is known to trap organic matter, protecting it against rapid decomposition. Andepts, therefore, are usually darker than adjacent nonvolcanic soils; on the other hand, they become rapidly depleted of bases, and once they have been leached and become acid, they often fix large quantities of phosphorus. At a low pH in the field, they have a low cation exchange capacity, which is strongly pH dependent. The richest members of the group, or those that have not been leached, are generally excellent soils.

Andepts are extensive in Central and South America along the

DISTRIBUTION OF ORDERS AND PRINCIPAL SUBORDERS AND GREAT GROUPS

In this legend, only general definitions for orders and suborders are given. For complete definitions of these, and for the great groups comprising some of the mapping units, see *Soil Classification, A Comprehensive System, 7th Approximation,* Soil Conservation Service, U.S. Department of Agriculture, 1960, and the March 1967 Supplement; also *Soil Taxonomy of the National Cooperative Soil Survey,* Soil Conservation Service, U.S. Department of Agriculture (in press).

A ALFISOLS Soils with subsurface horizons of clay accumulation and medium to high base supply; either usually moist* or moist for 90 consecutive days during a period when temperature is suitable for plant growth

- A 2 *Udalfs* temperate to hot, usually moist
  - A 2e with Troporthents
- A 3 *Ustalfs* temperate to hot, dry more than 90 cumulative days during periods when temperature is suitable for plant growth
  - A 3a with Tropepts
  - A 3b with Troporthents
  - A 3c with Tropustults
  - A 3d with Usterts
  - A 3e with Ustochrepts
  - A 3f with Ustolls
  - A 3g with Ustorthents
  - A 3h with Ustox
  - A 3j Plinthustalfs with Ustorthents

D ARIDISOLS Soils with pedogenic horizons, usually dry in all horizons and never moist as long as 90 consecutive days during a period when temperature is suitable for plant growth

E ENTISOLS Soils without pedogenic horizons

- E 1 *Aquents* seasonally or perennially wet
  - E 1b Psammaquents with Haplaquents
  - E 1c Tropaquents with Hydraquents
- E 3 *Psamments* sand or loamy sand textures
  - E 3b with Orthox
  - E 3d with Ustalfs
  - E 3e with Ustox

I INCEPTISOLS Soils with pedogenic horizons of alteration or concentration but without accumulations of translocated materials other than carbonates or silica; usually moist or moist for 90 consecutive days during a period when temperature is suitable for plant growth

- I 2 *Aquepts* seasonally wet
  - I 2c Haplaquepts with Humaquepts
  - I 2e Humaquepts with Psamments
  - I 2f Tropaquepts with Hydraquents
  - I 2g Tropaquepts with Plinthaquults
  - I 2h Tropaquepts with Tropaquents
  - I 2j Tropaquepts with Tropudults
- I 4 *Tropepts* continuously warm or hot
  - I 4a with Ustalfs
  - I 4b with Tropudults
  - I 4c with Ustox

*Soil moisture terms: Dry—soil moisture below permanent wilting
Moist—soil moisture above permanent wilting
Wet—soil saturated

M MOLLISOLS Soils with nearly black, humus-rich surface horizons and high base supply; either usually moist or usually dry

- M 1 *Albolls* light gray subsurface, seasonally wet
  - M 1a with Aquepts
- M 3 *Rendolls* subsurface has much calcium carbonate but no clay accumulation
  - M 3a with Usterts
- M 5 *Ustolls* temperate to hot, dry more than 90 cumulative days in year
  - M 5a with Argialbolls
  - M 5c with Usterts

O OXISOLS Soils with pedogenic horizons that are mixtures principally of kaolin, hydrated oxides, and quartz, and are low in weatherable minerals

- O 1 *Orthox* hot, nearly always moist
  - O 1a with Plinthaquults
  - O 1b with Tropudults
- O 2 *Ustox* warm or hot, dry for long periods but moist more than 90 consecutive days in the year
  - O 2a with Plinthaquults
  - O 2b with Tropustults
  - O 2c with Ustalfs.

U ULTISOLS Soils with subsurface horizons of clay accumulation and low base supply, usually moist or moist for 90 consecutive days during a period when temperature is suitable for plant growth

- U 1 *Aquults* seasonally wet
  - U 1b Plinthaquults with Orthox
  - U 1c Plinthaquults with Plinthaquox
  - U 1d Plinthaquults with Tropaquepts
- U 2 *Humults* temperate or warm and moist all of the year, high content of organic matter
  - U 2a with Umbrepts
- U 3 *Udults* temperate to hot, never dry more than 90 cumulative days in the year
  - U 3d Hapludults with Dystrochrepts
  - U 3e Rhodudults with Udalfs
  - U 3f Tropudults with Aquults
  - U 3g Tropudults with Hydraquents
  - U 3h Tropudults with Orthox
  - U 3j Tropudults with Tropepts
  - U 3k Tropudults with Tropudalfs
- U 4 *Ustults* warm or hot, dry more than 90 cumulative days in the year
  - U 4a with Ustochrepts
  - U 4b Plinthustults with Ustorthents
  - U 4c Rhodustults with Ustalfs
  - U 4d Tropustults with Tropaquepts
  - U 4e Tropustults with Ustalfs

V VERTISOLS Soils with high content of swelling clays; deep, wide cracks develop during dry periods

- V 2 *Usterts* cracks open more than 90 cumulative days in the year
  - V 2a with Tropaquepts
  - V 2b with Tropofluvents
  - V 2c with Ustalfs

X SOILS IN AREAS WITH MOUNTAINS Soils with various moisture and temperature regimes; many steep slopes, relief and total evaluation vary greatly from place to place. Soils vary greatly within short distances and with changes in altitude; vertical zonation common.

Andes Cordillera. Indonesia and the isles of Oceania have large areas of volcanic ash soils. In Africa, Andepts have been recognized in Cameroon, Kenya, Madagascar, Tanzania, Uganda, and the Republic of the Congo. Many soils of Hawaii and Central America, known locally as Latosols, are actually Andepts.

The value of the other Inceptisols in the tropics (Tropepts) is primarily governed by the quality of the parent rocks. This is not surprising, since the properties of these incipient soils are closely related to the rocks that have generated them. For example, Tropepts from basic rocks are generally productive soils, whereas parent material from acidic rocks as a rule develops into poor soils often mixed with stone-lines that may restrict root penetration at a shallow depth.

Alfisols and Ultisols

Two distinct but not necessarily exclusive processes are recognized in the more mature Alfisols and Ultisols. The first is the formation of an argillic horizon, which is the result of the accumulation of clay in a subsoil horizon. Deep weathering and clay destruction may be associated with the formation of some argillic horizons. The second process concerns the weathering of minerals into kaolinitic clays and free sesquioxides, which reaches maximal dimensions in what is called the oxic horizon. Both argillic and oxic horizons are diagnostic horizons in tropical soils.

The parent materials from which Alfisols and Ultisols have developed have by definition not reached the oxic weathering stages. As a rule, they still contain some weatherable minerals, and the clays are not exclusively composed of kaolinite and free sesquioxides. The argillic horizons seem to reach maximum development in climates that have a dry season.

Order of Alfisols

The order of Alfisols becomes important at the transitional zone to arid climates. Smith (1970) describes them as follows:

> Alfisols characteristically form under forest or savanna vegetation in climates with a slight to pronounced seasonal moisture deficit. At some season evapotranspiration exceeds precipitation and stored soil moisture is depleted or exhausted.

Suborders of Alfisols are defined in terms of their moisture and temperature regimes. Some suborders and their approximate equivalents in other classification systems follow.

Aqualfs Alfisols of wet places. Aqualfs are dominantly gray throughout and are seasonally saturated with water. They include soils called in French, Sols lessivés hydromorphes, Sols Ferrugineux Tropicaux lessivés, or remaniés à pseudogley. Soils formerly called Low Humic Gley and Planosols in the United States are included in this suborder.

Udalfs Alfisols of humid temperate or warm regions. Udalfs are brownish throughout and have no periods or only short periods (less than 90 cumulative days in most years) when part or all of the soil is dry. They were formerly called Gray-Brown Podzolic soils in the United States.

Ustalfs Alfisols of warm places with long periods (more than 90 cumulative days in most years) when the soil is dry. Ustalfs are brownish to reddish throughout. They include soils called in French Sols Ferrugineux Tropicaux lessivés ou appauvris. They were formerly called Reddish-Brown soils in the United States.

Great groups that are important in the tropics include Paleudalfs and Paleustalfs with strongly developed B horizons and Rhodustalfs that have dark reddish colors and are usually developed from basic rocks or hard limestone.

Order of Ultisols

Smith (1970) describes Ultisols as follows:

> The unique properties of Ultisols are: a B horizon of clay accumulation, a low supply of bases, particularly in the lower horizons; and a mean annual soil temperature of more than 8°C (47°F).

Ultisols characteristically form under forest vegetation in climates with slight to pronounced seasonal moisture deficits and surpluses. In the humid tropics, the soils have a relatively low cation exchange capacity. The bases not held in the plant tissue are depleted.

Suborders of Ultisols are defined in terms of their moisture regimes and organic matter contents. Four suborders and their approximate equivalents in other classification systems follow.

Aquults Ultisols of wet places. A few Aquults have black surface horizons on gray subsoils. They include some soils called in French, Sols à amphigley and Sols à gley lessivés, and some soils formerly called Humic-Gley and Low-Humic gley in the United States.

Humults Ultisols with large accumulations of organic matter

formed under relatively high, well-distributed rainfall in subtropical and tropical regions. Humults include some soils formerly called Reddish-Brown Lateritic and some Humic Latosols in the United States. The approximate French equivalents are Sols Ferrallitiques fortement désaturés humifères, and Ferrisols humifères.

Udults Ultisols of humid subtropical to tropical regions. Udults have moderate to very small amounts of organic matter, reddish or yellowish B horizons and no periods or only short periods when some part of the soil is dry (less than 90 cumulative days in most years). They include some soils formerly called Red Yellow Podzolic and Reddish-Brown Lateritic in the United States. Some soils called in French Sols jaunes et rouges blanchis belong to this suborder.

Ustults Ultisols of warm places with long periods (more than 90 cumulative days in most years) when the soil is dry. Ustults are brownish to reddish throughout. They include some soils formerly called Red Yellow Podzolic in the United States. Sols Ferrallitiques fortement désaturés lessivés (pro parte) is the approximate French equivalent.

Ultisols may have (1) thick dark surface horizons, (2) plinthite, a soft clayey material that hardens into ironstone if exposed to wetting and drying, (3) high enough contents of free iron oxides to impart dark red colors to the soil, and (4) very thick B horizons extending deeper than 150 cm. The soils with plinthite or thick B horizons are associated with mid-Pleistocene or older surfaces. The other great groups are largely restricted to late- or post-Pleistocene surfaces.

Oxisols

In the humid tropics, Oxisols generally occur on very old tablelands, where weathering products have been protected against erosion during long periods. Four suborders and their approximate equivalents in other classifications systems follow.

Aquox Oxisols of wet places. Aquox are dominantly gray, or mottled dark red and gray, and are seasonally saturated with water. They include some soils called in French Sols à accumulation de fer en carapace ou cuirasse and soils formerly called Ground Water Laterite soils in the United States.

Humox Oxisols of relatively cool moist regions with a large accumulation of organic carbon. Humox include soils called Sols fer-

rallitiques fortement désaturés humifères in French and formerly called Black Red Latosols and Humic Latosols in the United States.

Orthox. Oxisols of warm humid regions with short (less than 90 days) dry seasons or no dry season. Orthox include soils called in French Sols Ferrallitiques. They were formerly called Red Latosols, Earthy Red Latosols, or Red Yellow Latosols in the United States.

Ustox. Oxisols that are moist in some horizons more than 6 months (cumulative) or more than 3 consecutive months, but are dry in some horizon for more than 60 consecutive days (roughly equivalent to a 3-month dry season). Ustox include soils called Sols Ferrallitiques faiblement désaturés in French and some soils formerly called Low Humic Latosols in the United States.

Oxisols are the dominant soils of continental shields in the permanently moist and alternately wet and dry climates. Orthox soils are largely found in the south of West Africa, in the central part of the African equatorial belt, in the Asian humid tropics (Ceylon, Thailand, Vietnam), and in the low-altitude areas of the humid tropics of South America. Ustox soils are extensive in the Brazilian plateau and East Central Africa. Humox soils occur in Africa in the eastern Congo basin, Central Madagascar, South Asia, tropical Andes, and in many islands of Oceania. Aquox soils, with more or less indurated plinthite, are found over large areas in some regions, as for instance, the central, southern, and eastern part of Senegal; the central and southern part of Upper Volta; northern part of Guinea; the Ivory Coast; Ghana; the northern part of the Central African Republic; the southern part of the Sudan; and the plateaus of Katanga. Near the equator, the large continental basins may have been filled also with materials that have acquired oxic properties. The Congo and the Amazon basins are examples.

Oxisols depend mostly on the quality and the amount of the organic matter for retention of cations. Without fertilizers, they can support extensive agriculture only under shifting cultivation or with tree crops that protect the soil, or extensive grazing with poor-quality grass. When soft plinthite occurs near the soil surface, clearing of the natural vegetation may accelerate the irreversible induration of the free sesquioxides and alter the soil into a hard rock.

Other important soil orders such as Vertisols, Spodosols, and Histosols are not discussed in this short review. Members of these orders do occur in tropical and equatorial regions, but the Commit-

tee felt that major emphasis in this report should be given to the other groups.

SOIL MAPPING

Adequate land-use planning is based on knowledge of the properties of the soil. These properties are best learned from surveys that identify the important characteristics of the soil and show the geographic distribution of the kinds of soils on maps.

Depending on the purposes to be achieved, soil surveys in the tropics have been carried out at various levels of intensity. Most of them have been related to agricultural development programs aimed at a better use of the land resources.

Kinds of Soil Surveys

Exploratory Soil Surveys

Exploratory soil surveys are general surveys made largely by inferences drawn from a knowledge of soil-forming factors. A few points in traverses through the area are checked. Such surveys are normally the first stages in the preparation of a soil map of a country and are seldom used for immediate practical purposes. The scales differ according to the size of the countries, but are usually smaller than 1 : 250,000.

Reconnaissance Soil Surveys

Reconnaissance soil surveys are made by field observations in traverses or at selected points. The soil boundaries are interpolated between the traverses on the basis of correlations between the soil properties and external features. The latter may be landscape or vegetation, which may or may not be drawn from interpretation of aerial photographs.

There are several types of reconnaissance maps. Most have scales ranging from 1 : 50,000 to 1 : 250,000.

Maps of "Superficial Sediments" A limited number of maps of superficial sediments have been produced in French-speaking tropical

Africa, particularly in Upper Volta. They provide information on the parent rock and surface sediments, including texture and base status. They usually have intermediate scales (1 : 50,000 to 1 : 200,000) and are prepared mainly from photointerpretation. They have very limited use for direct agricultural purposes.

Landscape Maps Landscape maps show landscape units that are delineated on aerial photographs by means of geomorphological characteristics, vegetation types, and sedimentation patterns (Goosen, 1967).

Landscape units are easily recognized in cultivated areas or in regions not covered by a dense vegetation under arid or subhumid climates. Under wet equatorial climates, the rain forest frequently impedes accurate delineation of physiographic boundaries. In some cases it can be done, but only after a careful study of good-quality aerial photographs and detailed fieldwork, mostly based on an analysis of recognizable vegetation types and drainage patterns. Landscape maps do not show individual soil types, but they do show different soils that occur in geomorphic association.

The usefulness of these maps depends on many factors. The smaller the number of soil types in each landform, the easier the interpretation for a particular soil–plant relationship. The accuracy of the map itself will largely be determined by the degree of correlation between soil properties and landform, and a considerable number of field observations will be needed to check this correlation.

As a rule, landscape maps are most useful in regions with sharply contrasting ecological conditions. They permit rapid surveys but often lack accuracy in characterizing the soil units and hence make it difficult to correlate soils over long distances. At present, the system has not been sufficiently tested in the humid tropics to warrant recommendation of its general use beyond the purposes of broad reconnaissance surveys.

In Africa, landscape delineation as a basic component of soil surveys has been used in Nigeria and Lesotho and in northern Togo, Dahomey, and Uganda.

Soil Maps Combined with photointerpretation, analysis of the landscape has become a useful tool in many small-scale reconnaissance surveys. It is essential to maintain a proper balance between the demarcation of landscapes and the fieldwork necessary to define the soils in order to know the properties that are important for land use. Too many reconnaissance surveys have neglected the fieldwork, and

this has greatly reduced their practical value. More effort should be made to describe the mapping units in terms of soil properties. This can be done in various ways, some of which are described below.

Maps with analytical units Some selected soil properties are used independently of one another to designate the mapping units by a combination of symbols that are written on the map segments. These properties may be slope, erosiveness, depth, parent material, and diagnostic horizons—for example, oxic, argillic, or plinthic horizons. Examples of such identification methods are surveys that have been carried out in Panama and Nicaragua and that are planned for Mexico. Some work has been completed in Indonesia and Rhodesia with these techniques.

Usually, the maps are produced jointly with geological, geomorphological, and botanical surveys. Current scales are 1 : 5,000. Their value depends greatly on the choice of the soil properties identified and the number of field observations that support the identification symbols.

Maps with taxonomic units In developing maps with taxonomic units, soils that have a certain combination of properties are considered as a group and given a name. This system recognizes "great soil groups" that have common characteristics. The great soil groups may be subdivided into taxa of lower categories, depending on the degree of detail that is needed. The cartographic units that have been delineated by landscape mapping are then described in terms of these taxonomic subdivisions. For example, some "terrace soils" may belong to the "Sols Ferrugineux Tropicaux."

It is essential that the taxonomic level used for describing the mapping units be proportionate to the scale of the map and the purposes for which the survey work has been done. Great soil group names, for example, do not convey sufficient information to assess fertilizer requirements for individual plots, or even for recommendations for management practices at the farm level. In this case, the soil series level may be necessary, sometimes supplemented by phase criteria.

Numerous taxonomic systems are used in tropical areas. The most important are:

1. The 1938–1949 USDA great soil groups (Baldwin *et al.*, 1938; Thorp and Smith, 1949).
2. The French classification as particularly applied in Africa and

Oceania (Aubert, 1965; Commission de Pédologie et de Cartographie des Sols, 1967), together with the Portuguese approach, which is very similar.

3. The Institut National pour L'Étude Agronomique du Congo (INEAC) system in the Republic of the Congo (Tavernier and Sys, 1965; Van Wambeke, 1961).

4. The Soviet classification, particularly in Asia.

5. The Brazilian taxonomy based on experience in Latin America (Lemos, 1968).

6. The Australian and New Zealand systems (Stephens, 1962).

7. The new comprehensive U.S. Soil Classification (7th Approximation) (Soil Survey Staff, 1960).

The last-named system is being used in some tropical regions.

Maps with soil series units Associations of soil series are often used to name mapping units that have been recognized during reconnaissance surveys. In fact, the soil series class is too narrow a concept to be defined without a detailed field study. Series definitions need to specify ranges of variability to be classified into a general taxonomic system. In this case, the series can serve local purposes well and presents considerable practical value.

Excellent examples of how information on soil series can be channeled to farmers and agronomists are given in the reports on soil and land-use surveys prepared by the University of the West Indies. Effective use of the U.S. Department of Agriculture soil series concept is made in many countries in Latin America. It has also been used in Africa in some limited areas (Nigeria, Tanzania, and the Republic of the Congo); in Asia (Malaysia, Philippines, Taiwan, and Thailand); and in Oceania (Samoa).

Detailed Soil Surveys

In detailed soil surveys, the most intensive type of surveys, the soil boundaries are delineated in the field during the mapping operations. High-intensity surveys are normally restricted to areas that have considerable agricultural potential and that justify a detailed study because of heavy investments. Examples are irrigation or drainage projects and areas under high population pressure. There have been relatively few detailed soil surveys in tropical areas except in Hawaii and Puerto Rico. Some agricultural experiment stations or agricul-

tural development areas have been surveyed in detail, and some detailed soil maps have been prepared to help define soil associations. Their legends may be based on one of the previously mentioned systems at a lower level of generalization or on some specific properties of the soils, depending on the anticipated uses of the map.

Map Evaluation

Soil maps differ greatly in the scales, in the accuracy of the delineations, and in the definitions of the soil units. It would be unrealistic for countries in equatorial regions to engage in all types of surveys at the same time and, obviously, priorities have to be set for each situation. Each type of map has been devised for specific purposes and cannot, in spite of many attempts, serve other purposes equally well.

For a long time to come, reconnaissance maps will be the most useful investments in equatorial regions. These maps indicate areas that are worth studying in more detail. Excessive use of these kinds of maps should be avoided, however, especially to resolve problems that require more thorough investigations.

Two aspects of map evaluation are worth mentioning: First, delineations should be accurate; and second, the map units should be properly defined.

Accuracy is closely related to the density of field observations. As the scale of the map increases, the number of field checks per unit area should increase. If the soil boundaries coincide closely with observable landscape or vegetation patterns, the density of observations in the field can be decreased. As a rule of thumb, for scales greater than 1 : 200,000, one should approximate a minimum of one soil observation per square centimeter of the published map. Ideally, one may think of four soil borings per square centimeter, especially for detailed surveys. On a scale of 1 : 1,000,000, 1 cm^2 on a map represents 10,000 ha, while on a scale of 1 : 10,000, 1 cm^2 represents 1 ha. If no photointerpretation is possible, surveyors should adhere strictly to these principles.

Where conditions are favorable for photointerpretation or where good geological, geomorphological, or botanical maps are available, these densities may be reduced by a factor of 0.2 or even less.

Proper definitions of soil units imply good descriptions and a set of laboratory data on the profiles. If there are many soils, a taxonomic classification can best accomplish the task of defining the ranges of variability of the classes. Ideally, the classification should

permit comparison with soils of other areas and extrapolation of practical experience gained elsewhere. The degree of detail should be proportionate to the scale of the map and to the purposes of the survey. The limitations of the classification should be made known to the users of the maps. These aspects of the soil studies should be given in the soil survey report, which is an essential part of the soil inventory. The report should incorporate data on the environment: climate, lithology, geomorphology, vegetation, and present use. Emphasis should be given to the practical uses of the soils by including all data that would permit an agricultural interpretation.

Definitions of complex mapping units normally include data on the composition and distribution of its taxonomic components. It is currently accepted that from 15 to 25 percent of an association may consist of unclassified soils (Soil Survey Staff, U.S. Department of Agriculture, 1951).

SOIL SURVEY INTERPRETATION

Most soil surveys are carried out for practical agricultural purposes. This is particularly true for surveys related to large- and intermediate-scale maps. The soil survey reports normally include chapters dealing with the capability and the suitability of soils for different agricultural practices (Steele, 1967).

Interpretations are essential for adequate utilization of soil maps. Even if the reports contain all the information most users of the maps will need, not all users are interested in the same things. Each person should be able to easily find the data that are necessary to solve specific problems.

There are other reasons for stressing the need for interpretations. In the first place, all crops do not have the same requirements for producing optimum yields; second, the classification systems may be based on criteria that do not match specific crop requirements. A given soil property may be important for separating soils in map legends, but may have only a minor influence on the development of certain crops. To facilitate the use of the legend units, some interpretative groupings and interpretative maps are often necessary.

The interpretative maps are particularly efficient when they are produced at a scale compatible with the intended use of the maps. The larger the scale, the more detailed the classifications normally are, and the more precise the statements that can be made about the

capability of the soils. Therefore, large-scale maps usually provide better interpretations for specific crop requirements and fertility assessment than do small-scale maps.

Interpretations take into account the soil properties integrated into the landscape as they affect crop requirements under given ecologic conditions and management practices.

Close cooperation with agronomists is necessary to arrive at optimum conclusions. Various types of interpretative groupings have been used in equatorial regions.

Capability Groupings Applied to Field Crops

The soils are placed in capability classes according to their potential to support certain types of land uses. Subclasses may be framed on the basis of the limiting factors that are to be corrected in order to obtain maximum productivity.

Several systems have been utilized: those of Aubert and Fournier (1954) and Riquier (1954) for Africa and that of Klingebiel and Montgomery (1961) in Latin America.

As a rule, interpretations of the soil data are made for general land-use subdivisions, such as cropland, grassland, and forests. In most cases, only one management level is considered, although some attempts have been made to predict soil behavior under modern agricultural practices. This type of interpretation is particularly appropriate for a map on a relatively large scale (1 : 100,000 or larger).

Suitability Classes

The suitability of soils for certain agricultural crops, grasses, or forest species is estimated on the basis of experiments on key soils, or by rating soil properties with regard to specific crop requirements. The suitability is determined for well-defined crops or rotations such as industrial crops, food crops, cereals, legumes, forest species, horticulture, oil palm, rubber, coffee, and cocoa. Each rating takes into account the soil properties and the plant requirements and may emphasize limiting factors such as drainage, permeability, and acidity.

Establishment of suitability tables is particularly interesting where farming is to be intensified, where new crops are to be introduced, or where new land is to be opened for development. If sufficient data are available, improved management practices may be considered and the potential of land for certain types of farming predicted. The

necessity and feasibility of reclamation work may also be estimated.

In equatorial regions, however, very often the basic agricultural experimental work is lacking for adequately predicting soil behavior. Limited experimental work has been conducted on new land in these regions, and the experimental sites have often avoided problem soils.

In some cases, suitability maps are drawn at large scales of more than 1 : 50,000. Some, less specific, have been prepared at 1 : 100,000 in Central America, Principe, and Tanzania. Smaller-scale maps are known for Brazil, Ghana, Malawi, Malaysia, Sarawak, Swaziland, and Thailand.

Potential Farm Land-Use Maps

Potential farm land-use maps predict the suitability of soils under new management conditions created by important irrigation or drainage works that eliminate limiting factors. Examples are found in Nigeria, Swaziland, Tobago, and Trinidad and in Opération Pédo-hydrologique in Togo (Riquier, 1954).

UTILIZATION OF SOIL MAPS

Soil maps serve various purposes. Although in tropical areas most have been used to assist in planning and developing agriculture in selected regions, they are also useful for research purposes.

Assistance to Research

Pedogenesis and Soil Geography

The occurrence of certain soil constituents in profiles is very often determined by external factors whose geographical distribution can readily be determined. Therefore, investigations that verify the correlations between the soil properties and these pedogenetic factors have a practical value in expediting survey operations and lowering their costs.

Little pedogeographic research has been done in tropical areas, however, except by specialized institutions and universities. More is to be achieved in this field, if survey agencies want to increase their efficiency and accelerate mapping procedures.

Depending on the pedogenetic factors to be investigated, small- or large-scale maps, or combinations of various types, may serve these research purposes equally well.

Agricultural Research

Soil maps and classification have been utilized for the extrapolation of agricultural experimental data to areas having soils similar to those of the trial plots. Soil maps provide a basis for estimating the area of applicability of agricultural experiments. This is possible only when the edaphic characteristics of the experimental fields are known and when detailed taxonomy and cartography define the geographic area where similar soils occur. The level of generalization is defined by the categorical level at which the classification has been made. The more detailed the classification, the more accurate the predictions. An example of a small-scale map is provided by the FAO-UNESCO World Soil Map (1 : 5 million). Worldwide comparisons on a broad generalization will be possible when this map has been completed.

Soil maps are particularly important for extending experimental results of fertilizer trials. Much remains to be done, however. In Africa, for example, very often the soils where the experiments are conducted are not sufficiently characterized, and seldom has the experimental site been selected to represent a large area in a region. Adequate knowledge about the soils for multilocal experiments allows the inclusion of soil factors within the variables that otherwise cannot be taken into account.

Regional Agricultural Development

Examples of the utilization of soil surveys for the agricultural development of tropical regions are numerous. Practically every FAO and United Nations Development Programme project for land use is based on the soil survey of the sector. The high productivity potential of land is one of the main factors for a successful rural development. An example is the high plateau of Sakay and the lower Mangoky Valley in Madagascar. In the Republic of the Congo (Kinshasa), many rural settlement schemes have been based on soil maps. For example, edaphic investigations preceded the opening of new land for intensive food production in Katanga. Forestry development and a reforestation program in the Ivory Coast were based on soil surveys.

In Chad, Dahomey, northern Cameroon and northern Togo, cotton-growing areas were surveyed. Similar examples may be found in English-speaking Africa, particularly Ghana. In Thailand, soil investigations made valuable contributions to the development of the rubber industry, and in Malaysia, such investigations were valuable in rural development schemes. Latin American soil scientists have assisted many agricultural projects in their countries. Soil surveys have not always led to positive results, however. Many investigations, instead of promoting agricultural projects, have discouraged governments from engaging in schemes that were not soundly planned, thus avoiding the waste of scarce capital resources. The importance of these negative results as a contribution to the development of agriculture should not be overlooked.

A tremendous task remains in the field of soil surveys for regional development. In the Amazon basin, huge virgin areas are to be surveyed before they are occupied by spontaneous colonization. In South America alone, FAO estimates that 33 million ha should be cleared of forest and brought into cultivation before 1985 in order to absorb the population growth. An additional 8 million ha would be necessary for grassland.

Soil maps have been intensively used in agrarian reform projects and crop diversification programs. Most examples may be found in Latin America, for example, in Colombia. Some African countries, such as the Ivory Coast, have produced soil maps for these purposes. The scales of the maps are usually larger than those for other uses, and more detailed interpretations are necessary, including accurate crop requirement studies.

Cadastral surveys in some countries are often supported by soil maps, for example, in Colombia, Malaysia, and Panama. In Nicaragua similar operations are being conducted. In certain tax systems the capability of land is an important factor and has to be accurately evaluated.

Nonagricultural Uses

There are relatively few examples of the utilization of soil maps for nonagricultural purposes in equatorial regions. Some are used in connection with road construction, community and urban planning, and the establishment of airfields. Soil surveys usually contain data on the availability of gravelly materials, e.g., ironstone, for road building. Suitability of sites for housing, sewage conditions, permeability,

drainage, hazards of constructing buildings on Vertisols and other montmorillonitic clays, and the presence of saprolitic materials are often indicated in the soil survey reports.

PRESENT STATUS OF SOIL SURVEYS

Country Maps

Almost all countries have an exploratory small-scale soil map of their territory. Some of them, however, have not been published. These maps seldom serve direct practical purposes, except for selecting regions of high priority for development in a country and for teaching. They usually lack the accuracy required for other uses.

Some nations have maps developed from detailed and reconnaissance regional studies. These maps are more useful and can serve as a basis for the extrapolation of experimental data.

In the tropical regions, except for many of the French-speaking countries and countries like Ceylon and Thailand, there are only a few national soil maps with cartographic units that can be correlated with internationally accepted systems. Usually, there are no comparable units, and soil boundaries between neighboring countries seldom match.

An international effort should be made to correct this situation; the first step would be to complete and publish the FAO–UNESCO world Soil Map at the 1 : 5 million scale and the world soil map of the USDA Soil Conservation Service, at a 1 : 2.5 million scale. Larger-scale international maps for some regions will be needed in the near future (1 : 1 million).

Regional Reconnaissance Maps

As pointed out earlier, reconnaissance maps have considerable importance. Many countries at present are conducting or have completed mapping programs that cover the whole country or territory: British Honduras, Chad, Cuba, Dahomey, Dominican Republic, El Salvador, Guatemala, New Caledonia, the Philippines, Samoa, Sarawak, Sierra Leone, and many islands of the West Indies.

Partial surveys are under way in Brazil, Burma, Colombia, Ghana, Indonesia, Kenya, Madagascar, Thailand, Cambodia, Laos, Vietnam, Nicaragua, Panama, Príncipe and São Tomé, Rhodesia, Rwanda,

Senegal, Tanzania, Togo, and Venezuela. More modest efforts are being made in Bolivia, the Central African Republic, Costa Rica, Ecuador, Guinea, India, and Mali.

Map indexes giving the status of soil surveys in the French-speaking tropical countries are available at the Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM). The Organization of American States (OAS) published indexes in 1964–1965 on the coverage by soil surveys in the member countries in Latin America. Some countries have published their own indexes (Peru and several states in Brazil). The Food and Agriculture Organization of the UN has established a collection of soil maps published by the countries and periodically issues a catalog listing the cartographic documents.

Detailed Maps

Detailed maps cover only a very small area in the tropics and are related to irrigation or drainage projects, experiment stations, or pilot areas.

CONCLUSIONS

Economic development in equatorial regions will continue to depend on soil resources. Soil surveys are essential for knowing the potential of land.

1. Future efforts should be aimed at a better balance between mapping intensity, the taxonomic level of the classification, and the requirements for an agricultural interpretation. It is necessary to (1) relate the scale of the maps to the purposes of the survey, (2) link the density of the field observations to the selected scale, and (3) use the most appropriate level of generalization when classifying the soils. Moreover, the classes should be defined in such a way that they provide all the information necessary for an agricultural interpretation of the data for objectives defined beforehand. Any imbalance between these basic components of the soil survey leads to erroneous conclusions and wasted effort, and sometimes to bitter experiences.

Since developing nations in equatorial regions cannot engage in all types of soil surveys simultaneously, they should set up priorities in their mapping programs. Reconnaissance surveys will probably be the

most useful for a long time, particularly for regional development projects. These studies should not be used for other purposes without additional and more detailed investigations. For example, fertilizer trials need a taxonomic classification at the lowest level of generalization, and irrigation projects usually need large-scale maps. In any event, published maps should state the reliability of the delineations.

2. Interpretations of soil data for agricultural purposes and grouping of the soils into capability and suitability classes need to be based as much as possible on experimental data collected in ecologically similar environments. These data are usually lacking. In agricultural experimental work, the soils should be carefully characterized and classified to make the soil surveys more useful. On the one hand, this would give the experimental workers a basis for extrapolation of their findings to other geographic areas; on the other hand, it would permit the soil interpretation specialists to select their criteria properly. Modern statistical methods and computer techniques may greatly facilitate these studies (soil data bank).

3. Mapping priorities might be based on the following principles:

- All countries should be in a position to elaborate a map at a scale of 1 : 1 million. An increased international effort to complete the FAO–UNESCO World Soil Map at the 1 : 5 million scale is highly desirable, because it may serve as a basis for correlation and comparison. The World Soil Geography Unit of the United States Soil Conservation Service has compiled soil maps covering most of the world at a scale of 1 : 1 million. These are not available for distribution but may be consulted at the Soil Geography office in Hyattsville, Maryland. It is recommended that every effort be made to find ways and means to have the maps published at a scale of 1 : 2.5 million with an accompanying text.
- Reconnaissance maps of selected regions will continue to be particularly useful. International financial and technical assistance should be increased to produce them. These maps should not be overused, however, and only interpretations commensurate with the scale and classification should be made.
- Detailed soil maps at scales of 1:20,000 or 1:10,000 or less should be restricted mainly to specific intensive projects and research centers. The detailed classification of soils at fertilizer trial sites is strongly recommended.

4. Countries should be encouraged to continue their efforts toward a uniform method of soil descriptions and analytical procedures. The Soil Survey Manual of the U.S. Department of Agriculture is an excellent model for standardizing soil survey methods; it is widely used in the tropics, and many national manuals have been adapted from it. It is now being completely revised and updated.

In French-speaking countries, ORSTOM uses uniform soil descriptions (Délégation Générale à la Recherche Scientifique et Technique, 1969; Maignien, 1969). In the Republic of the Congo (Kinshasa) the INEAC system is widely used (Sys *et al.*, 1961).

The Food and Agriculture Organization of the UN (Soil Survey and Fertility Branch, FAO, 1962) has made a very valuable contribution in publishing guidelines for soil descriptions in the three official languages of the United Nations. For laboratory data, one may refer to the methods described in Soil Survey Investigations Report No. 1 (Soil Conservation Service, U.S. Department of Agriculture, 1967).

The number of chemical and physical laboratory determinations required depends on the purposes of the survey, the variability of the soil properties and their internal correlation, and the nature of the soils that are studied. For soil survey purposes, which are mainly concerned with permanent characteristics, the methods should clearly relate to the criteria used in the taxonomic system.

Tentatively, one may suggest for the tropics the following guidelines in acquiring laboratory data for all soils and all horizons: (1) the particle size distribution, (2) pH in water and normal potassium chloride, (3) cation exchange capacity at the pH of the soil, (4) exchangeable cations, (5) total porosity, (6) bulk density, and (7) water retention at field capacity on undisturbed samples. These analyses aim at characterizing the nature of the weathering products by testing their physical and chemical properties; they attempt to evaluate the major differences in parent materials and horizons by particle size analysis. The percentage saturation with bases will indicate the degree of leaching and to some extent the amount of available nutrients; water retention at field capacity along with bulk density and particle size distribution provides data for estimating the available water capacity. Surface soil horizons should be analyzed for organic carbon and nitrogen in order to assess the intensity of the biologic factors of soil formation. Subsoil horizons in key soils will require clay mineral and free sesquioxide analyses. Special mineralogical analyses are necessary to test the presence of allophane, gibbsite, and 2 : 1 or 1 : 1 lattice minerals for information on the stages of weathering.

Special groups of soils often necessitate special analyses; or, conversely, normal routine analyses do not suit all soils equally well, and particular care should be taken in interpreting data to give due consideration to the kinds of soils. In Andepts, data on particle size distribution obtained by normal methods are usually erratic; Oxisols may be tested by evaluating the so-called natural clay that disperses in water. Bulk density is a diagnostic property for soils that contain appreciable amounts of allophane. Other specific soils require further examination—for example, cations extracted with concentrated acids, ratios of fulvic acid to humic acid, exchangeable aluminum for Oxisols and Ultisols. The structural stability in the surface horizons of Aqualfs, Tropepts, and Aquepts should be determined.

A step-by-step approach to laboratory analyses is usually the most efficient when only limited resources are available. The kinds of analyses should be determined by the nature of the soils under study. The fieldwork, the morphological characteristics, and the study of the soil-forming factors will guide the preliminary choice of analytical methods. At later stages, the purposes, the scales of the maps, the categorical levels of the classification system, and the overall variability of the soil properties will determine the nature and amount of necessary laboratory data.

5. Better communication would be achieved among the agricultural disciplines if soil classifications were uniform within a country and correlated among countries. Any increase in the accuracy and standardization of definitions of the taxa will improve the situation markedly.

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Soil Microvariability

Growth of upland food crops in the tropics is generally characterized by considerable unevenness over short distances, particularly where no purchased inputs such as fertilizers and irrigation water are used. By and large, this uneven production level of agricultural lands in the tropics is induced by microvariability of soils, partly as a function of varying weather conditions. Spots that show a better than average growth in one season frequently show less than average growth in another season.

CAUSES OF MICROVARIABILITY

Physical and Chemical Properties of Soils

The fundamental reasons that upland soils in the humid tropics seem to vary more in crop production than do soils of temperate regions are largely related to the chemical and physical properties of the soils. The inherent fertility of most tropical soils is low. Plant nutrients are easily leached and lost because of a generally low cation exchange capacity, or they may not be readily available to plants.

Moreover, as a function of the dominant clay mineralogy and the amount and composition of organic matter, most soils in the humid tropics have a low capacity for holding available water, compared to soils of temperate regions with comparable texture. This leads to the general conclusion that in tropical soils, slight lateral changes in soil properties are strongly reflected in the growth of annual crops. Small changes in thickness of the surface soil, for instance, under certain rainfall distribution patterns, may lead to a very uneven growth of annual crops, especially cereal crops.

Some causes of soil microvariability in the tropics are comparable with those in temperate regions. Geogenetic and pedogenetic lateral variations of the regolith and the pedon are similar to those in temperate regions. As stated before, however, the effect of such microvariability on the growth of annual crops is likely to be more significant in tropical regions. Few quantitative studies on this exist.

Specific for the tropics is the presence of soft and hardened plinthite over wide areas, especially in the semihumid tropics. The very uneven depth at which laterite occurs is definitely a source of microvariability.

Biogenetic Causes

Of more importance for soils in the tropics are the biogenetic causes of microvariability. In the tropical forest and even more so in wooded savanna, certain tree species may change the soil considerably—though not necessarily permanently—under and in the immediate environment of the trunk. The effect on the crop planted after clearing a site of certain species is often remarkable. Thus, at the International Institute of Tropical Agriculture (IITA) near Ibadan, Nigeria, the sites of the native unfertilized oil palm tree (*Elaeis guineensis*) showed up distinctly in a much better growth of a subsequent maize crop.

Detailed studies on the soil-improving qualities of *Acacia albida* were carried out in Senegal (Charreau and Vidal, 1965; Danvette and Poulain, 1968). Similar studies for other tropical soils and other tree and shrub species are recommended.

Termite Mounds

A widespread cause of microvariability in tropical soils is mound-building termites. A conservative estimate would be that 1 percent or

more of the upland soils in the humid tropics are affected, and 2 percent or even more in the subhumid tropical areas. In places, the soil microvariability caused by termite mounds may affect well over 50 percent of the land surface.

The degree to which the soils of termite mounds differ from soils of their immediate surroundings varies greatly, and no general conclusion can be drawn from the available literature (Hesse, 1955; Nye, 1955; Pendleton, 1942; Sys, 1955). Harris (1961), who summarized most of the recent literature on the effect of termites on the soil and on various crops, concluded that termite mound soils mainly reflect the chemical and mineralogical composition of the subsoil *in situ*. Variations occur according to the species and habitat of the termites; also, many soils in the seasonally dry tropics have strong accumulations of lime. Little attention has been given to the effect on crop growth of changes in the physical properties of the termite mound soils; initial study of local mounds at the IITA indicates that such soils differ greatly from those in the immediate surroundings.

From the literature studied, and from my own observations, it appears that undisturbed abandoned termite mounds in the seasonally dry tropics provide a favorable milieu for plant growth. Hence, in some savanna areas in Africa and in the monsoon areas of Southeast Asia, crops such as tobacco and sugarcane may be grown on top of these mounds, while less demanding crops are grown around them. On the other hand, in the humid tropics, e.g., the central Congo basin, the soils of the mounds are reported to be poor.

Leveling the termite mounds, required for modern agriculture, appears to affect the growth of cultivated plants in most areas, at least for a considerable time. Such leveled spots show up by very poor growth and low production of food crops. Various methods of leveling termite mounds have been studied in Yangambi in the Republic of the Congo (Culot and Meyer, 1959; Meyer, 1960).

Man's Activities

Another cause of lateral soil heterogeneity in the tropics, and one that has not received much attention, is man. An example of man causing lateral changes in soil fertility is the Chitemene system of cultivation of southern Katanga and Zambia in which trees are cut, then assembled and burned on a small surface, roughly 6 to 10 percent of the cut area. Food crops are then grown on the burned area (Jurion and Henry, 1967). Soils in old village sites, numerous in areas

of shifting cultivation, have been greatly altered; they are richer in organic matter and most plant nutrients than are the surrounding soils.

CONCLUSIONS

A study of microvariability appears important for various reasons, some of which are eminently practical for improved crop production and soil management. Generally speaking, spots of superior growth indicate better soil conditions, and a study of the favorable soil factors at such spots may well offer a key to the management of the area as a whole. The implication of microvariability in regard to field experimentation and soil sampling for fertility testing is also worth noting. When standard techniques and small plots with a limited number of replications are used in field experiments, the results are often not significant. This is true not only for soil fertility experiments, but also for many other experiments where the objective is related to general plant growth and, hence, to soil conditions. A review of standard experimental techniques for such variable conditions is clearly indicated. The "average" sample of a plot of land used in soil fertility tests is often meaningless as it represents soils with a wide range in productivity and characteristics. Here again, further study and the development of adapted techniques are indicated.

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L. D. BAVER

Physical Properties of Soils

The physical properties of tropical soils are of primary importance in evaluating soil fertility and productivity (Guinard, 1967; Lawes, 1957). Arrangement of the soil particles strongly influences the air and water regimes in soils, which are so essential for the roots of cultivated plants. It also reflects the density of the soil, which is closely associated with mechanical impedance to root proliferation. The stability of soil aggregates is a function of climatic conditions, cultivation techniques, and the humus content and the mineral constituents of the soil

The basic soil physics problems arise from the removal of the protective vegetative cover when the forest or savanna is cleared for cultivated crops. The natural source of organic matter is removed, and the soil is exposed to the impact of raindrops from tropical rains and to the intense rays of the sun. These new environmental circumstances cause many physical changes at the soil surface that are reflected in the ability of the soil to produce crops.

CHARACTERIZATION OF SOIL STRUCTURE

Soils in the tropics are exposed periodically to severe desiccation by high surface temperatures and then are abruptly wetted by intense

rainfall. Good-structured soil must withstand such violent slaking and maintain a high rate of infiltration (Pereira, 1954a). The concepts of (1) Pereira (1954a, b, 1956) and Pereira *et al.* (1954), (2) the French group (Chevalier, 1949; Dabin, 1962; Henin *et al.*, 1958; Monnier, 1965), and (3) the Hawaiian group (Cagauan and Uehara, 1965; Uehara *et al.*, 1962) have contributed much to the characterization of soil structure in soils of the tropics. Uehara and his co-workers have associated soil structure with the mineralogy of soils. They consider formation of stable aggregates to be a function of the nature and arrangement of soil minerals with soil pedological units. They were working with Oxisols, Ultisols, and Inceptisols where the primary mineral is of the 1 : 1 type, namely kaolinite or halloysite. Hydrated and nonhydrated oxides of iron and aluminum are present. These oxides are often concentrated in the <2-μ fraction and exist as coatings on the mineral surfaces. They have suggested four types of structure:

Type A: Massive to weak, fine subangular blocky; isotropic mass of nonoriented clay with many very fine pores; occurs in the rainfall zone of about 1,000 mm annually. These soils are Low Humic Latosols (Oxisols).

Type B: Strong, very fine subangular blocky; highly anisotropic with a high degree of orientation within the peds, which have very fine pores; patchy to continuous coatings on the peds; occurs in the rainfall zone of 1,000 to 2,000 mm. These soils are also Low Humic Latosols (Oxisols).

Type C: Firm, strong, very fine subangular blocky; mixture of isotropic arrangement within the peds and anisotropic orientation of the coatings on the ped faces; continuous coatings on the peds of illuviation cutans; occurs in the rainfall zone of 2,500 mm. These soils are Humic Ferruginous Latosols (Ultisols).

Type D: Strong, very fine subangular blocky; anisotropic throughout with oriented clay on the interior of the peds and highly oriented cutans on ped faces; occurs in the rainfall zone of 2,500 mm. These soils are the Humic Latosols (Inceptisols).

Aggregate stability of kaolinitic soils with more than 5 percent of free iron oxide is generally related to soil anisotropy. The kaolinitic plates are oriented and cemented together by iron oxide through hydrogen bonding. Tropical soils containing amorphous or nonplaty clay usually have poorly developed structure.

Pereira has observed that a single soil physical measurement can-

not adequately characterize soil structure. Measurements of water stability of soil crumbs or granules have proven to be unsatisfactory indicators of pore space, rainfall acceptance, and permeability rates in lateritic clays and sandy loams. Wet-sieving techniques are considered inadequate to distinguish the physical conditions of soils that exhibit contrasting field behavior. The free-draining pore space and the percolation rate are used as criteria of the status of soil structure, even though they may reflect the level of insect activity rather than the stability of soil structure. Pereira has devised a rainfall acceptance test to evaluate soil structure. Large cores of soil of undisturbed structure are brought to a standard moisture content under a tension of 20 cm of water. The sample is then subjected to intense artificial rainfall. Raindrops 5 mm in diameter are forced to fall 2 m to provide impact on the soil surface. The ability of the soil to accept continuous rainfall is an indirect (1) measure of the stability of soil structure in the immediate surface, (2) evaluation of the soil's resistance to crusting, and (3) measure of soil permeability. The summation of these indirect evaluations serves as a critical guidepost for preventing accelerated soil erosion.

The French group characterizes soil structure through a combination of soil porosity and stability measurements. They measure the porosity at saturation with water and at soil moisture tensions equivalent to pF 3.0 and pF 4.2. Permeability is measured by the percolation rate of the screened soil in a glass tube. Aeration porosity equals the porosity at saturation minus that at pF 4.2.

Stability of structure is determined by wet-sieving the soil aggregates in water without pretreatment and after pretreatment in air, ethyl alcohol, and benzene. Without pretreatment, the soil aggregates are placed directly in the wet-sieving apparatus. The rapid entrance of water in the pores compresses the air and breaks down the aggregates, if the stability of aggregation is low. Pretreatment of small clods with ethyl alcohol displaces the air from the system and thus increases the stability of the structure. Pretreatment with benzene, which is nonmiscible with water, may produce one of the following types of results: If the soils are low in organic matter the aggregates tend to be a great deal less stable. The effect is as if the soil were imbibing water under strong pressure. If the soils contain appreciable amounts of organic matter, the stability of structure may be only slightly modified; or, in certain cases, it may be increased. The last reaction is attributed to the absorption of the benzene by the organic matter, which makes the soil less wettable.

The coefficient of stability is expressed by the equation

$$S = \frac{A + L}{\dfrac{A_{g_{\text{air}}} + A_{g_{\text{alcohol}}} + A_{g_{\text{benzene}}}}{3}}$$

where $A + L$ is the percentage of silt and clay; $A_{g_{\text{air}}}$, $A_{g_{\text{alcohol}}}$, and $A_{g_{\text{benzene}}}$ are the percentages of aggregates from wet-sieving without pretreatment and with pretreatment with alcohol and benzene, respectively. S is essentially an index of the instability of structure, since structure stability varies inversely with this ratio. It ranges from 0.1 for soils rich in organic matter to over 100 for sodium-saturated soils. Four stability groups are recognized as follows:

Stability Group (Type of Behavior) and Source of Soil	$A_{g_{\text{air}}}$ (%)	$A_{g_{\text{alcohol}}}$ (%)	$A_{g_{\text{benzene}}}$ (%)
High degree of aggregation and sensibly constant; alluvial clay-humus soils (from Dahomey)	79.0	76.5	68.1
High degree of aggregation for air and alcohol; low for benzene (Oxisols from Cameroon)	77.1	73.2	0.3
Average to high degree of aggregation for air; very low for alcohol and benzene; clay subsoils (from France)	47.6	2.3	0.7
Very low degree of aggregation for air, alcohol, and benzene; deep horizon of solonetz (from France)	2.0	0.5	1.1

POROSITY

Porosity Variations with Depth

One of the first measurements of the pore space in a soil from the tropics was made on Nipe clay, an Oxisol derived from serpentine rock (Roberts, 1933). Total porosity ranged from 57 percent in the surface 12 cm to 47 percent at 75 to 150 cm. The aeration porosity averaged about 6 percent throughout. More recent measurements on the Latosols of Hawaii have shown sizable differences in the porosities of Inceptisols, Oxisols, and Ultisols (Baver and Trouse, 1965).

The Low Humic Latosols (Oxisols) have a weakly granular to fine blocky structure. Bulk density ranges from 1.1 g/cc in the surface 30 cm to 1.2 in the subsoil. This uniformity in bulk density is reflected in total porosity, which ranges only from about 62 percent in the surface to 59 percent in the subsoil; the aeration porosity averages about 25 percent throughout the profile. The high aeration porosity is responsible for relatively high infiltration and percolation rates.

Humic Latosols (Inceptisols) have a strongly granular to weak blocky structure. Bulk density averages about 0.8 g/cc. Total porosity equals 70 percent or more; aeration porosity is about 40 percent throughout the profile. These Inceptisols are more permeable than the Oxisols.

Hydrol Humic Latosols (Inceptisols) have a granular to fine blocky structure. Bulk density ranges from about 0.5 g/cc in the surface 30 cm to 0.2 in the subsoil. Total porosity ranges from about 82 percent in the surface to 93 percent in the subsoil. Aeration porosity averages about 20 percent throughout, which means that these Inceptisols have a very high water-holding capacity.

Humic Ferruginous Latosols (Ultisols) have a fine blocky structure. Bulk density of the immediate surface is about 1.20 g/cc; that of the structureless dense subsoil is about 2.0. Total porosity of the immediate surface is about 60 percent. Aeration porosity, however, is only 10 percent. These Ultisols differ greatly from the Oxisols and Inceptisols; the Ultisols are poorly aerated and have lower infiltration capacities and percolation rates. Root development is generally restricted in the Ultisols.

Size of Soil Pores

Early studies on the porosity of Nipe clay, an Oxisol, suggested that the good permeability of this soil was related to a large number of fine pores that did not swell when water was absorbed (Roberts, 1933). Later investigations on Puerto Rican soils (Smith and Cernuda, 1952) partially verified this assumption. These studies showed that the shape of the aggregates was associated with the size of the pores that made up the internal porosity of the granules. Aggregates with a fine internal porosity were angular; the percolation rate of the soil ranged from 1.25 to 5.0 cm/hr. Aggregates with medium to coarse internal porosity were rounded; the percolation rate ranged from 1 to more than 25 cm/hr.

Grohmann (1960a) found that the tropical soils of Brazil con-

TABLE 1 Pore Size in Tropical Soils of Brazil[a]

Soil type	Depth (cm)	Diameter of Pores <0.02mm (%)	Diameter of Pores >0.20mm (%)
Red Latosol (Ultisol)	0–25	60.7	13.2
	25–50	51.0	15.5
	50–80	41.8	24.8
Terra Roxa (Oxisol)	0–25	77.0	16.4
	25–50	53.0	22.0
	50–80	58.4	15.5
Red-yellow Podzolic from Sandstone (Ultisol)	0–25	30.7	41.5
	25–50	40.0	25.1
	50–80	59.1	18.7

[a] Data from Grohmann (1960a).

tained a high percentage of fine pores with diameters of less than 0.02 mm. His results are summarized in Table 1.

Soil Aggregation

Analyses of Nipe clay showed that from two thirds to nearly three fourths of the upper 75 cm of soil was in the form of aggregates larger than 0.05 mm in diameter (Roberts, 1933). Over 80 percent of the silt and clay particles were aggregated. Only slightly more than one third of the deep subsoil (75-150 cm) consisted of aggregates greater than 0.05 mm. About 50 percent of the silt and clay in the deeper subsoil was aggregated. These relationships are as follows:

Soil Depth	Diameter of Aggregates >0.05 mm (%)	Silt and Clay in the Form of Aggregates (%)
Surface (0–12 cm)	67	94
Subsoil (12–75 cm)	71	82
Subsoil (75–150 cm)	38	53

The high aggregation of the surface layer of soil was associated with its organic matter content, which was 8.8 times that of the subsoil layers. The high aggregation of the upper subsoil (12–75 cm) was due primarily to its higher iron content.

Investigations in Puerto Rico (Escolar and Lugo-Lopez, 1968; Lugo-Lopez and Juarez, 1959; Smith and Cernuda, 1952) have indicated that the aggregate stability of the surface layer was from 10 to 500 times greater than that of the subsoil, depending on the type of soil. Surface soil aggregates that contained organic matter were more resistant to the normal forces of destruction than were subsoil aggregates.

From 86 to 95 percent of forest and savanna soils of South America consists of aggregates larger than 2 mm (Grohmann, 1960b). Organic colloids from the aerobic decomposition of cellulose have been found to be a good stabilizer of tropical soils (Molina and Spaini, 1947; Molina and de Giuffre, 1961).

Soil organic matter plays a major role in the stability of soil structure of the surface soils in Central America (Boyer and Combeau, 1960). Ferrallitic soils (mostly Oxisols) on either metamorphic rocks or sandstone exhibit good crumb structure in the surface, which varies in depth from 3 to 10 cm. Soils rich in organic matter are quite stable with benzene pretreatment; those poor in organic matter are unstable. The authors concluded that adequate organic matter is the first requisite for conserving soil structure. The organic-matter–clay complexes play a protective role for the clay as well as for the organic matter.

SOIL STRUCTURE CHANGES DURING CULTIVATION

Considerable information has been accumulated on the effect of cultivation on soil structure in Africa (Boyer and Combeau, 1960; Pereira, 1954a, b; Guinard, 1967) and in Brazil (Grohmann, 1960b; Grohmann and Conagin, 1960). In Africa, emphasis has been placed on the fact that the cultivation of many tropical lands after clearing the forest or savanna disturbs the original environmental balance. The soil is unprotected from the impact of raindrops and the intense heat rays of the sun. An increased activity of microorganisms results in rapid decomposition of organic matter. Aggregates are destroyed, and the fine particles illuviated to lower depths. Soil structure deteriorates, and there is general soil impoverishment. Increased runoff and soil losses due to erosion are the result.

The change in soil structure is rapid—only one or two years is required. Aeration porosity and the percolation rate are likewise decreased. The aggregates change from granular to polyhedric. The former

are porous, while the latter are dense and somewhat impervious. Grasses have been better than cover crops in restoring soil aggregation. Much of the improvement in structure reflects the higher fauna population under grass. The restored relatively good structure is rapidly lost under cultivation. The rate of deterioration of soil aggregation during the arable break is considered as important as its rate of restoration under grass.

The Brazilian experiences are similar to those in Africa (Grohmann, 1960b). High aggregation of woodland or grassland soils deteriorates rapidly under intensive cultivation. This is clearly illustrated in the following tabulation:

Soil	Aggregates (Virgin Oxisol = 100)		Decrease in Aggregation (%)
	Virgin or Pasture	Cultivated Annually	
Terra Roxa (Oxisol)	100	69	31
Red-yellow Latosol (Ultisol)	58	5	90

Note that the aggregation of the Oxisol is more stable than that of the Ultisol. This is undoubtedly due to the stabilizing effect of the iron oxides in the Oxisol.

Boyer (1970) cited the changes in the stability of soil structure in West Africa, as illustrated in Table 2.

TABLE 2 Changes in Stability of Soil Structure in West Africa[a]

Type of Soil and Crop	Stability
Rice paddy soils (Inceptisols?)	3.5 to 6.72
Tropical ferruginous soils (Ultisols?)	
Forest	0.6 to 0.72
Cultivated, 15 yr	1.25 to 1.57
Ferrallitic soils (Oxisols)	
Savanna	0.25
Fallow, 6 yr (Imperata); cultivated, 1 yr	0.35
Cultivated, 1 yr; fallow, 1 yr (Pueraria)	0.95
Vertisols	
Fallow, 3 yr (Calopogonium); cultivated, 2 yr	0.69
Continuous cotton and rice, 5 yr	1.71

[a] Data from Boyer (1970).

WATER RELATIONSHIPS

Rainfall Acceptance

Rainfall acceptance has been investigated by Bonnet (1968) and Pereira (1954b). The infiltration rates of a red latosol (Ultisol?) in Uganda under grass, cover crops, and cultivation were observed to be 10.8, 9.8, and 8.8 cm/hr, respectively. A red lateritic clay (Oxisol?) in Kenya showed an infiltration rate of 12.5 cm/hr when kept in elephant grass for 6 years; this rate was 10 cm/hr when the land was maintained in grass for 2 years and cultivated for 4 years; the infiltration rate was 10.5 cm/hr under 30 years of continuous coffee.

Studies in Puerto Rico (Bonnet, 1968) provided the infiltration rates for various soils (Table 3). The important values in Table 3 are the low minimum infiltration rates of the Vertisols and Entisols and the relatively high minimum infiltration rates of the Mollisols, Oxisols, and Ultisols.

Permeability and Percolation

Permeability and percolation of soils have been discussed by Pereira (1954b) and Schulze (1966). The average permeability of ferrallitic soils (mostly Oxisols) in Africa was observed to be about 14 cm/hr in the surface layer and 6.5 cm/hr in the subsoil. With soils low in organic matter, the percolation rate decreased rapidly after an intense rainfall (2,500 mm), which was followed by desiccation. Percolation rates for a red latosol (Ultisol?) in Uganda under grass, cover crops, and cultivation were 37, 28, and 24 cm/hr, respectively. Percolation

TABLE 3 Infiltration Rates for Various Soils in Puerto Rico[a]

	Infiltration Rate (cm/hr)	
Soil Group	Minimum	Maximum
Vertisols	0.18	9.58
Entisols	2.32	27.55
Inceptisols	2.75	13.25
Alfisols	2.78	11.58
Mollisols	8.22	19.55
Oxisols	8.45	15.40
Ultisols	7.40	23.68

[a] Data from Bonnet (1968).

rates for a red lateritic clay (Oxisol?) in Kenya under (a) 6 years of elephant grass, (b) 2 years of grass and 4 years of cultivation, and (c) 30 years of continuous coffee were 49, 12, and 23 cm/hr, respectively. The differences between the grass and cultivated areas of both the Uganda and Kenya soils were greater with respect to soil permeability than with rainfall acceptance.

Water Retention

Hawaiian studies (El Swaify *et al.*, 1970; Sharma and Uehara, 1966, 1968) have shown that water retention in the tension range between 0 and 0.3 bar is primarily influenced by the macrofabric of the interpeds (size, shape, and arrangement of the aggregates). The intrapedal fabric (size, shape, and arrangement of the particles) plays the dominant role at higher tensions. The moisture content of Low Humic Latosols (Oxisols) at 1/3 bar ranged between 26 and 35 percent by volume; at 15 bars, between 18 and 25 percent. This means that the available moisture in these Oxisols was about 8 to 10 percent. Apparently, the interpedal pores contribute to capillary conductivity in the tension range between 0 and 0.2 bar, but the intrapedal pores do not.

PLASTICITY

The methodology of determining the plasticity of tropical soils can greatly affect the results obtained. Air-drying of soils, especially those containing much amorphous material, may give an erroneous picture of their plasticity (van Schuylenborgh, 1954). This is emphasized in Table 4. The decrease in observed plasticity as a result of air-

TABLE 4 Plesticity of Moist and Air-Dried Soil[a]

Soil Depth and Condition of Soil	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index
1–3 cm			
Moist	273	227	46
Air-dried	146	128	18
13–41 cm			
Moist	210	170	40
Air-dried	82	74	8

[a] Data from van Schuylenborgh (1954).

drying is undoubtedly associated with the slow reversibility of the soil system when rehydrated.

Plasticity determinations on soils of Hawaii indicated that the liquid limit and the plasticity index of Oxisols, Ultisols, and the Inceptisol known as a Gray Hydromorphic Clay were quite similar. The liquid limit was about 25 percent, and the plasticity index ranged between 20 and 22. The high-allophane-containing Hydrol Humic Latosol (Inceptisol) possessed a liquid limit of 98 percent; the plasticity index was only 16. These values indicate a lower soil strength than for the Oxisols and a greater ease of puddling.

SOIL COMPACTION

Bulk density–moisture curves of Hawaiian latosols exhibit rather wide variations (Baver and Trouse, 1965). The maximum bulk density of an Oxisol was 1.56 g/cc at a moisture content of 28 percent. The maximum value for the Hydrol Humic Latosol (Inceptisol) was 0.87 at 70 percent moisture. As bulk densities approached the maximum value, the aeration porosity decreased to the point where aeration became a limiting factor in root elongation. These compaction curves have pointed out the hazardous effects of vehicular traffic on moist tropical soils.

Extensive investigations of the effect of soil compaction on root development in Hawaii (Trouse, 1965) have shown that root elongation in soils of low bulk density approaches an average rate of about 5 cm per day. The rate of elongation decreases rapidly with increased bulk density. Aeration porosity decreases rapidly at the same time. The critical bulk density for root penetration in a Hydrol Humic Latosol (Inceptisol) was about 1.1 g/cc; that of a Low Humic Latosol (Oxisol) was about 1.55; that of a Gray Hydromorphic Clay (Inceptisol) was about 1.75. Aeration porosity at these critical limits was found to be less than 10 percent by volume, and air permeability was zero. The critical bulk density of the Hydrol Humic Latosol (Inceptisol) was the same as that of the Low Humic Latosol (Oxisol) for normal rates of root elongation.

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W. V. BARTHOLOMEW

Soil Nitrogen and Organic Matter

A vast amount of knowledge concerning soil nitrogen and organic matter has been accumulated. Most of this knowledge has come from research in temperate environments. However, the fundamental principles established in research in temperate regions have application in tropical regions. There are numerous reasons to conclude that tropical regions differ from temperate regions largely in climatic environment, but the fundamental biological principles formulated in temperate regions apply equally well in tropical regions when adequate consideration is given for changes in environmental factors. The purpose of this chapter is to review the fundamental principles that should guide research on soil nitrogen and organic matter in tropical regions and to emphasize measurements that are required in order to manage tropical cropping systems efficiently.

NITROGEN SUPPLY CAPABILITIES OF SOILS

Nitrogen Supply Processes

Natural nitrogen supply processes have provided the nitrogen for crop production since the beginning of time. However, seldom have

they provided an abundance of nitrogen for long and sustained periods of crop production on the same land areas. Moreover, natural supply 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. The natural supply processes include (1) mineralization of nitrogen from soil organic matter and from crop residues and the reverse process of immobilization in the decomposition of plant and animal debris and soil organic matter; (2) fixation of nitrogen from the atmosphere, largely through biological processes; (3) addition of nitrogen added through rain and other forms of precipitation.

Soil Organic Nitrogen

The nitrogen in soil organic matter has been and is yet an important source of nitrogen for crop production. However, soil nitrogen is not inexhaustible; it must decline in quantity in the soil in order to supply net amounts of nitrogen to crops grown on the land. Consideration of several factors associated with formation and decomposition of soil organic nitrogen will illustrate its importance and also its limitations as a source of nitrogen for crop production.

Nitrogen in the soil is largely in organic form. The organic nitrogen is an integral part of the soil organic matter system. Changes in organic matter are always accompanied by parallel changes in organic nitrogen. Organic matter is a temporary product—a stage in a natural cycle of elements. Each increment of organic matter originated as a particle of plant or animal residue, and it remains in the soil while it passes through the several slow biological changes that eventually convert it to carbon dioxide, water, ammonium, and other mineral elements. The soil supply of organic matter is replenished by periodic additions of fresh plant or animal residues.

Under all nonsterile soil conditions, nitrogen is added to the organic supply in the soil annually through crop residues (immobilization). Also through biological decomposition, organic nitrogen in the soil is continuously converted to the inorganic form (mineralization). Under any sustained system of crop and soil management, these two processes tend to approach each other in magnitude so that mineralization balances immobilization (Bartholomew and Kirkham, 1960). When this balance is attained, the system is considered to be in equilibrium.

Soil areas differ markedly in the equilibrium level of soil nitrogen

attained after long periods of constant soil management. The equilibrium system is best illustrated by reference to the general mathematical expression used to describe soil nitrogen changes with time (Woodruff, 1950).

$$(dN/dt = A - rN) \tag{1}$$

is the primary differential equation that states that the rate of change in soil nitrogen is positively related to the rate of addition and inversely related to the rate of decomposition. N in the equation is soil nitrogen content. A is constant and is the annual rate of addition. The rate of decomposition, r, is a given fraction of the organic nitrogen in the soil. Upon integration, the expression in Eq. (2) results.

$$N = \frac{A}{r} - \frac{Ae^{-rt}}{r} + No\, e^{-rt} \tag{2}$$

The function e^{-rt} varies from 1 to 0 as rt varies from 0 to some very large number. Therefore, after a long time ($t\ \infty$), the last two components in the equation approach zero and the equation becomes

$$N = A/r \tag{3}$$

and

$$rN = A. \tag{4}$$

This means [Eq. (4)] that addition is equal to decomposition. Equation (3) shows that the amount of nitrogen in the soil at final equilibrium is influenced by both the rate of addition and the rate of decomposition.

The implications and consequences of equilibrium situations in soil 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 nitrogen in the soil remains unchanged. Consequently, the net amount that can be and is supplied to a crop is zero. Under these conditions, there must be as much organic nitrogen returned to the soil from crop residues as is liberated from decomposition. A critical examination of equilibrium situations reveals that when a part of the crop is harvested and removed from the land, equilibrium in organic matter can exist only if the nitrogen and organic matter inputs are

supplemented from sources apart from the land area in question. Fallow areas and permanent pastures most nearly provide conditions where equilibrium situations could exist without fertility input from outside sources. Also, at very low levels of soil nitrogen, rainwater and nonsymbiotic nitrogen fixation may furnish enough additional nitrogen to permit low levels of removal by crops for long and sustained minimum production.

Cropping Practices and Changes in Organic Matter

In virgin soils, some kind of an equilibrium situation must have been attained or closely approached with respect to soil organic matter. When cultivation of the virgin soils was begun, this equilibrium was disturbed. Either the rate of addition of soil organic nitrogen or the rate of decomposition or both were so altered that a new equilibrium level was approached. In most instances, this new level of organic matter was lower than that in the virgin soils.

Available Nitrogen in Relation to Supply Processes

Soil organic nitrogen must decline in quantity in order to supply net amounts of nitrogen for crops grown on the soil. This is still happening in some areas of the world. There is no simple method for determining the extent to which soil areas have attained organic matter and organic nitrogen equilibrium. Soil test procedures largely reflect total mineralization or total organic nitrogen. The time that the soil has been under constant cultivation is the best guide. Some long-time soil and crop management experiments in temperate regions show that a new equilibrium in nitrogen and soil organic matter is closely approached in 60 to 100 years of constant management. In some tropical and semitropical areas, the time to attain organic matter and nitrogen equilibrium may be much shorter.

During periods of virgin or noncultivated conditions, certain soils tend to build up soil organic matter and soil nitrogen. Some soils accumulate 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 (Schreiner and Brown, 1938). As cultivation continues and the organic nitrogen declines, the quantity of nitrogen becoming available each year declines. After long periods of cultivation, the soil organic matter becomes exhausted as a major source of available nitrogen, and, unless

legumes are grown, the annual available nitrogen from natural supply processes becomes chiefly that from rainwater and from nonsymbiotic nitrogen fixation.

Current Situation

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. Where little or no nitrogen fertilizer has been used, yields of major crops largely reflect the magnitudes of the natural nitrogen supply processes from rainwater and nonsymbiotic nitrogen fixation.

Yields of corn in the order of 600 to 1,200 kg/ha and of wheat of 400 to 800 kg/ha require supplies of available nitrogen only a little larger than could be expected from rain and from nonsymbiotic fixation. Moreover, such yields do not remove more than 15 kg/ha of nitrogen from the land in the harvested grain products. Such yields, therefore, could be sustained for long periods under primitive conditions of agriculture with the use of only small amounts of fertilizer and without the culture of leguminous plants. In many important food-producing areas of the tropics, these yield levels prevail, and the lack of available nitrogen is the chief limiting factor in production of crops. To increase yields in these same areas will require the use of nitrogen fertilizer or leguminous crops as well as other production inputs.

Large areas of land in tropical regions have not been cleared and cultivated within the known history of the land. Some of these areas—for example, the inland regions of Brazil—are expected to be cleared and cultivated in the near future. After clearing and cultivation, the soil would be expected to furnish some substantial amounts of nitrogen to the crops grown. The amounts furnished, the rate of anticipated decline in soil nitrogen, and the time required for a close approach to nitrogen and organic matter equilibrium are important research topics.

BIOLOGICAL NITROGEN FIXATION

Nitrogen Fixation by Biological Agents

Biological nitrogen fixation processes have been responsible for providing most of the large quantities of nitrogen currently used by and

tied up in plants and animals and in the decomposed residues found in soil (soil organic matter). Moreover, biological fixation processes still supply the major part of the nitrogen for crop production in world agriculture.

The chief process is symbiotic nitrogen fixation, in which a host plant (mainly leguminosae) and bacteria function in symbiosis in the nitrogen fixation processes. Numerous host plants function in this way, and a large number are employed in crop husbandry. The symbiotic process of nitrogen fixation may supply a part or all of the nitrogen used by the host plant for growth. As a result of the growth of the host plant, which has functioned in nitrogen fixation, other crop plants that are associated with or that follow the host in a crop sequence may benefit by being supplied with some increased quantity of nitrogen. An understanding of some aspects of the fixation process provides a basis for determining what may be expected of the host plant and the benefit that may accrue to the associated crops.

The amount of nitrogen fixed per acre per year under field soil conditions has been estimated by several investigators. It is presumed that in most instances the estimates are based largely on the quantities of total nitrogen taken up and immobilized in the plant tissue. Total nitrogen contained in leguminous crops ranges from a few kilograms per hectare in poor stands of legumes to as much as 500 kg/ha in large yields of soybeans and several cuttings of alfalfa.

An important aspect of biological nitrogen fixation is that the fixation processes are growth related. In both symbiotic and nonsymbiotic fixation, nitrogen is fixed and used only as it is needed for growth of the bacteria, the host plant, or both. The fixation process does not result in indiscriminate nitrogen fixation in which an excess of fixed nitrogen is transported to the exterior of the bacterial cell in nonsymbiotic fixation or to the outside of the host plant in symbiotic fixation. Fixation is growth bound, and the fixation processes are in some way regulated by growth processes and by needs for nitrogen.

Another important factor in biological nitrogen fixation is that in both symbiotic and nonsymbiotic processes fixation is inhibited by the presence of available inorganic nitrogen. When mineral nitrogen is in the system and available for use by the bacteria and the host plant, the inorganic nitrogen is absorbed and used first, and the fixation processes function only to supply the nitrogen deficit. In other words, available nitrogen substitutes for and replaces the fixation

processes (Allos and Bartholomew, 1959). A very small but sustained concentration of mineral nitrogen in the soil solution will completely inhibit fixation.

Fixation may be inhibited without inhibiting nodulation. Nodules on host plants do not necessarily indicate that extensive fixation is occurring or has occurred. When small but sustained amounts of available nitrogen are supplied to leguminous plants, infection processes of the roots may be normal and nodules may be formed, but very little, if any, nitrogen may be fixed. Higher concentrations of available nitrogen prevent the formation of nodules (Vincent, 1965).

Influence of Nitrogen Fertilization on Legumes

In considering the nitrogen nutrition of some leguminous crops, it should not be forgotten that legumes may respond in growth and yield to the presence of a favorable quantity of mineral soil nitrogen (Thornton, 1948). Greenhouse tests have demonstrated such responses (Allos and Bartholomew, 1959). Moreover, maximum yields of soybeans have most often been produced where high quantities of nitrogen fertilizers have been applied. Nitrogen fertilizer management for the production of legumes is largely an unknown field. About all that has been done so far is to try application practices that have been successful for nonleguminous crops. Some serious studies should be undertaken on nitrogen fertilization of legumes in the tropics, especially those that are important food crops.

Influence of Legumes on Associated Crops

The influence of legumes on associated crops or on crops that follow the legume is difficult to assess. During the active growing period of leguminous plants, very little nitrogen escapes and becomes available to associated crops. It is only when the legume matures or when environmental conditions induce parts of the plant to die that the nitrogen contained in the tissue of the legume begins to become available through microbial decomposition. Perennial legumes begin to exert a major influence on associated plants after the season of establishment, and annual legumes, at maturity or thereafter during decomposition of top and root residues.

An evaluation of meadow and catch crops has been made by Shrader *et al.* (1966), in terms of nitrogen supplied by the legumes to

crops that followed. The crop immediately following the legume obtained a rather large quantity of available nitrogen from the legume that preceded it. Their data indicate that a crop that followed a good legume crop in the rotation benefited to the extent of better than 110 kg/ha of nitrogen. The benefit to the second crop following the legume was one third to one half that obtained by the first crop.

The increase in available nitrogen in the soil immediately following the growth of the legumes is due in large part to the legume residues returned to the soil and to the release of nitrogen upon decomposition of the residues. The increase also reflects some increment in total nitrogen in the soil in the legume rotation plots over that in continuous corn plots.

Green manure and cover crops vary markedly in the quantities of nitrogen they supply to a crop that follows. All of the nitrogen in the green manure is not available to the following crop. The proportion of the nitrogen in the legume crop that becomes available is closely related to the percentage of nitrogen in the residue returned to the soil (Bartholomew, 1965). In general, green manure crops have furnished growth responses in crops that followed that were equivalent to those obtained from the addition of from 10 to 60 kg/ha of nitrogen. The amount of nitrogen supplied is not large in terms of fertilizer equivalents. The economics of the practice need to be critically considered before green manures are recommended as a source of nitrogen to crops that follow.

Place of Legumes in Modern Agriculture

It would be well at this point in the discussion to appraise the potential and the value of leguminous culture and of biological nitrogen fixation in modern agriculture. Where legumes are valuable as forage or food, they will continue to be important in modern agriculture. Their culture may not be justified, however, when a major purpose is only to supply nitrogen to associated crops. First, the cost of nitrogen supplied by leguminous crops, in terms of labor and land use, is often much too high to compete with fertilizer except where fertilizer is expensive and difficult to get. Second, leguminous crops cannot supply enough nitrogen to meet the needs of modern high-yielding crops. A perennial legume crop, after two or more years of

growth, may furnish from 50 to 150 kg/ha of nitrogen to a nonlegume crop that follows. Green manure crops and annual legumes may provide from 10 to 70 kg/ha. In some areas of the tropics and under some circumstances, these sources of nitrogen may be the most effective for a fair crop yield. However, the nitrogen for high and efficient yields will probably need to be supplied in substantial part from fertilizer. The natural supply processes—soil organic nitrogen and biological fixation—supply some nitrogen for crop production but do not appear capable, in light of present knowledge, of providing the nitrogen requirements for high production. However, further research on this subject in tropical environments may challenge current concepts.

Fixation by Free-Living Microorganisms

In nonsymbiotic nitrogen fixation by free-living bacteria in the soil, a limiting condition is food energy for the growth of the organism. For example, 10 mg of nitrogen fixed per gram of organic food decomposed is near the maximum efficiency obtained by young, fast-growing, heterotrophic nitrogen-fixing bacteria (*Azotobacter*). Assuming maximum efficiency in the use of food energy and the absence of available nitrogen—two conditions that seldom occur in a soil system—for 10 kg of nitrogen fixed per hectare, the nitrogen-fixing bacteria would have consumed 1,000 kg of energy food. In the case of nitrogen-fixing algae, the energy would come from light. The evidence strongly suggests very little nonsymbiotic nitrogen fixation in most soils.

In Brazil, a favorable environment for nonsymbiotic nitrogen fixation is under study (Döbereiner, 1961, 1968). *Azotobacter paspali* thrives in the root zones of sugarcane and some species of *Paspalum*. The plants, through the root system, may provide sufficient energy to result in significant fixation. A pseudosymbiotic association appears feasible. The importance of this to agriculture warrants further study. However, if the known principles that influence nitrogen fixation apply to the nonsymbiotic and pseudosymbiotic associations, only fair to moderate yields of the particular crops could be expected from nitrogen fixation. To obtain the higher yields required for modern economic agriculture would necessitate the addition of nitrogen fertilizer.

NITROGEN MOVEMENT IN RELATION TO CLIMATIC FACTORS

Loss Processes

A problem of major concern in the tropics is the apparent poor use made by plants of available soil nitrogen. Well-documented evidence from a number of sources indicates that plant recovery of available soil nitrogen ranges on the average between 50 and 60 percent (Rogers, 1961; Viets, 1960). The other 40 to 50 percent somehow escapes from the soil system. It could be lost by leaching, or it could escape by volatilization. Moreover, experimentation indicates that native soil nitrogen coming from mineralization of soil organic matter has not been used more efficiently by crops than has added fertilizer nitrogen.

The chief loss process has been considered to be removal of the available nitrogen from the root zone by water, usually referred to as leaching. Under high rainfall conditions and in friable well-drained soils, leaching may be quite rapid (Charreau, 1961; Roose and Godefroy, 1968). Under low rainfall conditions, as at the beginning or end of the dry season, leaching may be negligible, and other factors may make the nitrogen unavailable.

Denitrification and other volatile loss processes do occur in soil and account for some of the inefficiency in the use of nitrogen by crop plants. However, except for some unusual soil conditions, volatile loss processes do not appear to account for all of the nitrogen escaping use by crop plants. Reasonable estimates of denitrification are from 5 to 15 percent of the available nitrogen in the course of a single cropping season (Allison, 1966; Bartholomew, 1964).

Loss of ammonia nitrogen by volatilization has been a major loss process in some situations, e.g., where ammonia-yielding fertilizers have been applied to the surfaces of sandy soils. When the rate or method of addition results in a local or general concentration of ammonia too great for effective adsorption by the soil, some volatilization is inevitable.

Influence of Soil Water on Nitrogen Absorption

Soil water appears to be the most important single factor influencing or controlling nitrogen uptake and use by crop plants in field situations. This hypothesis derives from a critical evaluation of a large body of indirect evidence.

Soil water is directly involved in the transportation and absorption of nitrate nitrogen by plants. Also, it is involved in leaching, the chief mechanism of loss from the soil system. It is involved indirectly in denitrification. Soil water also influences the incidence and activity of roots in some soil horizons.

Four major premises relative to nitrate absorption by plants and loss from a soil by leaching are worthy of critical consideration. These are as follows:

Nitrate nitrogen absorption by crop plants from soil is closely related to water absorption and to water availability.

Nitrate nitrogen absorption by plant roots is negligible in soil zones where moisture conditions are low or are adverse for ion diffusion and plant uptake of water.

Root penetration into and root proliferation in the several horizontal layers that make up the solum vary markedly among soils and among plant species and varieties.

Nitrate moves with water, and an understanding of water movement and availability in soil largely explains nitrate movement and availability to particular crop plants.

If these premises are correct, they not only would provide explanations for much of the poor efficiency of nitrogen use by crop plants but also would point the way to formulating management practices to alleviate nitrogen losses by leaching.

In solution culture experiments in the absence of soil, it has been shown that the plant can take up nitrate more rapidly than it takes up water (Minotti *et al.*, 1968). In soil systems, however, nitrate nitrogen must be carried or moved in some way by or through the soil solution to the root boundary. This transport process is by and through water (Ohlrogge, 1969; Olsen and Kemper, 1968), and the chief limiting factor in nitrogen absorption is transport to the root surface.

In these situations, the nitrogen uptake by the plant from nitrate sources would appear to be passive (Jensen, 1962), in that it is dependent on water transport or the movement through water films. Another well-known feature of soil water is that not all of it is available to plants. Of the water held at field capacity, not more than 60 percent, and often less than that, is available to crop plants. Water held at moisture tensions above the wilting point can contain nitrate but would tend to prevent its movement to the roots of crops. If ni-

trate nitrogen absorption by the crop plant is dependent on water to transport it to the roots either through mass flow or by diffusion, then in soil systems where water is stored in the soil for subsequent crop growth, not more than 60 percent of the nitrogen could be absorbed by the crop. The water would have to be replenished and recharged a number of times in order to permit a large proportion of the soluble soil nitrate to be moved to the plant roots.

In field situations the moisture conditions would be different from those in solution culture experiments. In the field, incoming water from the surface, in part, may displace the old soil water to deeper depths. Incoming water also may only wet the surface of the soil and have little influence on the soil water in the lower parts of the root zone. Often the water supply for a crop comes largely from the top few inches of soil. In such situations, any nitrate nitrogen in the lower parts of the root zone would not be available for absorption.

Under conditions of high rainfall, the incoming moisture may rapidly leach most of the nitrate nitrogen from the confines of the root zone. Normal precipitation results in water entering the top layers of soil. Net movement of water downward through the top few centimeters of soil may be quite extensive. As a result of water absorption by plant roots and subsequent transpiration through the leaves into the atmosphere, net downward movement of water becomes progressively less through progressively deeper layers of soil. When a plant removes water from the subsoil, some upward movement of water must occur. When subsoil layers get dry during crop growth, there must be some depth position in the root zone where the net vertical movement of water is zero.

Water movement patterns vary markedly among soils, cropping practices, and climatic regions. Also, water movement at a single site may vary considerably from season to season. Because nitrate nitrogen is carried and moved by water, the water movement pattern in a soil may have a marked influence on plant absorption and on how fast and when nitrogen is moved down in the soil to positions beyond the reach of crop plants.

CROP NEEDS FOR NITROGEN

Nitrogen needs for some widely grown crops have been investigated and are quite well understood. However, for many crops peculiar to tropical regions, the total nitrogen requirements for particular levels of production are not known.

TABLE 1 Nitrogen Used and Needed by Selected Crops

Crop	Yield Level (tons/ha)	Nitrogen, kg/ha: In Grain	In Tops and Roots (Crop Residues)	Needed to Produce Yield Shown in Column 2
Corn	10–12.5	150–190	112–150	300–390
Corn	1	11	10	28
Rice	6–10	82–141	46–86	200–360
Wheat	5	140	78	300
Wheat	600[a]	12	6	27
Soybeans	4	245	115	–
Peanuts	3.5	128	205	–

[a] kg/ha.

Data on nitrogen use and needs for some cereal and leguminous crops give some indication of the total quantity of nitrogen that may be needed to achieve high crop production (Table 1). Such quantities can be compared to the magnitudes of the natural supply processes.

The actual use of nitrogen by the crop may be much lower than the total quantity of soluble nitrogen that may be required in the soil or may be applied as fertilizer in order to produce the crop. Use efficiency is often low and is one of the problems needing investigation in the efficient production of tropical crops.

NITROGEN AVAILABILITY AND ITS MEASUREMENT

Availability

Availability of a nutrient implies a condition that permits its use by a plant. This connotes that the nutrient is in the proper chemical form for plant absorption, that it is located where it is accessible for uptake, and that the local environment is conducive to plant use. However, we have only a meager understanding of the conditions that must obtain in the soil to satisfy the requirements for availability. Consequently, no precise methods for evaluation have been found. Plant uptake, therefore, has been used, and it still remains the best measure of an "available" situation. Conventional methods of measuring nitrogen availability do not necessarily indicate how much can be absorbed by the plant. Soil test methods for nitrogen generally re-

flect a quantity of mineral nitrogen in the soil or a potential to supply mineral nitrogen during a cropping season.

The quantity or proportion of the soluble nitrogen (chiefly ammonium and nitrate) that can be absorbed by the crop is dependent on or is influenced by several important local site factors. These are

Rooting habits of the crop

Volatile loss processes and the local environmental factors that influence these loss processes

Vertical movement of nitrate nitrogen and in some instances the complete removal of the nitrate by leaching

The moisture status in that part of the root zone where the nitrogen resides

The presence or absence of crop residues, which may immobilize nitrogen

Evaluation of Available Nitrogen in Soil

Crop needs for nitrogen fertilizers depend on the total crop requirement for nitrogen and the proportion of this total that can be supplied by natural processes. Both factors should be appraised in soil fertility evaluation programs. Test methods measure or reflect soluble soil nitrogen. Calibration of test methods with crop response to nitrogen applications should indicate crop needs.

A number of kinds of test procedures have been used to indicate availability of nitrogen in soil. Some are chemical extraction methods and reflect the total nitrogen in soil. Some are biological and measure mineralization. All are arbitrary and to be useful must be calibrated with plant use and plant needs.

Test procedures have had varying degrees of usefulness and success in soil fertility evaluation programs. Under specified soil and cropping conditions, the calibration relationships for some methods have been very good. However, no methods have been used widely for diverse soil and cropping conditions.

In general, test methods for nitrogen are expensive in terms of analytical time and equipment. This fact suggests the need for a critical appraisal of the usefulness of nitrogen test methods in soil fertility evaluation programs. Such an appraisal should include consideration of (1) the type or types of tests that could be used and the unit costs of making the tests; (2) the kind and extent of field calibration research needed to make the test meaningful; (3) the kinds and

values of the crops to be grown; (4) the general level of nitrogen in the soil and the cropping history of the area; and (5) other procedures for getting equally useful information about nitrogen fertilizer needs and crop response to fertilizer. For all cropping systems, a critical appraisal should be made of the precision in fertilizer recommendations that can be achieved by use of a test method and the relationship of this precision to the needs of the crop for nitrogen fertilizer.

Immobilization and Mineralization

The processes of immobilization (fix) and mineralization (release) often exert a very marked influence on nitrogen availability in soil (Bartholomew, 1965). Moreover, these transformation processes complicate the use and interpretation of a number of soil fertility analysis procedures for evaluating soil supplies of and crop needs for nitrogen. Practical appraisals of the influence of these processes generally take into account the influence of past cropping practices.

Nitrogen in organic form remains associated with crop residues during the decomposition process. The quantities remaining as organic nitrogen and the periods of immobilization and mineralization have been extensively studied (Bartholomew, 1965). Some important aspects of these transformation processes need to be emphasized. First, ordinary crop residues are rather similar in their capacity to immobilize nitrogen and will retain from 9 to 13 kg of organic nitrogen per ton of original residue when decomposition occurs under aerobic conditions. If the residue originally contains less nitrogen than needed by the microorganisms for decomposition, inorganic nitrogen is absorbed from the soil and immobilized by the organisms. If the residue contains more than is needed by the microbes, the excess nitrogen is mineralized and appears as inorganic nitrogen in the soil.

The major tie-up and release processes come early in the decomposition processes. In soil they are essentially complete within the first 2 to 4 weeks of decomposition. Low nitrogen residues, which immobilize extra nitrogen from the soil, tend to retain the total immobilized nitrogen for two or more seasons without any appreciable release. High nitrogen residues tend to release small amounts of nitrogen after the first initial decomposition surge. Small but measurable amounts of nitrogen become available from high nitrogen residues during the second and subsequent seasons of decomposition.

After the first early surges in decomposition, crop residues tend to

continue decaying slowly, losing chiefly carbon dioxide and water but retaining nitrogen. Consequently, with progressive decomposition, the percentage of nitrogen increases in the residue material and the carbon-to-nitrogen ratio decreases. In arable soils, environmental factors, chiefly weather, influence the nitrogen tie-up and release processes principally by influencing the rate of decomposition of the crop residues but do not significantly alter the amount of nitrogen retained or released by residues at particular stages of decomposition.

Many observed cropping and soil management practices exert part or all of their influence upon the soil or the crop through some modification or control of the tie-up and release of nitrogen. The marked influence that one crop may have on a crop that follows is often largely due to the influence of the crop residue on the nitrogen supply from the soil.

The amounts and kinds of residues left on the land and the manner in which the residues are managed determine the rate and extent of nitrogen tie-up and release. Although residue yields vary with season, with soil, and with crop variety, the residue yields tend to be closely related to the level of production of the particular crop. High production of a crop results in high yields of residue.

The practical handling of crop residues, including plowing versus subsurface tillage, and the time of year when tillage operations are carried out may alter the nitrogen supply. Residues left on the surface decompose more slowly than those plowed under. This slow decomposition, along with the fact that surface residues are in contact with less soil material, results in a much slower tie-up of nitrogen from low-nitrogen residues and a slower release of nitrogen from high-nitrogen residues than when residues are incorporated in the soil by tillage. Surface mulches also modify soil temperatures and moisture contents, which in turn influence tie-up and release of nitrogen in crop residues and soil organic matter.

Plowing-under low nitrogen residues well in advance of planting a crop is always likely to result in more soil nitrogen being available to the next crop than plowing just prior to planting. The chief reasons are, first, that weeds and other plants that absorb soil nitrogen are killed, leaving available nitrogen to accumulate in the soil; and, second, that the nitrogen tie-up processes of decomposition will have been satisfied long before planting, so that nitrogen made available from the soil will be available to the crop and not reabsorbed by the residue during early stages of decomposition. Plowing-under legumi-

nous residues too far in advance of planting a subsequent crop may provide opportunity for nitrogen loss by denitrification or by leaching.

Cultivation of the soil has been reported to stimulate microbial activity and to result in increased nitrogen becoming available from the soil. The validity of this principle has never been adequately investigated. It may or may not be correct. Factors other than just disturbing and aerating the soil, in most instances, can explain most of the benefits of cultivation. Changes in soil temperature or in soil moisture brought about by cultivation may account for the effects of cultivation.

The carryover effect of nitrogen fertilization into the second season after application may be explained in part by the amount and composition of crop residues left on and in the soil and in part by inorganic nitrogen remaining in the root zone. Even though increasing the rate of applying nitrogen fertilizer to nonlegumes increases the amount of residue returned to the soil, the higher nitrogen contents of the residues induced by high rates of nitrogen fertilization would tend to offset the effect of the amount of residue in total nitrogen immobilization.

Volatile loss processes and the impact of water on nitrogen availability and use were discussed in a preceding section. The incidence and activity of plant roots in the several horizontal layers of soil have a marked influence on nitrogen absorption. Some of the factors that influence root growth are discussed in other sections.

MANAGEMENT OF CROP RESIDUES

Crop residues should be considered apart from soil organic matter. They can have several important influences on soil. Also, they are much more subject to management than is soil organic matter. Crop residues function in the following ways in and on soil:

As a protective cover on the soil surface, crop residues prevent the deterioration of soil structure that may result from high-intensity rain. Such a function can be used to reduce erosion of surface soil and to increase infiltration of water into the topsoil.

Crop residues insulate the soil surface against rapid changes in temperature. Soils partially covered with a layer of crop residues tend to increase in temperature less rapidly than bare soil. This may be due

in part to the color of the residue and reflection of the incident energy rays and in part to moisture changes in the topsoil induced by the residue layer. Residue covers also reduce heat loss from soil.

Crop residues supply and regulate the supplies of mineral nutrients in soil. Upon decomposition, the mineral elements contained in the crop residues may be released and may become available (potassium is a special case in that most or all of plant potassium is water soluble and decomposition processes are not necessary for release). In the initial decomposition processes, all of the mineral elements are not released. The quantities released initially, or in the early stages of decomposition, are related (1) to the percentage of the nutrient in the residue and (2) to the susceptibility of the residue to decomposition. The most important influence of decomposition often is reflected in the nitrogen tie-up and release.

Crop residues often harbor diseases and insect pests. The management of residues, therefore, can have a marked influence on soil sanitation and on the incidence of diseases and pest damage to crops that follow the addition of the residue.

Residues on the surface of the soil impede and often restrict certain cultural practices. For this reason, as well as to control diseases and pests, residues are often burned. Residues on the surface decompose more slowly under many environmental circumstances than residues buried by plowing or other cultural practices. Large yields of residues are generally a much greater problem for tillage operations than are small yields.

A widespread conventional practice in tropical and subtropical areas is to burn crop residues during or near the beginning of a dry season. This practice cleans the land surface of coarse residues and permits new forage to emerge in grazing areas or eliminates tillage impediments on cultivated land. Although the literature concerned with burning is extensive, there remain a number of unanswered questions relative to the value of the practice as a practical means of handling crop residues. These questions need to be resolved.

Residues may also be of major concern in areas where multiple cropping is practiced. Fresh crop residues often pose tillage and cultivation problems when a second crop is planted immediately after the harvest of a first crop. When two or three crops are grown in the course of a single year, the accumulation of residues from high yields of crops could very well induce a number of operational and management problems.

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R. A. OLSON AND O. P. ENGELSTAD

Soil Phosphorus and Sulfur

Phosphorus and sulfur are similar elements in the soil–plant continuum in that they are required in approximately equivalent amounts for crop nutrition and a significant portion of each is stored in the soil's organic component. Experimentation with these elements to date has provided only partial understanding of the dynamics involved in their accumulation, storage, utilization, and loss in the various soil, climatic, and ecological regions of the tropics. Principles established for soils in temperate regions no doubt apply, but with qualifications imposed by the more intensive weathering and leaching forces and the different mineralogical and organic character of soils in the humid tropics.

OCCURRENCE OF PHOSPHORUS AND SULFUR IN TROPICAL SOILS

Total Amounts and Forms

Phosphorus

Extensive investigations with soils of temperate regions have shown declining levels of total phosphorus in surface soils with increasing

intensity of weathering. Total phosphorus in surface soils ranges from an average of 3,000 ppm in the subhumid cool temperate region to less than 500 ppm in the humid warm temperate region (Pierre and Norman, 1953). This projection seemingly carries through into the humid tropics, as evidenced by the common finding of less than 200 ppm total phosphorus in mature upland soils (Bouyer and Damour, 1964; Enwezor and Moore, 1966; Middleton, 1954; Nye and Bertheux, 1957). Beyond the fact of decreasing total phosphorus with increasing intensity of weathering is the recognized higher proportion of organic and occluded forms of phosphorus in Latosols (Oxisols). Relative distribution of the inorganic phosphorus of surface soil as water-soluble surface-adsorbed aluminum phosphate, iron phosphate, and calcium phosphate is about as variable from site to site as are tropical soils *per se.* Generally speaking, however, within a given soil group, aluminum phosphate increases as calcium phosphate decreases with declining pH; iron phosphate in occluded form with iron coating predominates as soils become ferruginous in character (Bouyer and Damour, 1964; Chang and Jackson, 1958). Rate of phosphorus loss from soils of the tropics is determined primarily by cropping intensity and erosion, leaching being slight except on very sandy soils. Gains depend entirely on the amount of phosphorus added in manure or commercial fertilizer.

Sulfur

Total sulfur in soils varies perhaps even more than total phosphorus, depending especially on soil-forming processes and the amounts of organic matter and clay in the soil. The presence of sulfur is closely tied to the accumulation of soil nitrogen, e.g., in the ratio of 10 nitrogen to 1.2 sulfur in acid soils of eastern Australia (Barrow, 1960), so that the role of sulfur in the accumulation and turnover of organic matter cannot be disregarded. As with phosphorus, investigations of soils in temperate regions show declining sulfur levels with increasing intensity of weathering, and average values of 540, 396, and 210 ppm of total sulfur for Chernozem (Mollisols), Brunizem (Alfisols and Mollisols), and Red-Yellow Podzolic (Ultisols) surface soils, respectively (Jordan and Reisenauer, 1957). It seems reasonable to project values generally below 100 ppm for most intensively weathered upland soils of the tropics. Most of the sulfur in surface soils is found in organic combination (Evans and Rost, 1945), whereas varying amounts of inorganic compounds such as gypsum and

pyrite may be found in lower horizons associated with specific leaching or drainage conditions. Important to crop nutrition are smaller quantities of inorganic sulfate ions in water-soluble or adsorbed form, the latter being particularly significant in subsoils containing kaolinite and hydrous oxides of iron and aluminum (Ensminger, 1954; Neller, 1959).

Influence of Soil and Climatic Conditions on Availability

Phosphorus

Phosphorus availability to plants grown on tropical soils varies tremendously with the morphological properties of the soil, previous management, and the local climatic environment. Surface soils of the derived savanna, which have been subjected to long periods of intermittent cropping and bush fallow, are likely to be very low in total phosphorus content and correspondingly low in their capacity to deliver available phosphorus (Nye and Bertheux, 1957; Russell, 1968). Moreover, increasing population pressure, which has resulted in shorter fallow periods, has been responsible for increased incidence of phosphorus deficiency (Enwezor and Moore, 1966). Fixation of applied increments of phosphorus is far more serious in certain tropical soils than in soils in temperate regions and is related to the clay mineralogy and the amorphous nature of the colloidal hydrated oxides of iron and aluminum. Hawaiian workers' ranking of fixation capacities of the more common components of the clay fraction of soil is pertinent: amorphous hydrated oxides > gibbsite – goethite > kaolin ⩾ montmorillonite (Fox *et al.*, 1968). Phosphorus fixation is recognized as the major obstacle to agricultural development of volcanic ash soils in Hawaii, where upwards of 1,350 kg of phosphorus per hectare may be needed to satisfy the phosphorus fixation capacity (Younge and Plucknett, 1966). Fixation is especially rapid and strong on ferralitic soils (Oxisols) high in goethite in West Africa (Dabin, 1970). The periodically humid tropical climate has indirectly contributed to fixation by its influence on the intensity of soil mineral weathering and by the potential for year-round chemical reaction between any phosphate increment and the soil's colloidal system.

Many soils of the humid tropics are very strongly acid by temperate region standards. Thus, liming the soil to a higher pH level has been responsible for enhanced phosphorus availability for crops

on the Campo Cerrado soils of Brazil, the eastern plains of Colombia, the Oxisols of Hawaii, the Ultisols of Central America and the southeastern United States, and the more acid soils of restricted drainage in Tanzania (Mtanana series). Benefits are usually attributed to an increased rate of decomposition of soil organic matter, which releases the phosphorus to the soil solution; a reduced aluminum uptake; and a blocking of fixation reactions. The pH level above which benefits cease and deleterious effects begin is usually between 5 and 6 (Fox *et al.*, 1964a; Kamprath, 1970; Le Mare, 1959; Spain and Ruiz, 1968), at which level most of the exchangeable aluminum has been neutralized. This is a notably lower pH level than is considered optimal for agriculture in temperate regions and may well account for the often-reported deleterious effects of liming in the tropics; i.e., rates based on experience in temperate regions may well have constituted overliming on the poorly buffered tropical soils.

Flooding the soil for rice enhances the availability of soil phosphorus for the crop (Bartholomew, 1931). This has been ascribed to the reduction of the iron in ferric phosphates under chemical reducing conditions induced by oxygen depletion and to the production of reduced inorganic and organic soil phosphorus compounds of greater solubility (Ahmad, 1967; Gasser and Bloomfield, 1955; Islam and Elahi, 1954). Thus a sharp break is noted in the curve relating extractable phosphorus to controlled redox potentials at +200 mV, which is the potential at which ferric iron begins to be reduced to the ferrous form (Patrick, 1964).

Sulfur

Sulfur availability in tropical soils is also highly variable, depending especially on the organic matter content of the surface soil, soil texture, and previous management of the soil. Much less investigational work has been done on soil conditions that influence sulfur availability than with phosphorus. As with phosphorus, problems of deficiency to date appear to be associated especially with upland savanna (Greenwood, 1951; McClung *et al.*, 1959). Presumably, this is a manifestation of the lower organic matter content of the surface soils of the savanna than of the forest soils, and the deficiency seems to be accentuated by drought (Dutt, 1962). In upland soils with good drainage, even where the organic matter content is substantial, leaching of available sulfur is appreciable to excessive with increasing rainfall. Losses of sulfur from tropical soils are associated with cropping

intensity, erosion, and leaching. Replenishment comes from various fertilizers, insecticides, fungicides, and irrigation water. Rainfall is not the contributing factor in the tropics that it is in industrialized temperate regions; moreover, the replenishment of sulfur in nitrogen and phosphorus fertilizers is rapidly disappearing with the trend toward manufacture of higher-analysis materials without a sulfur impurity.

Some tropical soils have productivity problems associated with excess sulfur, especially the acid sulfate "cat clays." Large quantities of reduced sulfur compounds have accumulated in these soils under the natural marshy environment of tidelands. When such areas are drained, the sulfur is oxidized to sulfate, and the pH is drastically reduced to as low as 2.5 (Bloomfield *et al.*, 1968). In submerged rice culture in the Far East, sulfur can have deleterious effects. If the soil is old, degraded, and low in iron, excluding oxygen from the soil by waterlogging may cause added or native sulfate to be reduced to hydrogen sulfide, a toxic material thought to be responsible in part for Akiochi disease of rice.

CROP RESPONSES TO APPLIED PHOSPHORUS AND SULFUR FERTILIZERS

Phosphorus

Good crop responses to phosphorus fertilizers with existing systems of farming are obtained in most upland areas of the humid tropics, as demonstrated by thousands of simple trials conducted by the Freedom from Hunger Campaign (FFHC) Fertilizer Programme of FAO (FFHC Fertilizer Programme, 1968). Positive response to phosphorus has occurred in slightly more than 90 percent of the locations investigated, with frequency of response exceeded only by that due to nitrogen. Response is especially large in tubers and vegetable crops, as evidenced by the following summation for West Africa and northern Latin America.

	Increase Due to Phosphorus (kg/ha)
West Africa	
Maize (794 trials)	173
Yam (377 trials)	895
Northern Latin America	
Maize (196 trials)	401
Potato (53 trials)	2,762

Other fertilizer trials in the humid tropics have demonstrated similarly that the majority of soils are deficient in phosphorus for the production of most crops (Bradfield, 1963; Greenwood, 1951; International Soil Testing, 1968; Le Mare, 1959; Mikkelsen *et al.*, 1963; Nye, 1952; Spain and Ruiz, 1968). The degree of response depends to a considerable extent on the length of the resting period and the time since the most recent fallow. Certainly, this would be expected from the known intensity of weathering and leaching in tropical environments and the basic chemistry of any existing phosphate in a medium high in iron and aluminum and low in silicon. Exceptions are certain locations where soils have developed in recent volcanic deposits; in coastal alluvium, inland alluvium, and lacustrine deposits, which have their origin in young geologic formations; and in fields with substantial manurial or chemical fertilizer history.

Sulfur

Responses to sulfur have been extensively recognized on acid soils of the Campo Cerrado of Brazil (McClung and Freitas, 1959), on soils of the Punjab in India (Dutt, 1962; Kanwar, 1967), throughout East Africa (Beauchamp, 1953; Russell, 1968) and West Africa (Braud, 1969; Greenwood, 1951; Nye, 1952) and in the Caribbean Islands. Needs in other areas, especially Southeast Asia, seemingly have been masked by the sulfur carried in the ammonium sulfate and ordinary superphosphate that have enjoyed widespread use on plantation crops of the region.

Groundnuts and forage legumes seem particularly sensitive to sulfur deficiency, in part because of the relatively high sulfur content of legume tissues and the influence of sulfur on root nodulation. Perhaps indicative of the sulfur problem in tropical soils is the summation of 202 field trials in West Africa (Braud, 1969), which showed 18 percent of all locations in a state of "serious" sulfur deficiency. "Marked" deficiency was apparent in yield response at 38 percent of the locations, leaving only 44 percent of the sites without statistically significant sulfur deficiency.

FERTILIZER MANAGEMENT INVESTIGATIONS WITH PHOSPHORUS AND SULFUR

On first consideration, it would seem reasonable to expect that many of the results obtained from fertilizer management investigations in

temperate regions could be transposed to the tropics, with allowances. Management studies with phosphorus and sulfur would appear to take on particular significance for the humid tropics, however, in view of the totally different mineralogical environment, the year-round warm temperatures, the periodicity of wet and dry seasons, the different crops and cropping practices, and the greater need for maximum fertilizer efficiency.

Time of Application and Placement

Phosphorus

The coordinated rice fertilizer research project of the International Atomic Energy Agency (IAEA) carried on in several tropical countries has proved surface placement of phosphorus fertilizer superior to shallow or deep placement for submerged rice culture (Joint FAO/IAEA Division, 1970). Delayed application and splitting the phosphorus treatment resulted in no benefit or a slight reduction in utilization of the fertilizer. A similar coordinated research program on fertilization of tree crops that involves isotope tracers is under way. It has provided indication of zones of maximum root activity for eventual prescription of optimum depth and distance of placement of fertilizer phosphorus from the trunk (IAEA Laboratory Activities, 1969). Comparable studies with maize have indicated a greater utilization of fertilizer phosphorus when nitrogen and phosphorus are applied in the hill than when banded adjacent to the row. Presumably, this reflects a reduced fixation reaction in the soil by reason of restricted surface area of soil–fertilizer contact and perhaps, additionally, an enhanced positional availability to the plant.

Work in Tanzania on "grey sands" with a very low level of phosphorus in the subsoil showed root systems of the common crops to be confined to the "humic" topsoil (Hagenzieker, 1956). Preliminary experiments suggested that deep placement of phosphorus would be effective; this was confirmed by field experiments with soybeans and maize. The deepest placement of superphosphate (30 cm) afforded highest yields. Whether the recorded benefit is due to improved positional availability in relation to the supply of soil moisture or to an expanded root system for absorption of other nutrients and water is conjectural. Perhaps something analogous is achieved in the first case by the native practice of heavy ridging, which deeply covers fertilizer phosphorus placed near the row at planting.

Sulfur

Investigational work on placement and time of application of sulfur fertilizers has been very limited in the tropics. This is probably explained by the fact that agronomists, recognizing the need for sulfur, have anticipated that the traditionally used ammonium sulfate and ordinary superphosphate providing nitrogen and phosphorus would take care of the sulfur need. In fact, recognition of the sulfur problem has developed largely since 1955, as high-analysis nitrogen and phosphorus fertilizers were being introduced without the sulfur component. Among chemical materials that might logically be used for correcting deficiencies, only elemental sulfur could present the problem of restricted plant availability, with its oxidation rate determining optimum time of application. Indications under West African soil conditions are, however, that microbial activity effects almost immediate mineralization of the elemental sulfur (Bockelee-Morvan, 1966); hence, little or no extra time before planting the annual crop should be required if finely divided sulfur is applied. Presumably, the dominant consideration as regards timing for applied sulfate would be similar to that for nitrogen under the high leaching potential of the humid tropics.

Rate of Application

Phosphorus

Numerous rate studies have been made with phosphorus fertilizers on many crops throughout the tropical regions. The picture derived from the resulting literature is quite cloudy. Many reports indicate good responses with appreciable residual effects from nominal rates (FFHC Fertilizer Programme, 1968; Greenwood, 1951; Le Mare, 1959; Nye, 1952; Russell, 1968), whereas other reports indicate the need to satisfy or "quench" the soil's phosphorus fixing capacity by heavy phosphorus dressings before effective crop response occurs (Bradfield, 1963; Le Mare, 1968; Younge and Plucknett, 1966). Fixation is especially severe in weathered soils developed on volcanic ash in which the inorganic colloidal complex is largely hydrated iron and aluminum oxides.

Rates of phosphorus application commonly reported as giving good results when applied to food crops are 10 to 20 kg/ha, but from 160 to 1,200 kg/ha are indicated for high yields at some locations.

The disparity is seemingly a result of the wide diversity among tropical soils. Heavy rates are needed particularly with the Oxisols and Ultisols and soils formed from volcanic ash parent material. Even with these, however, research needs to establish if the same result could be achieved with nominal annual rates assisted by optimum granulation and placement with the most suitable chemical carrier of phosphorus for the situation. The average small farmer producing the food crops of the tropics could not bear the cost of phosphorus fertilizer required to quench a soil of high fixing capacity.

Sulfur

A rather small number of sulfur rate studies *per se* in the tropics have been reported. Many of the indicated yield responses to sulfur were acquired because of its presence in superphosphate or ammonium sulfate. The total sulfur content of soils varies greatly from the severely eroded and strongly weathered cultivated site with a low level of organic matter to the less weathered native forest site high in organic matter; thus, the required rate of application could be expected to range between 20 and 0 kg/ha annually. This is based upon a crop removal of 5 to 10 kg/ha and an approximate leaching loss of 10 kg/ha, the reported average from lysimeter studies with different cropping conditions in Senegal (Tourte *et al.*, 1964). In French-speaking equatorial Africa, fertilizer treatment for the responsive cotton crop, for example, by design supplies an average 15 kg/ha of sulfur in ammonium sulfate (Braud, 1969), a nitrogen-to-sulfur ratio of 7:3 being considered optimal. On acid soils of the Campo Cerrado in central Brazil, it is postulated that 22 kg/ha of sulfur would likely be needed with intensive cropping and sufficient nitrogen and phosphorus treatments (McClung *et al.*, 1959).

Effectiveness of Fertilizer Carriers

Phosphorus

"Single" superphosphate has proved superior to other phosphorus carriers for groundnut production in northern Nigeria (Greenwood, 1951), particularly haulm production. Its superiority, however, has been proved to be a result of the gypsum present.

Eleven phosphatic fertilizers were compared with single superphosphate at nine locations for groundnuts, sunflower, maize, and sor-

ghum in Tanzania (Le Mare, 1959). Each fertilizer was applied at the rate of 10 kg/ha of phosphorus. Concentrated superphosphate was distinctly superior at four of the locations, all with soils near neutral to slightly alkaline in reaction. Dicalcium phosphate was distinctly inferior at two sites, but superior at three; calcium metaphosphate was inferior at three and superior at three; soda phosphate was inferior at five; basic slag was inferior at seven and superior at one; Seychelles guano was inferior at all but one site, where it was superior; four sources of rock phosphate were generally quite ineffective, except at one site where all proved equivalent or superior to superphosphate; and silicophosphate was superior at two and inferior at six. Among crops, sorghum was most effective in its utilization of the less soluble sources of phosphorus, sunflower the least. Questions raised by the data are how much needed secondary and trace element nutrition was afforded by impurities in the low-analysis materials where they beneficially influenced yields; how much better the low-solubility carriers might have functioned had they been disked or plowed into the soil rather than placed; what influence varied degree of granulation might have had; and how much sulfur contained in the superphosphate benefited yields relative to the non-sulfur-bearing carriers.

A number of studies report comparisons between rock phosphate and superphosphate. On lateritic red earth of Northern Territory, Australia, superphosphate gave greater immediate response in sorghum, but its residual effects declined more rapidly than those from rock phosphate (Arndt and McIntyre, cited by Jackson, 1966). Cumulative yields over a 7-year period, however, favored the superphosphate. Experiments in semihumid areas of West Africa have demonstrated the greater efficiency of the more soluble forms of phosphate (monocalcium, dicalcium, ammonium) over rock phosphates and slags (Bouyer, 1965; Braud, 1967). Even in humid areas, the soluble forms afford a quicker action than rock, despite rapid and strong fixation reactions with soil iron oxides. There are, however, major differences in plant availability of rock phosphate sources from different origins, some of which prove nearly as effective as acidulated sources for some crops (Terman *et al.*, 1970). Citrate solubility in relation to fineness of grind must be considered before the practicality of native phosphate sources can be discounted.

Studies in Costa Rica show that some of the less soluble phosphorus materials give excellent results compared with concentrated superphosphate when applied to an ashy isothermic Typic Dystrandept (Fassbender and Molina, 1969). Silicon contained in the mate-

rials of low solubility may have been partially responsible. An additional factor in this work was the extreme effect of granulation in promoting fertilizer phosphorus utilization by the crop—a sixfold yield increase was achieved with granulation of the superphosphate.

Of particular interest in the review of crop response to different phosphorus carriers in the tropics is the rather frequent reference to outstanding results from "silico-phosphates" (Fassbender and Molina, 1969; Tyson as cited by Jackson, 1966; Le Mare, 1959). These materials are usually called Rhenania phosphate and are prepared by heating rock phosphate with silica sand and sodium carbonate. Whether the crop response is due to a direct effect of silicon as such on the crop's nutrition or to an indirect enhancement of fertilizer phosphorus utilization is conjectural at this stage. Certainly, Hawaiian workers have found that addition of silicate slag has highly beneficial effects on sugarcane yields, with concomitant increase in phosphorus uptake and decrease in soluble soil aluminum (Baver and Sherman, 1963; Fox *et al.*, 1967); likewise, Japanese and Korean workers have measured a benefit of added silicate minerals like wollastonite for the rice crop. It would be of real value to know the extent to which silicate may be satisfying the soil's phosphorus fixation capacity in these cases, rendering added phosphorus fertilizer more available to the crop.

Sulfur

Comparisons of sulfur carriers in the tropics have been limited because the major fertilizers used in the past to supply nitrogen and phosphorus have provided a source of sulfur as well. Introduction of high-analysis materials without the sulfur component has modified the situation, however, and for much of the humid tropics a new sulfur source must be established. Research in West Africa suggests that similar effects are obtained from virtually all forms of sulfur used as fertilizer, including sulfites, sulfates, sulfur combined in fertilizer formulations, and mineral sulfur (Bockelée-Morvan, 1966), which conforms with findings in temperate regions. A question requiring resolution over a range of tropical soils concerns the effect that prilling of elemental sulfur for convenient handling and distribution might have on retarding the rate of mineralization and concomitant leaching losses. A strongly granulated gypsum product has been effective (Millington and Powrie, 1968).

Tests To Determine the Need for Supplementary Phosphorus and Sulfur

Discussion to this point has implied that the majority of soils in the humid tropics are deficient in phosphorus and sulfur and that getting corrective treatment under way should be the prime consideration. However, a portion of the land area in the tropics is well supplied with these nutrients, and prescribing more at the moment would constitute an unnecessary and costly burden to the peasant farmer (International Soil Testing, 1968; Nye, 1952). Furthermore, as fertilization practices become established, some system of checks will become increasingly necessary to prevent buildup of excess concentrations of the added elements in the low-buffer-capacity soils involved. The problem with sulfur would presumably be minor because of its high leachability in the sulfate form, but phosphorus will accumulate. In soils without high fixation capacity, excess phosphorus could become a problem because its interaction with certain other nutrient elements would limit their uptake.

Phosphorus

A number of early attempts to predict crop response to fertilizers by direct soil analysis procedures met with poor success in tropical regions (Birch, 1952; Friend and Birch, 1960; Nye, 1952; Russell, 1968). One explanation was that most of the phosphorus available to the crop is released by organic matter decomposition and is not readily determinable by quick test. Recently, however, a comprehensive international soil testing program in Latin America has proved effective in distinguishing phosphorus-responsive areas from those that do not respond to fertilizer. Similarly, correlation and calibration studies in individual countries give evidence that extraction procedures adapted to the soils involved can indeed give good indication of response probabilities to applied fertilizer (Ahmad, 1967; Ayres and Hagihara, 1955; Baver and Ayers, 1962; Braga and Yahner, 1968; Le Mare, 1959; Monteith, 1966). A series of well-conceived field experiments on the important crops and soils of the locality for effectively measuring response to applied phosphorus is required, followed by correlation of these data in the laboratory with soil-testing values from surface as well as subsurface horizons. The North Carolina method (dilute hydrochloric and sulfuric acid extraction) and

the Bray and Kurtz No. 1 extraction procedure have proved effective in many situations.

Sulfur

Although a far smaller number of extraction procedures have been conceived for estimating the available sulfur status of soils than for phosphorus, some have been investigated successfully with particular reference to tropical soils (Fox *et al.*, 1964b; McClung *et al.*, 1959). It does appear that subsoil sources of adsorbed sulfate may be particularly important in tropical regions, considering the relative ease with which sulfate leaches from the surface soil. This will presumably necessitate testing of subsoil as well as surface soil (Ensminger, 1954; Hesse, 1957).

Conclusions

It seems likely on the basis of these experiences that soil testing can become a valuable tool in assisting in the judicious use of fertilizer phosphorus and sulfur and the development of an effective fertilizer marketing system in the tropics. Undoubtedly, a large amount of research will be required for placing soil testing on a sound foundation across the full range of soils and cropping practices of the tropics, but the costs will be small compared with any other measure that might be attempted with the same objective.

Efforts should be made to strengthen national laboratories in keeping procedures properly oriented and in monitoring test results. Experienced technical personnel might work with technicians in the national laboratories in organizing basic studies for evaluating the significance to calibration of such things as seasonal variations in pH and available nutrient levels. These have been found to be important in temperate regions (Grimes and Hanway, 1967; Olson *et al.*, 1954; Van Der Paauw, 1962) and also in rice culture of the tropics (Ahmad, 1967). Seasonal variations could be considerable where wet and dry seasons occur in the tropics. Likewise, there could be considerable variation between savanna and partial or full forest cover, between heavily ridged and flat cultivated surface, and with other extreme conditions of the soil environment peculiar to equatorial regions. Competence in foliar analyses should be built into these laboratories to assist in diagnosing nutrition problems of all the crops grown in the region.

Interactions of Applied Phosphorus and Sulfur with Other Amendments

Effects of Lime on Phosphorus and Sulfur Availability

Cotton grown on Campo Cerrado soils in Brazil evidenced a decreasing response to 39 and 77 kg/ha of phosphorus with increasing rates of lime from 0 to 6 tons/ha (McClung *et al.*, 1962). The interpretation was that the lime increased the rate of mineralization of native soil organic phosphorus to the available form, especially as soils were first brought under cultivation. Isotopic dilution studies on three soil series of the same region found evidence of increasing soil phosphorus availability with increasing lime rate (Malavolta *et al.*, 1964), as did work with Central American Ultisols (Cordoba, 1968). The Central American studies showed a beneficial effect of liming soils up to pH 6.4 on availability of both native and applied phosphorus. In all experiments, however, overliming reduced the availability of fertilizer phosphorus. Soils of the Llanos Orientales in Colombia similarly afforded maximum response of maize to applied phosphorus only with concurrent lime treatment (Spain and Ruiz, 1968). Increased availability of fertilizer phosphorus in these situations was undoubtedly related to elimination of exchangeable aluminum and a reduction in phosphorus adsorption with concomitant effects on phosphorus availability to the plant (Woodruff and Kamprath, 1965). Work on Hawaiian Latosols indicates an increased uptake of fertilizer phosphorus by plants with very modest rates of liming and small changes of pH (Fox *et al.*, 1964a). Minimum aluminum concentration in the plant corresponded with maximum phosphorus uptake in these studies.

It would seem that liming, where a source of native limestone is in reasonable proximity, should be considered a necessary step toward improving soil and fertilizer phosphorus relations in tropical soils with a pH below 5.5, particularly where ammonium sulfate is used to satisfy nitrogen requirements. Liming will undoubtedly speed up the mineralization of native soil organic sulfur and the oxidation of elemental sulfur as well by enhancing the activity of the *Thiobacillus* microorganism responsible for these processes. The more rapid rate of sulfate production, however, could increase leaching losses and hasten depletion of the soil sulfur supply. This seems likely, just as accentuation of nitrate leaching losses is a probability with liming of the acid tropical soil. Perhaps the minimal lime rates required for

eliminating exchangeable aluminum as previously discussed will not have the profound effect on nitrogen and sulfur oxidation observed with conventional liming of temperate region soils, nor will they have the effect of reducing yields often noted in early experiments (Russell, 1968). The research needed to confirm these suggestions remains to be done.

Effect of Ammonium on Phosphorus Uptake

Many field studies with fertilizers have demonstrated a complementary effect of one nutrient on another, whereby yield response to the two nutrients applied simultaneously exceeds the sum of the responses achieved by applying each separately (Russell, 1968). Such effects are encountered throughout biological systems and can be anticipated in any situation where more than one element is deficient. Beyond the mutual dependence aspect, fertilizer nitrogen, especially in the ammonium form, has been shown to enhance uptake of fertilizer phosphorus by plants if the phosphorus and nitrogen are chemically or physically associated (Grunes, 1959; Olson and Dreier, 1956). The phenomenon is most evident in the more acid soils where the ammonium ion persists longer against nitrification and is probably related to some plant metabolite that influences absorption and translocation of phosphorus.

Impact of nitrogen on uptake of fertilizer phosphorus accounts in considerable part for the widespread use of "starter" fertilizers containing nitrogen and phosphorus on many crops in temperate regions. It would seem to be especially significant for the tropics for some years to come, in view of the relatively high cost of fertilizer and the need for maximum efficiency of fertilizer utilization.

Silicon-Phosphorus Relations

Earlier discussion of phosphorus carriers covered the apparent silicon–phosphorus interaction in the production of some crops. Improved uptake of fertilizer phosphorus is generally noted where added silicate is beneficial to yield, just as high silicate content of native soil is associated with limited crop response to applied phosphorus (Birch, 1953; McGeorge, 1924; Némec, 1932). Alleviation of phosphorus fixation to some degree by the added silicate seems quite

probable in Oxisols and Ultisols, which have high levels of iron and aluminum and low levels of silicon (Bradfield, 1963).

Sulfur–Phosphorus Interactions

It is doubtful that applied sulfur will afford the benefit to phosphorus uptake by crops in the acid soils of the humid tropics that is reported for the neutral to alkaline soils in temperate regions. In the latter, the acidifying action of the applied sulfur has received credit for the prolonged availability of added phosphorus. It might rather be expected that further acidification of a tropical soil already strongly acid would accelerate phosphorus fixation reactions. Complementary beneficial effects on yields of the two elements added simultaneously could be expected, however, where both are nutritionally inadequate.

Deleterious Effects from Applied Phosphorus

Depressive action of applied phosphorus on zinc uptake of several crops is well established in temperate regions, particularly under conditions of high soil pH. There is good reason to expect that many of the highly leached soils of the tropics are currently at marginal availability levels for zinc and other heavy element nutrients, and that repeated application of high-analysis phosphorus fertilizers with little or no trace-element impurities could induce a deficiency state of those micronutrients. The Upper Veldt of Swaziland is perhaps a case in point; supplementary zinc and molybdenum are considered essential with applications of nitrogen and phosphorus for maize production (Jackson *et al.*, 1965).

Influence of Applied Sulfur on Other Nutrients

Sulfur applied in quantity has an acidifying influence on soils that can cause a sharp reduction in pH and concomitant excessive sulfur and manganese uptake by the plant (Hassan and Olson, 1966). Otherwise, sulfur treatment at moderate rates beneficially influences crop utilization of nitrogen, phosphorus, sulfur, manganese, zinc, iron, and copper on neutral and calcareous soils of a cool temperate region. Similar results could probably be expected in the neutral soils of the tropics, with deleterious effects being accentuated by increasing soil acidity.

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J. BOYER

Soil Potassium

FORMS OF POTASSIUM IN SOILS

Definition

There is general agreement on the definition of the different forms of potassium in soils. For example, Wiklander (1954) distinguished four kinds of potassium, excluding that found in bacteria and in the soil's fauna and flora in general: potassium in the soil solution, exchangeable potassium, fixed potassium, and potassium of crystalline matrixes. Although his definition referred to soils of northern Europe, it may also be applied to soils of the tropics.

Potassium in the Soil Solution

Potassium in the soil solution is in equilibrium with the exchangeable potassium. It is difficult to distinguish one from the other, since equilibrium occurs rapidly and varies according to prevailing conditions.

Exchangeable Potassium

The amount of exchangeable potassium in soils depends on the clay content, on the intensity of mineral decomposition, and on the quantity of fertilizers used. In temperate regions, the exchangeable potassium is about 1 percent of the total soil potassium (Barbier, 1962; Wiklander, 1954), but the percentage can vary considerably from soil to soil. There is not much information on the ratio of exchangeable potassium to total potassium in soils of the humid tropics.

Fixed Potassium

Potassium may be "fixed" on the inner surfaces of clay particles (i.e., position of Nemeth *et al.*, 1970) and inside the hexagonal cavities of clay minerals such as illite, where potassium is one of the constituents of the crystalline matrix.

Potassium of Crystalline Matrixes

Potassium of crystalline matrixes is a part of the structure of some minerals, such as illitic clay, hydrated micas, and micas and feldspars. It represents the largest part of total potassium (Barbier, 1962).

Forms of Potassium Available to Plants

The potassium of the soil solution and the exchangeable potassium are directly available to plants. There is some evidence, however, that part of the nonexchangeable potassium might be available to plants, as indicated in the following references: Acquaye *et al.* (1967) and Ahenkorah (1970) in Ghana; Aubert (1958) in Gabon and southern Cameroon; Middelburg (1955) in Indonesia; Ng (1965) and Coulter (1970) in Malaysia. In soils rich in illite and montmorillonite, this might be due to the reversibility of the fixed potassium to the exchangeable form (Wiklander, 1954). Alteration of soil minerals, especially in soils formed from volcanic ash, may free appreciable quantities of potassium, as shown by Middelburg (1955) in Indonesia and by Segalen (1967) in Cameroon. Also, plant roots probably can extract nutrient elements directly from minerals (Barbier, 1962).

Various American and English investigators have defined the following forms of potassium according to the method of extraction:

(1) exchangeable potassium extracted with neutral normal ammonium acetate; (2) potassium extracted with dilute nitric, sulfuric, citric, or other acids; (3) potassium extracted by boiling with six normal hydrochloric acid or other strong acid solutions; (4) total potassium extracted with hydrofluoric acid.

The first three forms should represent available potassium. Unfortunately, results often are too inconsistent to generalize from one particular soil to another. Correlations between laboratory results and plant needs are often poor (Ng, 1965).

Agronomists in French-speaking Africa measure exchangeable potassium and what is termed "total potassium" at the same time. The latter, extracted by boiling with concentrated nitric acid for 5 hr, amounts to a much larger quantity of available potassium but is less than the true total potassium extracted with hydrofluoric acid.

ESTIMATION OF THE POTASSIUM USED BY PLANTS

Exchangeable Potassium and Minimum Level Requirements

Two limiting amounts of potassium have been found in intertropical soils: the absolute minimum requirement and the relative minimum requirement.

The Absolute Minimum Requirement

The absolute minimum level of exchangeable potassium, close to 0.10 meq/100 g of soil, may vary between 0.07 and 0.20 meq/100 g, the level depending on the kind of cultivated plants and soils.

Minimum Requirement Close to 0.10 meq/100 g of Soil In intertropical French-speaking African countries, various investigations have indicated that symptoms of potassium deficiency appear on most plants when the exchangeable potassium in the soil is less than 0.10 meq/100 g: pineapple in Guinea (Martin-Prevel, 1953); bananas in the Ivory Coast (Dabin and Leneuf, 1960); coffee and cocoa in the Ivory Coast and in the Central African Republic (Aubert and Moulinier, 1954; Beley and Chezeau, 1954; Forestier, 1964; Loue, 1961, 1962; Moulinier, 1962); oil palm in the Ivory Coast (Boye, 1962; Prevot and Ollagnier, 1958) and in Dahomey, Togo, and Cameroon (Institut de Recherches pour les Huiles et Oléagineux, 1968); various

crops, especially cereals in Upper Volta (Boulet and Leprun, 1969; DuPont de Dinechin, 1967) and groundnuts in Senegal (Bockelée-Morvan, 1964; Charreau and Fauck, 1970).

Forde *et al.* (1966) confirm that the minimum requirement of exchangeable potassium for oil palm is 0.10 meq/100 g of soil in southern Nigerian soils. According to Ochs (1965) and Tinker and Ziboh (1959), in Dahomey and the Ivory Coast it would probably be 0.15 meq/100 g.

In Brazil (São Paulo), Malavolta *et al.* (1960) find the same minimum requirement of 0.10 meq/100 g of soil for sugarcane growing in a sandy soil. Similar results (between 0.10 and 0.12 meq/100 g) are obtained by Vallance (1951) in Australia. The same holds true for sweet potatoes in Formosa (Ho, 1965).

Minimum Requirement Less Than 0.10 meq/100 g of Soil In Madagascar, at least for manioc, there seems to be a minimum requirement for exchangeable potassium of about 0.6 meq/100 g in ferrallitic soils (Oxisols) with low exchange capacity (Roche *et al.*, 1959).

In Niger the very sandy soils formed on dunes, with low exchange capacity, are frequently found to have less than 0.10 meq/100 g of soil. Potassium fertilizer applications on millet and groundnuts on these soils give no response, and leaf potassium appears normal (Bouyer, 1970, Private communication).

Minimum Requirement Higher Than 0.10 meq/100 g of Soil In Hawaii (Baver, 1970; Humbert, 1958), it was found that sugarcane shows a deficiency if the exchangeable potassium is less than 0.18 meq/100 g of soil. Exchangeable potassium at 0.30 meq/100 g is considered to be the level where no response is received from potassium fertilizer applications.

In Formosa, the critical level of exchangeable potassium for pineapple is 0.17 meq/100 g of soil (Su, 1969).

In the Philippines, Locsin *et al.* (1955) found a positive response to potassium fertilizers when the original content of exchangeable potassium was less than 0.24 meq/100 g of soil.

In South Africa, according to Stewart (1969), response to potassium fertilizers on sugarcane occurs at an exchangeable potassium level of 0.31 meq/100 g of soil.

Discussion The critical minimum of exchangeable potassium and the minimum level for response to potassium fertilizers show a wide

range of values in different countries and for different crops. To account for such differences, some arguments can be presented:

Neither all species of plants nor all varieties within a species have the same potassium requirements–see, for example, the work of Boswell and Parks (1957) with hybrid corn and of Prevot and Ziller (1957) and Prevot and Ollagnier (1958) with oil palm.

On the other hand, natural plants, well adapted to the environment, are able to use soil nutrients efficiently, even if they are at low levels. Improved varieties require appreciably larger quantities of potassium. For example, sugarcane in Hawaii requires about 0.20 meq of exchangeable potassium per 100 g of soil. Before 1955, this was considered to be the average potassium content of soils in southern France, and those soils were not considered deficient in potassium at that time (Drouineau, 1955). In countries of intensive agriculture, such as France, agronomists believe that amounts of 0.3 to 0.5 meq of exchangeable potassium per 100 g of soil are frequently required (Crahet, 1968; Drouineau, 1955). Increased yields in the tropics will probably depend on a similar increase of potassium levels in the soil.

The Relative Minimum Requirement

Exchangeable potassium must meet a second condition: It must be equal to at least 2 percent of the sum of all exchangeable bases. This value has been estimated principally by Australian, English, and American investigators.

In Australia, in highly unsaturated acid soils of Queensland, Vallance (1951) claims that an exchangeable potassium content of 0.12 meq/100 g and larger might be considered "average" only if this amount is larger than 2 percent of the sum of the exchangeable bases. In the West Indies, for bananas, Martin-Prevel (1966) comes to the same conclusion. This was partially verified for coffee by Forestier (1964) in the Central African Republic.

However, it is frequently argued that the ratio of exchangeable potassium to the cation exchange capacity is a better measure (Blanchet, 1959). In Nigeria, for the palm tree, Tinker and Ziboh (1959) use the ratio of exchangeable potassium and the square of exchangeable potassium to the cation exchange capacity. They estimate the critical levels at 0.015 and 0.001, respectively. Chaminade (1963) estimates that in Africa the optimum level of exchangeable potassium is 2 to 3 percent of the total exchange capacity.

The importance of the ratio of potassium to the total exchange capacity is confirmed by Forestier's observations (1964) on the coffee tree growing on ferrallitic soils (Oxisols) in the Central African Republic. He makes a correction of the minimum requirement level depending on the clay and silt content of the soil. Tinker and Ziboh (1959) in Nigeria and Ochs (1965) in the Ivory Coast and Dahomey use similar levels for oil palm.

In any case, one can see how much importance tropical agronomists attach to the potassium content of the absorbing complex, whether it is expressed as the ratio of exchangeable potassium to the sum of exchangeable bases or to the cation exchange capacity or as a minimum requirement level depending on the clay and silt content of the soil.

The values indicated for each category—(1) exchangeable potassium equals 2 percent of the sum of exchangeable bases, and (2) exchangeable potassium equals 0.015 times the total exchange capacity—relate to crop requirements under normal conditions.

Under intensive cultivation, it is considered that exchangeable potassium should be 4 percent of the total exchange capacity as a minimum. This value should be increased to 5 percent for fruit growing (Crahet, 1968). Probably the steady increase of yield and the necessity of intensified agriculture in tropical countries will put the requirements of exchangeable potassium close to these levels.

Fertility Scales

In tropical countries, fertility scales have been established according to the data gathered thus far. One can cite, for example, Vallance's fertility scale (1951) for sugarcane in Queensland (Australia) in strongly unsaturated acid soils:

Exchangeable Potassium (meq/100 g of Soil)	Estimated Soil Fertility
<0.10	Very low
0.10 to 0.12 (exchangeable potassium is less than 2 percent of the sum of bases)	Low
0.10 to 0.18 (exchangeable potassium is more than 2 percent of the sum of bases)	Average
>0.18	Good to excellent

Another example is Dabin and Leneuf's fertility scale (1960) for bananas on ferrallitic soils (Oxisols) in the Ivory Coast:

Exchangeable Potassium (meq/100 g of Soil)	Estimated Soil Fertility
<0.10	Low
0.10 to 0.20	Fair
0.20 to 0.40	Average
0.40 to 0.60	Good
0.60 to 1.00	Excellent

When soils are very sandy (less than 10 percent of clay), these figures can be multiplied in general by 0.7 to 0.6. On the other hand, if soils have a high clay content (more than 60 percent of clay), it is reasonable to multiply by 2.

On low-base-saturated ferrallitic soils (Oxisols) in the Central African Republic, Forestier (1964) states that good exchangeable potassium values for the coffee tree (*Coffea canephora* var. *robusta*), taking the clay-plus-silt content into account, are as follows:

Exchangeable Potassium (meq/100 g of Soil)	Clay + Silt (%)
0.10	10
0.12	20
0.20	30
0.40	55
0.50	65

Groundnut requirements for potassium fertilizers according to the exchangeable potassium content of the soil have been suggested by Faure and Ginouves (1955). These data are for slightly leached, sandy ferruginous soils (Tropepts).

Exchangeable Potassium (meq/100 g of Soil)	Groundnut Requirements for Potassium (kg/ha of K_2O)
0.05	12.5
0.10	10.3
0.15	8.5
0.20	8.0
0.30	6.6
0.40	6.0

Available Potassium

Exchangeable potassium is not always a good measure of soil potassium available to plants. This was shown on cocoa trees in Indonesia by Middelburg (1955) and in North Gabon and southern Cameroon by Aubert (1958); on millet and groundnuts in Niger (S. Bouyer, Personal communication); and in Ghana by Acquaye *et al.* (1967). Many other examples could be reported. Thus it is certain either that a plant is able to extract nonexchangeable potassium or that the nonexchangeable potassium is transformed to exchangeable potassium.

From a practical viewpoint, it is also important to measure the reserves of potassium in the soil.

"Total" Potassium

French agronomists, working in Africa, Madagascar, Central America, and the Pacific Islands, extract part of the potassium, rather improperly designated "total" potassium, by boiling the soil for 5 hr in concentrated nitric acid. Thus, a soil from Upper Volta, formed from ferruginous materials, is said to have an exchangeable potassium content of 0.13 meq/100 g and a "total" potassium content of 0.60 meq/100 g (DuPont de Dinechin, 1967).

When one goes into the problem more deeply, it is difficult to find a satisfactory correlation between "total" potassium and yields—see, for instance, the work of Ollagnier and Prevot (1956) for groundnuts in Senegal. Although the measurement of "total" potassium is an estimate of the amount of the element utilizable by plants, the method is probably too crude to allow for a precise interpretation of the results.

Available Potassium

Some investigators, mainly English and American, define what they call available potassium as follows: (1) exchangeable potassium extracted by ammonium acetate; (2) slowly available potassium extracted with weak acids; (3) nonexchangeable or fixed potassium extracted with strong acids.

Unfortunately the extraction methods are numerous, and the following can be cited for the determination of slowly available potassium:

Morgan's reagent (10 percent sodium acetate and 3 percent acetic acid), used by Middelburg (1955) in Indonesia

Citric acid (2 percent), used by Middelburg (1955) in Indonesia
Dilute nitric acid, used by Acquaye *et al.* (1967) and Maclean (1964) in Ghana; by Haylock (1956); and by Ng (1965) in Malaysia
Dilute sulfuric acid method of Hunter and Pratt (1957), used by Ahenkorah (1970) in Ghana

Dilute sulfuric and hydrochloric acids appear to be widely used in Brazil.

Many methods have also been used for the so-called nonexchangeable or fixed potassium for potassium extracted with strong acids. Although Middelburg (1955) used 25 percent hydrochloric acid in Indonesia, the most frequently used method is the treatment of soil for 2 to 3 hr with 6 *N* hydrochloric acid, e.g., in Malaysia by Ng (1965), reported by Coulter (1970) and by Mohinder Singh and Talibudeen (1969); and in Ghana by Ahenkorah (1970).

Middelburg (1955) reports a satisfactory correlation between slowly available potassium and yields on volcanic ash soils in Java. Ng (1965) also found some correlations in Malaysia between crop yields and the different potassium fractions. However, the correlations varied, depending on the type of soil.

In Malaysia, Coulter (1970) found that the fractionation methods do not give good results in differentiating between potassium-rich and potassium-poor soils except in extreme cases.

Activity Ratio of Potassium and Potential Buffering Capacity of the Soil for Potassium

Measurements Based on the Soil–Solution Equilibrium

Agronomists, especially English agronomists (Beckett, 1964), pointed out that exchangeable potassium, extracted with neutral normal ammonium acetate, is a good measure of the potassium immediately available to plants but not of the potassium reserves, which can become available with time. They stressed also the inadequacy of further fractionation of soil potassium. They emphasized that the analytical techniques used do not take into account the cationic environment of the potassium in the soil, particularly calcium, magnesium, and aluminum. They have sought to develop a more dynamic method to estimate the level of available potassium in soils.

The activity ratio of potassium according to Beckett (1964) is de-

rived from Gapon's equation, which defines the equilibrium between soil and solution as follows:

$$\frac{\text{soil potassium}}{\text{soil calcium}} = \text{a constant } (k) \times \frac{\text{potassium in solution}}{\text{calcium in solution}}.$$

Woodruff's research (1955) as reported by Beckett (1964) also has contributed to the activity concept. It represents "the level of exchange energy of potassium by calcium":

$$\text{Activity ratio of potassium} = \frac{\text{the activity of potassium}}{\text{the square root of the activity of calcium plus magnesium}}.$$

The Q/I ratio expresses the quantity–intensity relationship in soils. Practically, this ratio is represented by a curve showing the values of the activity ratio of potassium related to different levels of soil potassium after equilibrium has been reached between soil and solution, the latter being at variable levels of concentration.

The "potential buffering capacity" of soil for potassium is a measure of the labile quantity of potassium. It is the slope of the curve, thus the first derivate $\frac{\Delta Q}{\Delta I}$. It is a function of exchangeable calcium and exchangeable magnesium as well. These values of the activity ratio of potassium are also a function of exchangeable magnesium and calcium.

Application to Soils of the Tropics

Without much modification, this method has been used by Acquaye *et al.* (1967) with soils of Ghana and by Moss and Coulter (1965) in the West Indies.

On the other hand, Forde *et al.* (1966) and Tinker (1964) wanted to include the aluminum ion in the activity ratio calculated for Nigerian soils. The influence of the aluminum ion is important in the dynamics of potassium in unsaturated soils. They defined the United Activity ratio with aluminum integrated in the formula:

$$\text{The United Activity ratio of potassium} = \frac{\text{the activity of potassium}}{\text{square root of the activity of calcium plus magnesium plus a constant times the cube root of the activity of aluminum}}.$$

Mohinder Singh and Talibudeen (1969) suggested replacing calcium chloride with aluminum chloride in the equilibrium solution while keeping the same expression as Tinker for the potassium activity ratio. These investigators have compared the analytical results with field responses to potassium fertilizers, e.g., oats (Acquaye *et al.*, 1967), *Pueraria phaseoloides* (Mohinder Singh and Talibudeen, 1969), and oil palm (Tinker, 1964). In general, the correlations between the potassium used by plants and the potassium activity ratio are better than those relating to exchangeable potassium.

Evaluation of the "potassium potential" of the soil has not yet been developed enough to establish a useful fertility scale or even reference limits. Results to date, however, are promising.

Tinker (1964) believes that it is a complicated procedure and that practical application of the experimental technique takes a long time. To cope with the presence of the aluminum ion in the exchange complex, it seems simpler to inactivate it by liming and then to determine the exchangeable potassium and the ratio of exchangeable potassium to the cation exchange capacity. These two determinations can provide reliable information on the potassium needs of oil palm.

Fundamental Equilibria among Potassium and Other Mineral Elements in the Soil

Potassium–Magnesium and Potassium–Calcium Equilibria

Antagonisms between potassium and magnesium and between potassium and calcium in soil are well known. They can be studied as a function of the (calcium + potassium)/magnesium equilibrium, the components being in the exchangeable form.

Unbalanced Ratios of Magnesium to Potassium and Calcium to Magnesium (meq of Exchangeable Cations per 100 g of Soil) Julia (1962), studying unsaturated ferrallitic soils (Oxisols) with a high content of clay (70 percent in the surface soil) in the Congo (Brazzaville), estimates that the magnesium-to-potassium ratio ($<2:1$) and the calcium-to-potassium ratio ($<5:1$) are not satisfactory for oil palm. These ratios indicate a soil disequilibrium that results in excessive absorption of potassium by plants and a deficit in calcium and sometimes in magnesium.

Dugain (1960) argues that banana trees in the Ivory Coast,

Guinea, and Cameroon are sensitive to "blue disease" when the magnesium-to-potassium ratio is 3 : 1. In Togo, cotton yields decrease with potassium fertilization when the ratio in the soil of magnesium to potassium is 3 : 1 (Dabin, 1956). The same occurs in oil palm growing on acid sandy soils deficient in magnesium in eastern Nigeria and Cameroon (Ochs, 1965; Olson, 1970; Tinker and Gunn, 1962).

Referring to the work of Coulter and Rosenquist (1955) and Turner and Bull (1967) on oil palm research in Malaysia, Coulter (1970) points out that, on soils relatively poor in magnesium, fertilizing with potassium and nitrogen can induce a deficiency in magnesium.

When the soil has an exchangeable potassium content of 1 meq or more per 100 g, a disequilibrium of the magnesium-to-potassium ratio is probable, resulting in excessive potassium absorption by plants, at least with coffee trees in Africa, as reported by Forestier (1964) in the Central African Republic, by Frankart and Croegaert (1959) in the Republic of the Congo (Kinshasa), and by Loue (1962) in the Ivory Coast.

Correct Values of the Magnesium-to-Potassium Ratio (Magnesium and Potassium Measured in Milliequivalents of Exchangeable Elements) Dabin and Leneuf (1960) consider that for bananas in the Ivory Coast the magnesium-to-potassium ratio must be between 4 : 1 and 25 : 1. According to Forestier (1964), the ratio of magnesium to potassium must lie between 2.1 : 1 and 3.8 : 1 for coffee trees growing on soils of the Central African Republic. For ratios larger than 3.8 : 1, magnesium is excessive in the leaves, but there is no deficiency in potassium unless the soil exchangeable potassium is less than 2.5 percent of the exchangeable bases. In the Ivory Coast, according to Loue (1962), many satisfactory values of magnesium to potassium range between 3 : 1 and 3.8 : 1 for the coffee tree. In general, a ratio of magnesium to potassium close to 3 : 1 or slightly larger is considered satisfactory for most crops.

The (Calcium + Magnesium)-to-Potassium Ratio Middelburg (1955), referring to Venema's research in Indonesia, states that if the (calcium + magnesium)-to-potassium ratio is 80 : 1, using Morgan's reagent, there is a lack of potassium available to plants. The correct ratio should be 25 : 1. Since Venema used Morgan's reagent, these data may not be comparable with those of the following studies, in which neutral normal ammonium acetate was used.

Martin-Prevel (1953) estimates that with bananas in the Ivory Coast, Cameroon, and French West Indies, the effects of lack of potassium appear only if the (calcium + magnesium)-to-potassium ratio is >40:1. According to Forestier (1964), disequilibrium in coffee occurs if the ratio is <24:1 with clay plus silt at 10 percent, <18:1 at 30 percent, and <12:1 at 70 percent. Usually this nutritional disequilibrium is responsible for calcium deficiency only when the soil potassium is greater than 11 percent of the sum of the exchangeable cations, in which case potassium excess and magnesium deficiency appear simultaneously in the leaves.

The upper limit of this ratio (excess of calcium and magnesium) in soil is not well defined. For coffee, Forestier (1964) gives (calcium + magnesium)-to-potassium ratios ranging from 33:1 to 43:1. Loue (1962) noticed a large potassium deficiency in Ivory Coast soils where the ratio was 150:1. In this case, the exchangeable potassium was 0.8 to 0.9 percent of the sum of the exchangeable bases.

Calcium-to-Potassium-to-Magnesium Ratios in Other Plants For irrigated plants, tuberous plants, or cereals, there are only a few cases where ratios of magnesium to potassium, calcium to potassium, or (magnesium + calcium) to potassium have been studied, in spite of the importance of potassium in their mineral supply.

Potassium–Nitrogen Interaction

In soils with just enough potassium, nitrogenous fertilizers in general increase the plant needs for potassium, and the result is a deficiency of that element. This was shown by Borget *et al.* (1963) for coffee in the Central African Republic and by Fremond and Villemain (1964) for coconut trees in the Ivory Coast.

Various investigators report potash (K_2O)-to-nitrogen ratios between 1:1 and 2:1 in mineral fertilizers, as satisfactory: for bananas in Formosa (Yang and Pao, 1962); for sugarcane in South Africa (Stewart, 1969); and for pineapple in Cameroon on Andosols (Andepts) (Gaillard, 1970).

Potassium–Phosphorus Interaction

Groundnuts and millet on tropical ferruginous soils in Senegal usually receive phosphorus fertilizers along with applications of

potassium (millet, 30 kg/ha of potash (K_2O); groundnut, 50 kg/ha). Poulain and Mara (1965) state that potassium is always enhanced by phosphorus fertilizers and vice versa, except for high fertilizer inputs (Poulain, 1967). This was also found for corn and manioc in western Nigeria (Amon, 1965). In sandy soils of the Ivory Coast, potassium fertilizers improved the phosphorus nutrition of the coconut tree even without applied phosphorus (Brunin, 1968).

Potassium–Iron Interaction

In India an input of potassium may correct iron chlorosis of the coconut tree (Pandalai and Menon, 1957). Conversely, Robusta coffee seems to require a good supply of iron for satisfactory potassium nutrition in the Central African Republic (Forestier and Beley, 1969).

Conclusions

From the data cited, the following conclusions may be drawn:

There is an absolute minimum requirement level below which the effects of lack of potassium appear, approximately 0.10 meq of exchangeable potassium per 100 g of soil. This amount must be adjusted with respect to the soil particle size distribution, the type of the absorbing soil complex, the nature of the crop, and the desired yield of the crop. The limits of variation are between 0.07 and 0.20 meq/100 g of soil.

All researchers have stressed the importance of the ratios of potassium to total exchange capacity, magnesium to potassium, calcium to potassium, and (magnesium + calcium) to potassium, and of the equilibria that these ratios determine. The numerical values vary widely according to plant needs and the clay and silt contents of the soil. However, a magnesium-to-potassium ratio of 3 : 1 seems to be favorable to the majority of crops.

Methods of evaluation of "total" potassium and available nonexchangeable potassium (extracted with strong acids) cannot easily be generalized. Methods based on "activity ratio" and "potential buffering capacity" of potassium do not seem to be commonly used. They must be carefully studied, however, because their results are promising.

POTASSIUM IN DIVERSE KINDS OF TROPICAL SOILS

In any kind of soil, the exchangeable potassium content can vary widely from one place to another (Boulet and Leprun, 1969). However, some generalizations based on the kinds of soils are possible.

Ferrallitic Soils (Oxisols) of the Humid Region

Savanna Soils

In Africa the most severe potassium deficiency appears in the savanna on sandy, largely unsaturated soils in the humid intertropical regions.

In the lower Ivory Coast, on sandy, highly unsaturated ferralitic soils (Oxisols), the application of 1 kg of potassium chloride (60 percent K_2O) per tree per year (approximately 170 kg/ha) increased the yields of palm oil from 250 or 300 kg to 2 metric tons per hectare (Boyé, 1962). With finer-textured soils—for example, those having 20 to 30 percent of clay in the surface—deficiencies appear on annual crops only after many years of cultivation without potassium fertilization. They disappear after 2 to 4 years of fallow in the Central African Republic (Braud, 1966).

Potassium deficiencies were noticed in southwestern Cameroon on soils formed on basalts (Valet, 1967), in Madagascar on ferrallitic soils (Oxisols) of the high plateaus (Vely *et al.*, 1965), and in Brazil on sandy ferrallitic soils (Van Wambeke, 1970b).

Forest Soils

At Yangambi in the Republic of the Congo (Kinshasa), ashes of a 30-year-old forest fallow have a potassium content ranging from 118 to 130 kg/ha. The exchangeable potassium content increases from 0.067 meq/100 g of soil before burning the surface to 0.325 meq/100 g after burning. Unburned residues include a similar amount of nonexchangeable potassium, which rapidly converts to the exchangeable form (Laudelout, 1954). Thus, clearing the forest fallow by burning the vegetation substantially increases the potassium content of the soil.

This increase in potassium persists for a reasonably long time when the soil is well covered by cultivated trees and cover crops. Busch (1958), in the Central African Republic, found that the sum of ex-

changeable bases was still 11 to 19 meq/100 g of soil under coffee trees 3 years after burning the forest, in comparison with 2 to 3 meq/100 g in the original forest. However, workers at research stations in French-speaking Africa recommend adding 50 to 100 g of potash (K_2O) per coffee tree without waiting for the first signs of a deficiency—Borget *et al.* (1963), Colonna (1964), Forestier (1966), Loue (1957), and Moulinier (1962) in the Ivory Coast and Deuss (1967) in the Central African Republic.

In southern Nigeria, lack of potassium appeared about the 13th year after clearing of a secondary forest and planting of oil palm (Tinker and Smilde, 1963). In Malaysia, hevea and oil palm plantations established on Latosols (Oxisols) originally having an exchangeable potassium content of 0.15 to 0.30 meq/100 g of soil do need potassium fertilizer, although they were planted on cleared land (Guha and Yeow, quoted by Coulter, 1970). In the Republic of the Congo (Kinshasa), potassium deficiencies appear on annual crops 3 to 4 years after burning the forest (Van Wambeke, 1970a). Outside of the biological cycle, potassium reserves of these soils are low. Thus to establish high-yielding crops after clearing the forest, large inputs of potassium fertilizer are required, frequently more than once a year.

Ferruginous Soils of the Semihumid Region

Potassium deficiencies are seldom found on tropical leached or nonleached ferruginous soils (the Haplustalfs, Psamments, and other little-developed soils) of the semihumid region. This holds true at least for Africa, where the native cultural system allows for fallow. Potassium fertilizer responses are infrequent and inconsistent after the land has been cleared. This was verified in Tanzania (Anderson, 1965; Gunn, 1953; Le Mare *et al.*, 1966), in North Dahomey and Togo [Institut de Recherches Agronomiques Tropicales et de Cultures Vivrières (IRAT), 1965a]; and in Upper Volta and Nigeria (IRAT, 1965b). After many years of cropping, however, soils are depleted in potassium (Bockelée-Morvan, 1966; Poulain, 1969; Tourte *et al.*, 1964). Under some circumstances the soils might lack potassium just after clearing the native vegetation. This is the case of the "tache de Patar" in central Senegal (Bockelée-Morvan, 1964) and in Tanzania (Le Mare, 1970).

Brown Eutrophic Soils (Eutropepts)

Brown Eutrophic soils are more commonly used in the humid tropical regions than in semihumid regions. In Ghana, they are depleted in potassium when used for growing cocoa and fertilized with phosphorus (Burridge *et al.*, 1963). In Tanzania, despite an original high content of potassium, a wheat crop grown for many years will significantly decrease the exchangeable potassium in the soil (Anderson, 1965).

Vertisols

Little is known about the potassium content and the potassium needs of Vertisols. This soil occurs in localized areas in the humid tropics.

Hydromorphic Soils

Hydromorphic soils probably differ from upland soils in dynamics of potassium, and potassium absorption by plants seems to be more difficult (Wallace, 1958). However, Dabin (1951) did not find any response to potassium fertilizers in the waterlogged paddy fields of Mali. This differs from Madagascar, where potassium fertilization is profitable in paddy fields on hydromorphic soils of the high plateaus around Tananarive (Institut de Recherche Agronomique de Madagascar, 1965).

POTASSIUM DYNAMICS IN SOILS

Potassium Sorption and Desorption in Soils

Potassium "Interlayer Fixation" in Soils

Soil potassium is held along with other cations on the exchange sites of the absorbing complex. But in the case of potassium there is an "interlayer fixation" (Chaminade, 1936). Potassium enters the interlayers of the clay crystals (Page and Baver, 1940; Reitemeier, 1951; Schuffelen and Van der Marel, 1955). Entry of potassium is accompanied by a contraction of the clay layers; their thickness might be reduced from 15.6 Å to 10.8 Å, according to Van der Marel in Holland (quoted by Barbier, 1962). This results in a fixation of the

potassium, which is no longer exchangeable. However, it can be released again slowly, if the external solution is low in potassium (Barbier, 1962; Wiklander, 1954).

This phenomenon of interlayer fixation of potassium as a reserve form occurs only with illitic-type clays (and perhaps montmorillonitic), which are not common in most soils of the humid tropics. Instances of high fixation in the intertropical region occurred on soils considered to be Vertisols and Andosols (Andepts) in Cameroon (Gaillard, 1970), in Hawaii (Hagibara, 1952), in Java (Middelburg, 1955); and such instances occurred in Trinidad on Oxisols containing a certain amount of illite (Ahmad and Davis, 1970). Some cations, e.g., aluminum, can reduce the interlayer spacing.

In most of the soils of the humid tropics, little or no buildup of potassium reserves by means of interlayer fixation is observed. Indeed, leaching of potassium fertilizers may be intense—in the Republic of the Congo (Kinshasa) (Laudelout, 1950, mentioned by Van Wambeke, 1970a), in Hawaii (Hagibara, 1952; Humbert, 1958), and in the Ivory Coast (Roose and Godefroy, 1968; Blanchet *et al.*, 1965). A single large application of potassium fertilizers should be avoided in soils devoid of illite (Blanchet *et al.*, 1965).

Factors Influencing the Fixation of Potassium in the Soil

Several authors have shown that in Alfisols and Tropepts the exchangeable potassium constitutes from 1.5 to 4 percent of the total exchange capacity (Ahmad and Davis, 1970; Chaminade, 1936; Matthews and Sherrel, 1960).

The influence of drying on the fixation and liberation of potassium in soils has been studied (Attoe, 1946), and the results obtained by the different workers may appear contradictory (Luebs *et al.*, 1951; Reitemeier, 1951). For example, alternate drying and wetting can cause potassium fixation in soils recently fertilized with potassium. In contrast, alternate drying and wetting can cause potassium release in soils that are low or deficient in potassium (Barbier, 1962).

Most of these studies have been done with soils of temperate regions. Ahmad and Davis (1970), however, have shown a continuous fixation of potassium in the Oxisols of Trinidad, if the moisture content in the soils is less than half of the field capacity.

The hydrogen and aluminum ions held on the soil absorption complex are not readily replaced by potassium ions (Barbier, 1962; Larson, 1954; Wiklander and Gieseking, 1948). It is useful, therefore,

to replace the aluminum ions of the exchange complex with calcium by liming in order to favor the adsorption of potassium ions.

The ammonium ion, added in the form of ammonium fertilizer, can be fixed in the interlayer sites of the absorption complex and is replaced with great difficulty by potassium (Merwin and Peech, 1950; Stanford and Pierre, 1946; Welch and Scott, 1961). Dugain (1959) found in the banana fields of Guinea that heavy applications of ammonium sulfate had a tendency to lower the level of exchangeable potassium or to limit the amount of potassium that could be fixed. This was observed as long as ammonium was not transformed to nitrate.

Fixation of potassium depends partly on the nature of the anion that accompanies the potassium. De Turk *et al.* (1943) observed that potassium phosphate or metaphosphate fertilizers caused a greater retention of the applied potassium than did potassium chloride fertilizers.

In Hawaii, Ayres and Hagibara (1953), mentioned by Humbert (1958) and Baver (1970), showed that in the Humic Latosols (Inceptisols) and in the Hydrol Humic Latosols (Inceptisols), where severe leaching occurs, less potassium is found in the drainage water when supplied in sulfate form than when supplied in chloride form. The same was observed in the Oxisols of Malaysia (Bolton, 1968). The different potassium phosphates are less susceptible to leaching than are chlorides and sulfates (Baver, 1970).

In Trinidad, Ahmad and Davis (1970) observed that the retention of potassium (exchangeable + nonexchangeable) in the acid Oxisols (pH 5.5) is greatest with potassium metaphosphate and decreases with potassium chloride, potassium sulfate, and potassium nitrate in that order (the last two are about equal).

Transformation of Nonexchangeable Potassium to Exchangeable Potassium

Release of potassium fixed in interlayers as exchangeable potassium has been described by Wiklander (1954) and by Barbier (1962) in temperate soils, which are relatively rich in illite. Hence, it is of only minor importance for soils of the humid tropical regions.

Decomposition of Potassium Soil Minerals

Lysimeter studies have shown that even under temperate climates, ground or crushed granites can release some potassium to drainage

waters (Barbier, 1962). This phenomenon appears more intense under a tropical humid climate, particularly in young soils on recent volcanic material and in older soils covered with volcanic dust; this has been noted in Java (Middelburg, 1955), in Cameroon (Segalen, 1967), and in Central America (Arana, 1969, mentioned by Van Wambeke, 1970b). But this can also happen in soils formed from metamorphic rocks, as in southwestern Congo (Brazzaville) and in northern Gabon (Aubert, 1958). According to the way the soil evolves and ages, the potassium-supplying minerals of the bedrock become more and more rare and the release of potassium from this mineral becomes more and more insignificant (Middelburg, 1955). Also, potassium may be released because of a breakdown of illitic clay crystals under humid tropical conditions (Segalen, 1968; Segalen and Leal Silva, 1969). However, there is usually only a small amount of this clay in soils of the humid tropics.

Influence of Fallow

On the ferruginous soils and the ferrallitic soils (Oxisols) of the savannas of French-speaking tropical Africa, a deficiency in potassium appears after several years of cultivation (Braud, 1966; Gillier, 1960; Poulain, 1969). A 2- to 4-year fallow is sufficient to re-establish an adequate level of exchangeable potassium. This is probably due to the release of potassium from the grasses and shrubs of the savanna. Charreau and Fauck (1970) in southern Senegal (Casamance) noted a dramatic drop in the exchangeable potassium of the soil, from 0.15–0.20 meq/100 g of soil to 0.05–0.02 meq/100 g during 15 years of continuous cultivation of mostly groundnuts and sorghum. However, the level of "total" potassium (extracted by boiling in nitric acid for 5 hr) stayed practically the same in these soils during the 15 years.

Leaching of Potassium in Soils

Without Fertilization

Relatively few data are available on leaching of potassium in tropical soils without fertilization. Tourte *et al.* (1964) studied the balance of the bases in the ferruginous sandy tropical soils of Senegal in the following 4-year rotation: (1) fallow or green manure, (2) groundnuts, (3) millet, (4) groundnuts. They noted in their lysimeters under the low precipitation in the area (800 mm) that

- Under natural fallow or a green manure crop, losses by leaching are small, 3.9 to 6 kg/ha of potash (K_2O).
- Under groundnut cultivation, losses range from 3 to 11 kg/ha of potash (K_2O), depending on the year and the yields.
- Under bare fallow, losses are always more than 11 kg/ha of potash (K_2O).

In general, losses of potassium by leaching are small in soils under natural vegetation (forest or savanna). But in cultivated soils, losses are considerable, either directly or through erosion. Losses from erosion may reach 35 kg/ha of potash (K_2O) with losses of 20 tons of soil per hectare per year for leached ferruginous sandy soils of the lower Ivory Coast. This is equivalent to less than 0.10 meq of potassium per 100 g of soil (Roose *et al.*, 1970).

Verney and Willaime (1965) in Dahomey noted that the losses in potash (K_2O) are only 7 kg/ha with an annual loss of 500 to 1,000 kg of soil when the land is under a 3-year-old bush cover. However, losses can be 200 kg/ha under cultivation with losses of soil as high as 30 tons/ha per year.

With Fertilization

As discussed before, retention of potassium from fertilizers is favored by the phosphate anion and also by the sulfate anion at low pH levels.

Ferrallitic Soils (Oxisols) After the addition of fertilizer, the potassium can be largely retained by ferrallitic soils (Oxisols), as has been shown by Ahmad and Davis (1970) for Oxisols (pH 5.5) of Trinidad. Retention depends on the anion of the fertilizer. In general, in this type of soil, the potassium is easily leached out. Bolton (1968) has studied leaching of potassium in sandy Latosols in lysimeters maintained under bare fallow. He observed in Malaysia that a large fraction of the potassium chloride was carried down more than 60 cm in 6 months under the equivalent of 700 mm of rainfall. In the Ivory Coast, 50 to 60 percent of the potassium fertilizer applied in banana fields is leached out from the sandy unsaturated ferrallitic soils (Oxisols) under a yearly rainfall of 1,900 mm (Roose *et al.*, 1970).

Ferruginous Sandy Soils In central Senegal, under 800 mm annual rainfall, in experiments in pots and in lysimeters, Tourte *et al.* (1964) investigated the variation in leaching of potassium as a function of the

addition of other fertilizers and management practices on ferruginous sandy soils. Under bare fallow, the annual loss by drainage is 14 to 16 kg/ha of potash (K_2O). It increased to 29 kg after addition of 40 kg of potash as chloride, and it reached 108 kg when the applied fertilizer contained 140 kg of nitrogen as ammonium sulfate. Under cultivation, with or without the addition of 50 kg/ha of K_2O as chloride, the loss of potassium by leaching remained the same: 25 kg/ha for millet, 10 to 15 kg/ha for the first crop of groundnuts, and 3 to 5 kg/ha for the second crop.

In southern Senegal under 1,100 to 1,200 mm rainfall, drainage removed 200 kg/ha of potash (K_2O) from the upper horizon (25 cm) of ferruginous soils and moderately unsaturated, ferrallitic sandy clay soils (Oxisols) in 15 years of a millet–groundnuts rotation (Charreau and Fauck, 1970). These data are similar to those obtained for a crop of maize (Blondel and Poulain, 1970).

Hydromorphic and Other Soils In Guinea under banana cropping, the addition of 200 kg/ha and 400 kg/ha of nitrogen in the form of ammonium sulfate lowered the level of exchangeable potassium from 1.10 meq/100 g of soil to 0.95 meq (Dugain, 1959). In contrast, with Andosols (Andepts) in Cameroon, leaching of potassium was very low (Gaillard, 1970).

Reducing the Leaching of Potassium

Agronomists have tried to reduce losses of potassium by adjusting the amount of fertilizer applied to the needs of the plants and by using split applications. In the Ivory Coast, Roose *et al.* (1970) split the potassium fertilizer into seven applications per year in banana fields on unsaturated ferrallitic soils. However, they still observed a leaching loss of 50 percent of the applied fertilizer. In Hawaii, Humbert (1958) recommends waiting until the roots of the sugarcane are well developed before applying potassium fertilizer. At that time, losses by drainage are practically nil.

POTASSIUM FERTILIZERS IN TROPICAL SOILS

Forms of Potassium Fertilizers

The potassium fertilizer most commonly used around the world is potassium chloride, usually containing about 50 percent of potas-

sium. About 90 percent of the potassium supplied to soils in the tropics is applied in the form of potassium chloride. The chloride form is advantageous in that it is lower in price and higher in potassium content than other forms. Potassium sulfate is sometimes preferred for pineapple and tobacco. The three other forms of potassium–metaphosphate, bicarbonate, and nitrate–seem to be used only in small field plot experiments, probably because of their high price.

Comparison between Potassium Fertilizers

Certain crops respond as well to potassium chloride as to potassium sulfate, for example, the oil palm on ferrallitic soils (Oxisols) of the Ivory Coast, Cameroon, Dahomey, and the Congo (Brazzaville) (Bachy, 1968). This is also true for tobacco and sisal in Tanzania (Akehurst, 1966, mentioned by Le Mare, 1970) and for bananas (Kampfer and Zehler, 1967).

The superiority of potassium sulfate, when it occurs, can often be explained by the presence of the sulfate ion. Sulfate of potassium is superior to the other forms of potassium fertilizer when a need for sulfur is associated with a deficiency of potassium in the soil. This is the case with pineapple in Guinea (Py, 1964), with tea in Indonesia (Kampfer and Zehler, 1967), and with the oil palm in Indonesia (Venema, 1959).

Depressive Action of Potassium Chloride for Certain Crops

Miller and Blair (1906) in Florida, Johansen (1911) in Natal, and Henriksen (1925) in Puerto Rico have found that the pineapple crop is of lower quality when it receives potassium chloride instead of potassium sulfate. This has also been reported by Chow (1966) in Formosa, Samuels and Gandia-Diaz (1960) and Beaton (1966) in Puerto Rico, and Cannon (1954) in Australia. The burning quality of tobacco seems to be increased by potassium sulfate and decreased by the chloride (Kampfer and Zehler, 1967).

The depressive action of potassium chloride on the yields of certain crops was observed with sweet potatoes in Formosa, with applications of 120 to 180 kg/ha of potash (K_2O) as potassium chloride. It has also been found with ramie, as mentioned by Kampfer and Zehler (1967), with avocado (Haas and Brusca, 1955), with beans in the "dark red latosol" of Brazil (Mascarenhas, mentioned by Van

Wambeke, 1970b), with groundnuts in Niger and in the Upper Volta (Boyer, 1970), and with cotton in Tanzania on acid sandy soils with a pH<5 (Le Mare, 1967, mentioned by Le Mare, 1970). Symptoms of manganese toxicity appeared on the cotton at the same time.

Various explanations of the depressive action of potassium chloride follow:

- The drop in pH brought about by the chloride ions might have been part of the cause of the trouble with cotton in Tanzania, where the initial soil pH is low (Franquin, 1958).
- The presence of sodium chloride in the potassium chloride is sometimes suggested (Kampfer and Zehler, 1967). However, the fertilizers on the market are usually pure enough for the amounts of potassium chloride normally used and do not contribute much sodium chloride.
- A small increase in the concentration of salts in the soil solution has been noted in temperate regions upon the application of potassium chloride at the beginning of a dry spring season: in the United States by Chapin and Smith (1960), in France by Barbier (1962), and Kampfer and Zehler (1967). This can occur in the subhumid tropics.
- The toxicity of the chloride ions is the principal reason mentioned by most authors. According to Buchner (1951), the chloride ion may become toxic after it gets into the plant. Nevertheless, a toxic concentration of the chloride ion is rarely observed in the humid tropics (Prevot and Ollagnier, 1958).

Another consideration is the specific resistance to the chloride ion by the different plant species. Some species, like bananas, tolerate heavy applications of potassium chloride. On the other hand, avocado, ramie, and other plants are not tolerant to chloride in the soil, which damages the roots and the leaves, according to Kampfer and Zehler (1967).

Addition of Potassium to the Soil by Other Means

Farm Manure

Farm manure is often used as a source of nitrogen, but it also adds an important amount of potassium (Prevot and Martin, 1964). For example, in Senegal 20 tons/ha of manure increased the yield of groundnuts by 67 percent and of sorghum by 150 to 300 percent.

According to Gillier (1967), this is due to the fact that the nitrogen and potassium needs of sorghum are better supplied by manure than are those of groundnuts. The results are even better, a 500 percent increase, with maize in Upper Volta and on the "terres de Barre" (Oxisols) in Dahomey; the same supply of nutrients as inorganic fertilizers gave only a 100 percent increase. Thus, the beneficial effect of farm manure greatly exceeded that which could be accounted for by the supply of mineral elements and nitrogen (unpublished reports of IRAT and Siry mentioned by Boyer, 1970).

Irrigation Water in Rice Fields In Java, irrigation water contains from 3.5 to 6 mg of potash (K_2O) per liter. It supplies the rice fields with 64 to 110 kg/ha of K_2O in a 5-month period, and the addition of potassium fertilizer is not necessary (Van Dijk, mentioned by Middelburg, 1955). This is not the case for most of the tropics, since the waters are relatively low in potassium. Nevertheless, in order to have a balanced nutrient supply in rice fields and irrigated crops, it is necessary to take this source of potassium into account.

Fallow

Fallow is not strictly an application of potassium; rather, nonexchangeable potassium is transformed to exchangeable potassium by the plants, and the ion is returned to the soil. This situation is particularly interesting for forest fallow. Laudelout (1954) indicates that in Yangambi in the Republic of the Congo (Kinshasa) the clearing and burning of a 30-year-old forest supplies the soil with 120 to 130 kg/ha of exchangeable potassium and at least the same amount of nonexchangeable potassium.

In the savanna, an increase in exchangeable potassium is also brought about by fallow (Braud, 1966). However, no improvement of the potassium nutrition of groundnuts was observed in Senegal after annual burning of a poor savanna.

GENERAL CONCLUSIONS

The various studies permit some conclusions about the importance, the characterization, the dynamics, and the utilization of potassium in humid tropical regions.

• The exchangeable potassion is the form that is most often determined in order to evaluate the soil potassium available to crops. A minimum level of exchangeable potassium has been established at about 0.10 meq/100 g of soil. This level varies somewhat according to the plant and the productivity of the crop. A relative minimum level has also been established on potassium at 1.5 to 2 percent of the exchange capacity or 2 to 3 percent of the sum of the exchangeable bases.

• The exchangeable potassium does not always give an exact idea of the potassium nutrition of the plants. Attempts have been made to define the amount of potassium that can be taken up by the plants. The method of English and American investigators, based on the soil–solution equilibrium, is the most promising. The magnesium-to-potassium, calcium-to-potassium, and (magnesium + calcium)-to-potassium ratios are especially important for ferrallitic soils (Oxisols). Although the ratios vary depending on the crop, it is considered that when the magnesium-to-potassium ratio is $<2:1$ to $3:1$, there is danger of a disequilibrium due to excess of potassium. However, there may be a considerable divergence from these figures, depending on the species of the crop. For example, a magnesium-to-potassium ratio ranging from $4:0$ to $25:1$ may be adequate for bananas, whereas a ratio ranging from $2:1$ to $3.8:1$ is optimum for the Robusta coffee tree.

• The soils of the humid tropical regions are not usually lacking in potassium immediately after clearing the vegetation. Some exceptions are the sandy ferrallitic soils (Oxisols) of the Ivory Coast, Nigeria, and Malaysia. Continuous cultivation for 3 to 5 years may give rise to potassium deficiency, but it can be corrected by some years of fallow.

• In tropical soils dominated by kaolinite, the interlayer fixation of potassium by clay is minimal. Hence, alternate wetting and drying does not seem to be as important as in temperate regions.

• Retention of potassium in the exchangeable form is strongly inhibited by the presence of aluminum and hydrogen, and also by iron and ammonium (when ammonium is added as ammonium fertilizer). Phosphate favors the retention of potassium on the absorbing soil complex; sulfate seems to facilitate this only slightly under acid conditions; and chloride has no influence.

• Leaching of potassium from the soil is slight under natural vegetation but increases markedly in bare soil and under cultivation. Potassium fertilizers leach readily, especially potassium chloride.

• The potassium fertilizer used most commonly in tropical regions is potassium chloride. Decreases in yield or even toxicity occur with the use of high levels of potassium chloride. With pineapple, potassium chloride lowers the quality of the fruit.

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E. J. KAMPRATH

Soil Acidity and Liming

Intensive agriculture in the humid tropics has been primarily conducted on soils with a high level of native fertility. These soils generally have a reserve of weatherable minerals that provide calcium and magnesium and prevent formation of highly acid soils. On the other hand the soils that are not being used intensively often have a low soil pH and are very low in exchangeable bases, which limits crop production. The Campo Cerrado of Brazil and the Llanos of Colombia and Venezuela are examples. Attempts to lime the soils in the humid tropics close to neutrality according to the procedures used for soils in temperate regions have very often ended in failure. However, since 1950, ideas about soil acidity and liming have undergone marked changes. These new concepts about soil acidity should be very helpful in providing the basis for determining which soils in the humid tropics will respond to liming and how much lime is required for optimum crop growth.

CONCEPTS OF SOIL ACIDITY AND CATION EXCHANGE REACTIONS

Nature of Soil Acidity and Cation Exchange Reactions

For many years, it was assumed that soils with a low pH were primarily hydrogen saturated. However, in the early 1950's a great deal

of work by soil chemists showed that exchangeable aluminum was the predominant cation in acid mineral soils with a pH of 5 or lower (Coleman and Thomas, 1967). The acid nature of soils containing exchangeable aluminum is a result of the hydrolysis of aluminum in the soil solution and the production of hydrogen ions. Acid mineral soils were found to contain essentially no exchangeable hydrogen since hydrogen clays are very unstable and decompose to give aluminum ions and siliceous acid (Coleman and Craig, 1961). Thus, with acid mineral soils, we are dealing with exchangeable aluminum and not hydrogen. Above pH 5.6, most soils will have relatively small amounts of exchangeable aluminum.

Determinations are often made of the titratable acidity of soils by adding base to a soil. The amount of titratable acidity is generally much greater than the amount of exchangeable acidity. The titratable acidity includes not only exchangeable aluminum but also acidity that is not replaced with a neutral unbuffered salt. It consists of nonexchangeable hydrogen associated with carboxyl groups and hydrated oxides of iron and aluminum. This nonexchangeable acidity has no detrimental effect on plant growth, as does the exchangeable acidity (exchangeable aluminum).

Since the activity of aluminum is related to the pH of the soil, the method of extraction becomes very important. The conventional ammonium acetate procedure and other buffered solutions are unsatisfactory for measuring exchangeable aluminum. A neutral unbuffered salt solution such as potassium chloride or sodium chloride has been found to extract aluminum ions (Lin and Coleman, 1960). For all practical purposes, the pH of the soil in a neutral unbuffered salt solution will be close to that of the soil. Therefore, the amount of aluminum ions extracted will approximately equal the amount on the cation exchange sites. This is in contrast to the much higher amounts of aluminum extracted by acidified ammonium acetate solutions.

Relation between Exchangeable Aluminum and Aluminum in the Soil Solution

Exchangeable aluminum is held very tightly by soil colloids. Nye *et al.* (1961) found very little aluminum in the soil solution until exchangeable aluminum comprised 60 percent of the total exchangeable cations of clays. Likewise, Evans and Kamprath (1970) found that with surface soils an exchangeable aluminum saturation of 60 percent was required before a large amount of aluminum was present

in the soil solution. Soils of Guyana had less than 1 ppm of aluminum in the soil solution when the aluminum saturation was lower than 60 percent (Cate and Sukhai, 1964).

With an increase in the amount of salt in the system, there is an increase in the amount of aluminum in the soil solution (Fried and Peech, 1946). Thus, high rates of fertilization could result in an increase of aluminum in the soil solution.

Effective Cation Exchange Capacity and Base Saturation

Traditionally, the cation exchange capacity of a soil has been determined from the amount of the ammonium ion adsorbed by a soil equilibrated with ammonium acetate at pH 7. The cation exchange capacity determined from the use of buffered ammonium acetate would include not only sites occupied by exchangeable cations but also pH-dependent exchange sites associated with carboxyl groups and hydrated oxides of iron and aluminum. It has been amply demonstrated that the cation exchange capacity of soils with a substantial dependent charge increases as the pH increases. Thus, the cation exchange capacity of acid soils measured with ammonium acetate exceeds the sum of the exchangeable aluminum, calcium, magnesium, and potassium. Therefore, the base saturation of a soil calculated on the basis of the cation exchange capacity determined with ammonium acetate at pH 7 will always be less than 100 percent for soils with a pH less than 7 even though the soils do not contain any exchangeable aluminum.

Based on these kinds of considerations, Coleman *et al.* (1959) suggested that the sum of the exchangeable calcium, magnesium, potassium, and the acidity extracted with a neutral unbuffered salt solution be called the effective cation exchange capacity. The effective cation exchange capacity can be considered the exchange sites that are participating in exchange reactions at the particular soil pH. On this basis most mineral soils would be 100 percent base-saturated at pH 6. As judged by plant growth, this is a much more realistic manner of expressing base saturation.

Causes of Acid Soil Infertility

Poor growth of plants on acid soils is in many instances related to the toxic effect of aluminum and manganese. This is discussed in detail by Adams and Pearson (1967). Also, calcium and other nutrients may

be seriously deficient on the highly leached acid soils. Under acid conditions, molybdenum tends to be held quite tightly by soil clays and hydrated oxides of iron and aluminum, and thus its availability to plants may be inadequate. Magnesium deficiencies have been observed on sandy soils where the pH is 5 or less and the exchangeable aluminum saturation is relatively high (Kamprath, 1967).

Crop Tolerance to Aluminum and Manganese

Crops vary in their tolerance to aluminum and manganese. Hewitt (1948) has classified a number of plants on the basis of their tolerance to aluminum and manganese. Tomato, lucerne, carrot, celery, barley, and sugar beet were particularly susceptible to aluminum toxicity. Swede, kale, lucerne, and tomato were the crops most affected by excess manganese content.

Cotton and barley were very sensitive to aluminum toxicity; soybeans were not as sensitive; and corn was relatively tolerant (Foy and Brown, 1964). Varieties of a particular plant species may vary widely in their tolerance to aluminum. Wheat varieties developed in the eastern United States where the soils are acid were more tolerant to aluminum than those developed in the Great Plains and western states where the soils are neutral to alkaline. Wheat varieties from Brazil had the highest tolerance to aluminum (Foy *et al.*, 1965).

The acidity problems of surface soils can be eliminated by liming. However, at present it is not feasible to lime acid subsoils. Where subsoil acidity is a problem, selection of aluminum-tolerant varieties is very important so that roots will grow into the subsoils and utilize moisture and nutrients present there. Where the amount and distribution of rainfall are adequate, liming the surface soil may be sufficient.

Response to Liming Based on Neutralization of Exchangeable Aluminum

Coleman *et al.* (1958) suggested that lime recommendations should logically be based on the amount of exchangeable aluminum in the soil. Kamprath (1970) found that lime rates based on milliequivalents of exchangeable aluminum times 1.5 resulted in neutralizing 85 to 90 percent of the exchangeable aluminum in soils containing 2 to 7 percent of organic matter. As the pH is increased from 5.5 to 6.0, some of the hydrogen ions associated with organic matter and hy-

drated oxides ionize and react with lime. For this reason a factor of 1.5 is used.

Results of field and greenhouse studies indicated that the aluminum saturation at the pH of the soil in the field should be less than 45 percent for maximum growth of corn, 20 percent for maximum growth of soybeans, and 10 percent for maximum growth of cotton (Kamprath, 1970). 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 fourfold increase in growth (Abruna and Vicente-Chandler, 1967).

Root Development

Considerable research has been done on the effects of calcium and aluminum on the root development of the cotton plant (Adams and Lund, 1966; Adams *et al.*, 1967; Adams and Pearson, 1970; Howard and Adams, 1965; Lance and Pearson, 1969; Rios and Pearson, 1964). Cotton roots do not penetrate a calcium-deficient soil; roots are restricted when the calcium concentration in the soil solution is less than 0.5 meq/liter. Roots will grow at pH 4.6 in the presence of adequate calcium. The root restriction in acid soils may be attributed to aluminum toxicity rather than to calcium deficiency; restriction is observed when the concentration of the aluminum ion in the soil solution is greater than 0.002 meq/liter. Aluminum depresses the uptake of calcium by the roots and reduces the permeability of the plasmalemma. When the concentration of aluminum in the roots exceeded 0.2 percent, yield was reduced. There appeared to be a close interaction between aluminum toxicity and calcium deficiency.

Peanut roots behaved differently from cotton roots. The former penetrated acid subsoil layers that cotton roots would not penetrate. This was explained by assuming that peanut roots absorb lower-valence ions to the exclusion of the higher-valence aluminum ions. Consequently, they are tolerant to relatively high aluminum ion concentrations in the soil solution. These experiments on cotton and peanut root development were done on Ultisols.

Ragland and Coleman (1959) observed that growth of sorghum and corn roots in unlimed subsoils was inversely related to the amount of exchangeable aluminum present. Addition of potassium chloride to unlimed soils increased the concentration of aluminum in the soil solution to the point of drastic root reduction. This interference with root growth was corrected by liming.

Experiments on root development of the leguminous plant *Leucaena glauca* in Hawaii (Plucknett, 1961; Plucknett *et al.*, 1963) strongly indicated that phosphorus deficiencies in the subsoil restricted root proliferation. Phosphorus had to be applied to the subsoil to stimulate root growth. Root development in the subsoil was more highly related to the phosphorus supply than to aluminum toxicity. Lime in the subsoil decreased active aluminum but did not stimulate root growth. Phosphorus, on the other hand, did not decrease the amount of active aluminum present but did stimulate root development.

There has been no evidence of aluminum toxicity to root development of sugarcane in acid soils in Hawaii, even at pH values below 5.0. Adequate available calcium was the determining factor. In Hawaii, calcium is added as a nutrient, rather than to change the acidity. Aluminum toxicity in sugarcane soils in Guyana did not occur unless the exchangeable aluminum saturation was more than 60 percent.

Effect of Liming on Availability of Fertilizer Phosphorus in Ultisols and Oxisols

Woodruff and Kamprath (1965) found that liming increased the efficiency of fertilizer phosphorus on acid soils that had an appreciable amount of exchangeable aluminum. The optimum level of liming for improved solubility of fertilizer phosphorus in Hawaiian soils was between pH 5 and 6 (Fox *et al.*, 1962). The increase in phosphorus solubility was related to neutralization of exchangeable aluminum.

When the pH of acid aluminous soils was adjusted to 7, phosphorus uptake was drastically decreased (Fox *et al.*, 1964). As pH 7 is approached, these soils have a very high buffer capacity so that high rates of lime are required. Since calcium is readily replaced from pH-dependent sites, excess calcium at the root surfaces may have precipitated phosphorus.

CHEMICAL CHARACTERIZATION AND MEASUREMENTS OF SOIL ACIDITY

Characterization

Analysis of some soils from the Llanos of Colombia indicates that these highly weathered, acid mineral soils are predominately satu-

TABLE 1 pH, Exchangeable Cations, and Percentage of Aluminum Saturation for 26 Soils of the Llanos Orientales, Colombia[a]

Comparison	pH	Exchangeable Calcium plus Magnesium (meq/100 g)	Exchangeable Aluminum (meq/100 g)	Aluminum Saturation (%)
Average	–	1.54	3.05	68
Range	4.15–5.12	0.05–9.09	0.6–5.80	29–86

[a] Data from Vargas (1964).

rated with exchangeable aluminum and that they have a low content of exchangeable bases (Table 1). The effective cation exchange capacity of these soils is quite low, compared with Mollisols of the temperate region.

Chemical data of representative soils from Brazil show that when the pH is less than 5, aluminum is the predominant exchangeable cation (Table 2). Above pH 5, the exchangeable aluminum saturation was low.

Samples of acid soils from the state of São Paulo, Brazil, were low in exchangeable calcium and magnesium and had an appreciable content of exchangeable aluminum (Table 3). These soils from the Campo Cerrado had a very low effective cation exchange capacity, generally in the range of 2 to 5 meq/100 g of soil.

Representative soils from Malaysia also had a high exchangeable aluminum saturation and a low effective cation exchange capacity (Table 4).

TABLE 2 pH, Exchangeable Cations, and Percentage of Aluminum Saturation for Representative Soils of Brazil[a]

Soils (Number)	pH	Exchangeable Calcium plus Magnesium (meq/100 g)	Exchangeable Aluminum (meq/100 g)	Aluminum Saturation (%)
14	5.0	1.2	1.9	58
18	5.0–5.5	5.9	0.6	16
11	5.5–6.0	6.5	0.1	2

[a] Data from Anastacio (1968).

TABLE 3 pH, Exchangeable Cations, and Percentage of Aluminum Saturation for Various Classifications of Soil in São Paulo, Brazil[a]

Classification	pH	Exchangeable Calcium Plus Magnesium (meq/100 g)	Exchangeable Aluminum (meq/100g)	Aluminum Saturation (%)
Red Yellow Latosol (Ultisol)	4.3	0.3	1.7	83
	4.0	0.2	1.2	82
	5.5	4.2	0.1	2
	4.6	0.2	1.9	89
	4.3	1.2	3.2	72
	4.5	1.3	0.8	36
Red Latosol (Oxisol)	4.2	0.2	1.0	67
	4.2	0.1	0.7	82
	4.1	0.2	1.9	88
Red Yellow Podzolic (Ultisol)	4.8	1.8	2.3	54
	4.5	6.0	3.5	35
	3.7	0.3	3.8	90
	5.4	0.9	0.1	10

[a] Data from Pratt and Alvahydo (1966).

The available evidence indicates that many acid soils of the humid tropics have a high percentage of exchangeable aluminum saturation when the pH is less than 5, are very low in calcium and magnesium, and have a low effective cation exchange capacity. The nature of soil acidity in many humid tropical soils, therefore, is similar to that of

TABLE 4 pH, Exchangeable Aluminum, Total Exchangeable Cations, and Percentage of Aluminum Saturation for Some Malaysian Soils[a]

Soil Series	pH (Calcium Chloride)	Exchangeable Aluminum (meq/100 g)	Total Exchangeable Cations (meq/100 g)	Aluminum Saturation (%)
Rengam	4.0	1.92	2.93	66
Serdang	3.8	5.08	5.89	86
Selangor	3.6	12.40	15.96	78
Kuantan	4.3	0.90	2.63	34
Segamat	4.3	0.70	2.05	34
Batu Anam	3.8	3.10	4.75	65
Chemor	4.2	1.33	2.25	59
Ulu Tiram	4.2	1.60	2.51	64

[a] Data from Mohinder Singh and Talibudeen (1969).

the highly weathered, acid mineral soils of the southeastern United States.

Measurements of Soil Acidity

Meaningful measurements of soil acidity can be obtained by extracting soils with a neutral unbuffered salt solution such as potassium chloride, sodium chloride, or barium chloride. This will extract the aluminum ion, the predominant exchangeable cation in acid mineral soils at pH 5 and below. Inferences can then be made as to whether soil acidity *per se* is likely to be a growth-limiting problem.

The effective cation exchange capacity—sum of exchangeable aluminum, calcium, magnesium, and potassium—gives a meaningful characterization of the exchange properties of humid tropical soils. Use of the effective cation exchange capacity to calculate the base saturation of soils provides a more realistic basis for evaluating the fertility status of soils.

Characterization of the Cation Composition of the Soil Solution

Since plants absorb cations from the soil solution, the composition of the soil solution is important in determining the cation content of plants. The concentration of cations in the soil solution depends upon the percentage of saturation of the cation exchanger by the cation and the nature of the cation exchanger. Montmorillonite, kaolinite, sesquioxide-coated clays, allophane, and organic matter are important cation exchangers. As these cation exchangers bind cations with different affinities, it is necessary to determine not only the cation saturation of the exchanger but also the cation composition of the soil solution. This will give a better understanding of the availability of cations and differences between soils in their response to the addition of fertilizer cations, such as magnesium and potassium.

Calcium, magnesium, and potassium are generally held more strongly by montmorillonite clays than by kaolinite, organic matter, allophane, and sesquioxide-coated clays. Generally, when the exchange sites are pH dependent, the basic cations are not held as tightly as when the exchange sites have a permanent charge.

Measurement of Exchangeable Manganese and Water-Soluble Manganese

Since manganese has been identified as being the cause of poor growth in certain acid soils, exchangeable manganese and water-

soluble manganese should be measured. Problems of manganese toxicity in acid soils are most likely to occur on soils formed from rocks having a high content of ferromagnesium minerals.

LIME STUDIES ON SOILS OF THE HUMID TROPICS

Rate and Frequency of Liming

The rate of liming should be based on the amount of lime required to neutralize the exchangeable aluminum. Sufficient rates should be tested to obtain a range of exchangeable aluminum saturation. This will provide information on the amount of exchangeable aluminum that needs to be neutralized in order to obtain maximum growth. Measurements also should be made of the calcium and magnesium content of the plant. One of the objectives of lime studies should be the development of a soil test for determining the amount of lime to add. Since the predominant cation of very acid soils is exchangeable aluminum, it seems logical that a soil test for determining lime rates should be based on a measurement of exchangeable aluminum.

One question that will have to be answered is how frequently to apply lime to soils of the humid tropics. Rainfall, evapotranspiration, occurrence and intensity of a dry season, cation exchange characteristics of the soil, water adsorption and movement characteristics of the soil—all will influence how fast calcium and magnesium are leached from soils. Mahilum *et al.* (1970) reported that considerable amounts of calcium were leached from a Hydrol Humic Latosol (Inceptisol). One interesting aspect of their work was that once the exchangeable aluminum was displaced, it did not readily reoccupy exchange sites even when calcium was removed by leaching.

Frequency of liming will depend upon how quickly calcium and other basic cations are removed by leaching and how soon exchangeable aluminum reappears on the exchange sites. Long-term field studies are needed to answer these questions.

Sources of Lime

Since many highly weathered acid soils are low in magnesium, studies are needed to determine the need for magnesium. Use of both calcitic and dolomitic sources of lime would be desirable. Another approach would be to determine the level of exchangeable magne-

sium required for optimum crop production. Where magnesium-containing limestones are not available, the use of soluble magnesium fertilizer materials should be evaluated.

Tolerance of Crops to Soil Acidity

As has been pointed out, crops vary considerably in their tolerance to soil acidity. In addition, varieties within a species may differ in this respect. Where new varieties are to be introduced in an area, information should be obtained on their tolerance to soil acidity.

Tolerance to soil acidity as it relates to growth of roots into acid subsoils can be very important in utilization by the plant of water and nutrients from the subsoil.

LIME-FERTILIZER INTERACTIONS

Phosphorus Availability as Influenced by Liming

Availability of fertilizer phosphorus has been increased by liming when the soils contained appreciable amounts of exchangeable aluminum. The addition of high rates of lime markedly reduced phosphorus availability in certain acid soils but not in others (Fox *et al.*, 1964). These authors suggested that the decreased availability was due to the greatly increased availability of calcium, which resulted in precipitation of phosphorus. This could very likely happen where calcium is not held tightly by the soil complex and where the concentration of phosphorus in the soil solution is relatively low because of fixation of phosphorus in sparingly soluble forms.

On the other hand, in some instances large amounts of phosphorus appear to be fixed, but the phosphorus is easily desorbed and a high concentration of phosphorus is maintained in the soil solution. Under these conditions, a high concentration of calcium might not be as detrimental as it is where the concentration of phosphorus in the soil solution is much lower.

Studies are needed to determine the nature of these lime-phosphorus interactions and to characterize the soil properties associated with different kinds of reactions. With sufficient information, it should be possible to identify soils where high calcium levels will have a detrimental effect on phosphorus availability.

Effect of Lime on the Availability of Micronutrients

Molybdenum

One beneficial effect of lime on certain soils is an increased availability of soil molybdenum, which is of particular importance in the growth of legumes. Most studies indicate that a pH of around 6.5 is required in order to get maximum availability of soil molybdenum. However, at pH 6.5, availability of some of the other micronutrients may be markedly reduced. Thus, it becomes important in liming studies to evaluate the interaction between lime and availability of soil molybdenum. Where humid tropical soils are low in molybdenum, treating seed with molybdenum is more feasible than liming the soil to pH 6.5.

Other Micronutrients

Availability of zinc, copper, manganese, and boron is often drastically reduced when highly weathered soils are limed much above pH 6. Liming studies with humid tropical soil should take into account any possible effect on the availability of these micronutrients.

NEED FOR CHARACTERIZATION AND CLASSIFICATION OF HUMID TROPICAL SOILS

Interpretation of the results of liming studies requires a knowledge of ion exchange reactions in soils and the nature and properties of cation exchangers in soils. One of the objectives of liming studies is to be able to extrapolate the findings to soils with similar chemical properties. This requires detailed soil chemistry studies and use of the chemical data in classifying and grouping of soils.

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M. DROSDOFF

Soil Micronutrients

Under traditional systems of agriculture in the humid tropics, micronutrient deficiencies are seldom a limiting factor in crop production.* The long fallow period in shifting agriculture in both forested and the savanna areas usually regenerates in the plant material returned to the surface soil sufficient micronutrients and macronutrients to supply the needs of subsistence crops. The use of refuse, composts, and animal manures where available also provides a good source of micronutrients to the surface soil. The low crop yields obtained under shifting agriculture require such small amounts of micronutrients that their importance in crop production in the humid tropics has been obscured.

Only with the advent of modern technology and intensification of crop production in the humid tropics has there been an awareness of the need for supplying one or more of the micronutrients along with other fertilizers. The increased productivity of commercial export crops in the tropics with the use of high-yielding varieties and the greater use of nitrogen, phosphorus, and potassium fertilizers has

*The term "micronutrients" is used in this chapter to refer to the plant nutrients zinc, copper, boron, molybdenum, iron, and manganese. Other terms commonly used in the literature to refer to these elements are "trace elements," "minor elements," and "oligoelements."

brought into sharper focus the need for greater attention to the micronutrient supply. Reports on deficiencies of zinc, molybdenum, boron, and other micronutrients in commercial plantings of coffee, cacao, rubber, oil palm, sugarcane, pineapple, citrus, and other crops grown extensively in the humid tropics are becoming more common (for example, Aldrich, 1960; Ananth *et al.*, 1965; Bould, 1968; Chapman, 1966; DuToit, 1963; Fox, 1969; Jordine, 1962; Lott *et al.*, 1961; Mestanza and Lainez, 1970; Muller, 1959; Newton and Said, 1957; *Plant Analysis and Fertilizer Problems*, 1954–1964; Tollenar, 1966; Vicente-Chandler *et al.*, 1968). Reports on micronutrient deficiencies of annual food crops are less common, but undoubtedly the increased use of nitrogen, phosphorus, and potassium fertilizers on high-yielding varieties will stimulate a need for the application of micronutrients (Nye, 1966).

Sauchelli (1969) in his book *Trace Elements in Agriculture* reviews the background on the use of micronutrients for crop production and the soil–plant and animal interrelationships. He makes the point that, with the increasing use of higher and higher analysis fertilizers containing less micronutrient impurity, it would be expected that there would be a greater requirement for supplementary micronutrients. Also, the present limited use of organic fertilizers, which in the past usually furnished a sufficient supply of micronutrients, tends to accentuate the need for these elements.

GEOGRAPHIC OCCURRENCE OF MICRONUTRIENT DEFICIENCIES

Extensive soils in the humid tropics are formed on old land surfaces, and they have a very low natural fertility. Where these soils have a favorable topography and are deep, permeable, and well drained, they have a high potential productivity under good soil management, which requires the substantial use of fertilizers including one or more micronutrients. However, most of the soils now under continuous cultivation in the humid tropics have a relatively good level of natural fertility and they are less likely to be deficient in micronutrients. These soils are formed from recent alluvium or young terraces, volcanic ash, basic igneous rock of relatively recent origin, and loessial deposits relatively rich in primary minerals (Hodgson, 1963). Usually, nitrogen, phosphorus, and potassium fertilizers and occasionally lime are required for high production on these soils, but the

natural micronutrient supply has generally been adequate for the level of production attained.

Africa

Investigations with micronutrients by Cunningham (1964) on cacao in Ghana did not indicate any yield response to applied zinc, molybdenum, boron, copper, manganese, and iron except under special circumstances. Later, Cunningham (1966) stated that there was no evidence to suggest that any micronutrients need to be included in the fertilizer applied to cocoa. However, he did go on to say that most of the good cocoa in Ghana is confined to the slightly acid to neutral forest Ochrosols, and it was on such soils that much of the fertilizer work was done.

The fact that much of the experimental work in Africa has been on soils fairly well supplied with micronutrients prompted Russell (1968) to state that there is very little evidence that crop yields are limited in any extensive areas of tropical Africa by either deficiencies or excesses of micronutrients. However, Russell did indicate that in isolated areas boron deficiency may become important: In an area in Kenya, the soil derived from a particular volcanic ash shower is low in copper; in some areas, zinc deficiencies have been found; and in some high-altitude pastures in Kenya, molybdenum deficiency has been recognized.

In his review of soil research in Tanzania, Le Mare (1970) states that boron deficiency probably occurs widely in Tanganyika, especially on light-textured soils in wetter areas. It has been observed on sisal in the northeastern part of the country, and slight symptoms of the deficiency occur widely on cotton in the western area. On Ukerewe Island, a severe deficiency occurs, and cotton has given yield responses to applications of boron. Dieback in wattle, pines, and coffee in southern Tanganyika has been cured by boron or boron plus zinc. With the occurrence of dieback on other perennial crops and ornamental trees, Le Mare postulates that a micronutrient deficiency may be the cause of the trouble.

In a survey of minor element deficiencies in Africa, Schütte (1954) reports that they are widely distributed throughout Africa. About 80 percent of the agricultural land in South Africa shows some minor element deficiency. Citrus orchards especially show deficiencies of zinc, boron, copper, and manganese.

Chaminade (1970) has reviewed the agricultural research work car-

ried out by the Institut de Recherches Agronomiques Tropicales et de Cultures Vivrières in Africa, and there is not much indication of response to micronutrients on the soils investigated. However, in field tests to determine response curves for nitrogen, phosphorus, and potassium, there seem to be differences in the magnitude of responses to the macronutrients on the different soils, which indicates that other limiting factors, such as an insufficient supply of micronutrients, may be operating.

In the cultivation of groundnuts in northern Senegal, Nutramin containing iron, manganese, copper, zinc, boron, and molybdenum applied at the rate of 3 kg/ha markedly increased yields. Factorial experiments showed the active element to be molybdenum, and ammonium molybdate at 28 g/ha gave responses as good as those obtained with Nutramin at 3 kg/ha (Martin and Fourrier, 1965). Stephens (1959) investigated the responses of annual food crops to manganese, boron, copper, magnesium, iron, zinc, and molybdenum at 10 agricultural stations in Ghana in small-scale and factorial field trials. The only favorable response was a small one to molybdenum by groundnuts.

In field trials in northern Nigeria with cotton and maize on a well-drained, acid ferruginous soil formed over acid crystalline rock, Heathcote (1970) got increased yields from applications of lime. Foliar analysis and other evidence indicated that the increased availability of molybdenum may account for much of the response due to liming. Trace-element analysis of leaf samples from the 1967 cotton crop showed that molybdenum increased from 0.05 to 0.24 ppm while boron, copper, and zinc did not increase much, if at all, though these elements were applied.

To sum up, this sampling of references and some others (Bouyer, 1963; Calton and Vail, 1956; Chenery, 1958; Duthie, 1953; Jackson *et al.*, 1967; Peive, 1963; Stephens, 1969) on micronutrient deficiencies in Africa indicate that more and more micronutrient deficiencies are being recognized in a wide variety of crops on a wide range of soils. This is especially true of acid soils that have a relatively low reserve of micronutrients and that are under continuous cultivation and improved cultural practices and are receiving relatively high applications of nitrogen and phosphorus fertilizers. As diagnostic techniques are perfected, greater attention will undoubtedly be given to micronutrient deficiencies and their control. Apparently, molybdenum, zinc, and boron deficiencies are the most prevalent, but copper, manganese, and iron deficiencies have oc-

casionally been identified under particular conditions. On acid soils high in manganese, instances of manganese toxicity have been reported.

Asia

Considerable work has been done in India on micronutrient deficiencies of various crops and on the micronutrient status of different soils (Ananth *et al.*, 1965; Eswarappa *et al.*, 1969; Govinda *et al.*, 1964; Jain and Mehta, 1963; Kanwar, 1964; Nair and Mehta, 1959; Newton and Said, 1957; Randhawa and Kanwar, 1964). This work has been reviewed in a publication on micronutrient research in soils and plants in India (Kanwar and Randhawa, 1967). Much of the micronutrient research in India has been on soils relatively well supplied with micronutrients and on neutral to alkaline soils. On alkaline soils, zinc deficiency is widespread in several states on a variety of crops, including the cereals (Rahaja *et al.*, 1959). Manganese deficiency is also common on alkaline soils. In a study on 44 surface soils and subsoils in Uttar Pradesh, many had relatively low levels of "available" (hot water extractable) molybdenum, which could be in the deficiency range (Pathak *et al.*, 1968).

In his review of investigations on the fertility and management of the soils of Malaysia, Coulter (1970) cites several articles on micronutrient deficiencies in rubber, oil palm, pineapple, and cocoa. They were mainly zinc and boron deficiencies, but copper deficiency in the field was reported on peat soils. There were no reports on molybdenum deficiency in the field. In pot experiments with three soil types, Watson (1960) found that the uptake of molybdenum at pH less than 5 was low enough to limit growth. Liming the soil to pH 6 increased the molybdenum content of the plant and increased dry weight production. Molybdenum deficiency of groundnuts has been reported on the Latosols of Java (Newton and Said, 1957). Applications of various combinations of phosphorus, potassium, lime, and trace elements indicated a response to molybdenum. Sodium molybdate applied at the rate of 1 kg/ha increased yields and improved nodulation of the roots.

Latin America

Dramatic responses have been obtained to the application of micronutrients to crops on the Campo Cerrado soils in the central plateau

area of Brazil. These soils have been developed mostly from parent materials of ancient sediments and are highly weathered and leached, but they generally have good surface and internal drainage and favorable topography. The dominant vegetation is grass with scattered shrubs and small trees, and the climate is characterized by a strong wet–dry cycle with a mean annual rainfall of about 1,500 mm. It is estimated that there are about 160 million hectares of land in the central plateau of Brazil with this kind of vegetation and climate.

Zinc deficiency of corn was first noted in the Campo Cerrado near Matão, in the state of São Paulo, in a commercial planting that had been fertilized with nitrogen and phosphorus (Igue and Gallo, 1960). The symptoms were corrected by either foliar sprays or soil applications. In subsequent field tests on similar adjacent soils previously uncultivated, zinc applications increased yields, but in two cases there was no yield increase though the zinc deficiency symptoms were corrected. A nearby area fertilized with only nitrogen, phosphorus, and sulfur produced moderately well and had no zinc-deficiency symptoms.

In subsequent experiments on Campo Cerrado soils in Brazil, zinc, boron, and molybdenum applied in combination to supplement nitrogen, phosphorus, potassium, and lime treatments increased seed cotton yields 72 percent on a deep sandy soil, 12 percent on a Yellow Latosol, and 41 percent on a Dark Red Latosol (Mikkelsen *et al.*, 1963). Maize yields were increased 41 percent, 17 percent, and 5 percent on these same soils by the added micronutrients. No attempt was made to separate the effects of the three micronutrients. In two other field experiments on previously uncultivated Humic Latosols, one near Anápolis, Goiás, and one near São Joaquim, São Paulo, a definite response to zinc applications by soybeans was obtained in the first location and not in the second (Freitas *et al.*, 1960). No response was obtained from application of molybdenum in either location. With maize, there was a significant depression in yield in the minus zinc plots. In general, the results of these experiments were inconclusive and indicate considerable differences in responses to micronutrients by the different crops in the different locations.

Similar conclusions were drawn from results of cotton fertilization experiments on Campo Cerrado (McClung *et al.*, 1961). There were significant yield differences in a few experiments with boron and molybdenum, and though zinc deficiency was noted in some plots, there was no yield response to zinc. No clear-cut pattern of response to applications of micronutrients was apparent, but it was suggested

that this area of soil fertility research on the Campo Cerrado soils deserves closer attention.

Boron deficiency has been reported for several crops on some volcanic soils in Ecuador (Tollenar, 1966). In a field trial on a sandy loam to loam soil of pH 6.2, a boron spray corrected leaf symptoms of cacao and increased yields (Mestanza and Lainez, 1970).

Using the missing-element technique in greenhouse studies, Martini (1969, 1970) studied a number of Andosols and Latosols of Costa Rica. He concluded that both groups of soils were low in micronutrients, showing significant deficiencies, especially under successive cropping and fertilization with nitrogen, phosphorus, and potassium. Among other recommendations, he suggested that work be intensified on the micronutrients, especially on the Andosols and Latosols.

The results of micronutrient research in Puerto Rico during the period 1949–1954 have been summarized by Landrau and Samuels (1956). In general, they found no consistent yield increases with the use of micronutrients. Deficiency symptoms of several of the micronutrients occurred on a number of crops without affecting yields. One marked increase in yield of pineapples resulted from the use of iron sprays and fritted trace elements. Some crops such as maize and plantains showed no yield response in any of the work on which Landrau and Samuels (1956) reported. More recent field experiments with plantains showed that soil applications of micronutrients on Lares clay (Aquic Tropohumult) significantly increased yields (Hernàndez and Lopez, 1969). Omission of both zinc and iron from foliar sprays significantly reduced yield. Recent field observations of severe zinc deficiency in fertilizer experiments with corn on two different soils in Puerto Rico illustrate the range of pH conditions under which zinc deficiency may occur. One soil is a sandy Oxisol with a pH less than 5 and the other is a clayey Oxisol with a pH over 6 and with free calcium carbonate in the lower subsoil.

GENERAL EVALUATION

From this brief review of the literature, it appears that no systematic or definitive study has been undertaken of the role of micronutrients in crop production in the humid tropics. There are many reports of the occurrence of deficiency symptoms of zinc, boron, molybdenum, manganese, copper, and iron, and of successful measures of control. In some cases, increased yields have been associated with control of the

symptoms, and in other cases they have not. This inconsistency of response to treatments characterizes many of the studies.

There are many difficulties in assessing the micronutrient investigations in the humid tropics with respect to the soil-plant relationship. One is the general lack of specific information on the characteristics of the soils under study. In many instances, no information at all is given on the kind of soil, merely the location. In other cases, a series or local name is given without any additional information. Sometimes a few chemical or physical properties of the soil, such as pH, texture, or drainage, are reported, but generally the information is limited and difficult to interpret. Commonly, the soil under study is described in terms of a broad group such as Latosols, which covers a rather wide range of characteristics.

Bleeker and Austin (1970) attempted to show the relationship between the total micronutrient content and a number of other soil variables in horizons of six texture-contrast soils from Papua-New Guinea. The soils were classified according to the new United States soil taxonomy. One conclusion of the study was that the variation in the behavior of the trace elements appears to be closely associated with the processes determining the differentiation of soil types. However, no attempt was made to evaluate the significance of the total amounts of the elements to their availability to plants. Other studies have also reported total micronutrient contents in soils without any follow-up on the soil-plant interrelationship.

One of the more definitive micronutrient studies was made in Hawaii on the relation of total and extractable zinc to the occurrence of zinc deficiency on soils classified at the great group level in the new United States soil taxonomy (Kanehiro and Sherman, 1967). Though a correlation at the 1 percent level of significance was found between the extractable and total zinc levels for all the soils studied, the correlation coefficient of 0.30 is not very conclusive. There appeared to be no consistent pattern in total zinc content among the highly weathered Oxisols and Ultisols, although, in general, they had relatively low total zinc contents and low extractable zinc. The authors suggest that most of the zinc deficiency problems are associated with the highly weathered Oxisols, Ultisols, and Inceptisols in the tropics, although their data are not conclusive.

With reference to the occurrence of zinc deficiency, Stanton and Burger (1967) present evidence that sesquioxides play a prominent role in limiting zinc availability to plants. Using millet seedlings and root sorption techniques, they found that phosphated hydrous iron

oxides fixed zinc against absorption by plant roots. In the absence of phosphate ions, the availability of sorbed zinc decreases as the crystallinity of the sesquioxides increases. Although the amorphous hydrous sesquioxides readily sorb zinc, they do not fix it in an unavailable form, whereas goethite does. On the other hand, the zinc is fixed just as strongly against plant uptake by the amorphous and crystalline sesquioxide varieties if linked through the medium of polyvalent phosphate ions.

A number of studies have indicated that molybdenum may be deficient for many crops on the leached, highly weathered, acid soils in the humid tropics, especially those developed from old parent materials. Since Anderson (1942) demonstrated molybdenum deficiency on soils formed from old materials in South Australia, the necessity for supplying this element on these kinds of soils has been given much attention. In South Australia, hundreds of thousands of acres of pastureland are now treated with molybdate along with superphosphate. One of the principal effects of supplying molybdenum was the stimulation of nitrogen fixation of legumes, and this has received considerable study (Andrew, 1962; Younge and Takahashi, 1953). In many cases, liming was found to increase molybdenum availability to plants. However, in some instances, while the addition of lime corrected molybdenum deficiency, it caused manganese, zinc, iron, and boron deficiencies in some plants if these elements were at marginal levels in the soil or if too much lime was used.

Boron deficiency commonly occurs on some crops in the humid tropics on highly acid, deeply weathered soils, on deep sands, and on neutral to alkaline soils. There is some indication that soils high in sesquioxides have a marked affinity for boron. Okazaki and Chao (1968) found that hot-water extractions of boron adsorbed on iron and aluminum oxides required longer periods of heating, wider soil-to-water ratios, and a greater number of extractions.

Reports on deficiencies of copper, iron, and manganese on crops in the humid tropics are less common than those on deficiencies of zinc, molybdenum, and boron. Copper deficiency is most commonly associated with peat soils in the tropics as it is in temperate regions, and occasionally it occurs on very sandy soils. Iron and manganese deficiencies are usually associated with neutral to alkaline soils, especially those containing free calcium carbonate in the profile. In acid soils high in soluble manganese, iron deficiency or manganese toxicity may occur. This can be accentuated by heavy applications of residually acid nitrogen fertilizers. Abruña-Rodriguez *et al.* (1970)

found in experiments with tobacco on an Oxisol (Tropeptic Haplorthox) high in exchangeable and easily reducible manganese, that yields were substantially increased by liming. They attributed the increase to a reduction of manganese toxicity. Vicente-Chandler *et al.* (1964) also found that heavy applications to pastures of residual acid nitrogen fertilizers can result in manganese toxicity unless corrected by applications of lime.

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J. D'HOORE AND J. K. COULTER

Soil Silicon and Plant Nutrition

Although from 10 percent to 50 percent of the ash from plant and animal tissues and from the dry matter of soil solutions may be silica (SiO_2), silicon is not normally regarded by physiologists as an essential element. Furthermore, the soils used for intensive agriculture in temperate regions are usually very well supplied with soluble silica, and the substitution of phosphorus for silicon probably masks any deficiency.

In the humid tropics, silica deficiency has not been recorded either in the natural vegetation or in the crops from traditional agricultural systems. However, the widespread phosphorus deficiency and the comparative ease with which silica is removed from the weathering zone, as illustrated by the relative accumulation of sesquioxides in freely drained humid areas and the accumulation of silica in poorly drained areas, would indicate probable low levels of soluble silica in many areas in the tropics. Where there is intensive agriculture on highly weathered and highly leached soils, there is increasing evidence of the beneficial effects of added silicate on the growth and yield of certain species of Gramineae.

RESPONSES TO SILICA

The amount of silica in plants is determined by both species and soil factors and the relatively large accumulation by grass species has been known for a long time. Although its accumulation appears due mainly to the passive uptake of monosilicic acid in the transpiration stream (Jones and Handreck, 1967), the concentration in the soil solution and the quantity of water transpired thus controlling the amount of silica in the plant, there is some evidence that uptake by plant roots is not entirely passive but can be selectively influenced by metabolic inhibitors (Okuda and Takashi, 1963). There is ample evidence that different species with access to a soil solution with the same concentration of silica and transpiring the same amount of water will take up greatly differing amounts of silica. Legumes and other dicotyledons have much lower levels than monocotyledons—for example, the Gramineae—whereas within this group, rice appears to take up more silica per unit of water transpired than do dry-land crops.

The tropical crops that have received most attention are rice and sugarcane, and there is a voluminous literature, mostly emanating from Japan, on the effects of silicate on rice. Rice takes up large quantities of silica, and Jones and Handreck (1967), in reviewing the Japanese work, quoted values of 13 percent silica (SiO_2) in the leaf sheath. About 1 million tons of calcium silicate slag are used annually in Japan. Imaizumi and Yoshida (1958) reported that of the 3 million hectares under rice, one third responds to silica, one third does not, and the remaining third may respond, depending on circumstances.

Sugarcane absorbs large amounts of silica. Samuels (1969) reported that the aboveground parts of a 12-month crop contain 800 kg/ha of silica, compared with 430 kg/ha of potash (K_2O) and 140 kg/ha of nitrogen. Because of well-developed leaf-analysis techniques for sugarcane, there is considerable information on levels of silica in the leaf. Halais and Parish (1964) found that the lowest levels in the leaf sheath, less than 1 percent silica on a dry-matter basis, occurred on Regosols derived from coral sands. Highly weathered soils, which had lost almost all their silica as well as bases, produced cane with a low silica content (1 percent silica) and a high manganese content (up to 300 ppm of manganese). The leaf sheaths on the best cane-growing soils contained about 2.5 percent silica and from 50 to 75 ppm of manganese. Using the third to sixth leaf sheath, Halais (1967) suggested critical levels of 1.25 percent of silica and 125 ppm of

manganese. If the silica level was below or the manganese level was above these values, silica responses could be expected.

YIELD INCREASES FROM SILICA

Experimental work on the response of sugarcane to silicate fertilizers has been done in both Hawaii and Mauritius. The Hawaiian work was described by Fox *et al.* (1967), who showed increases in yield of cane of about 12.5 tons/ha by the addition of 5 tons/ha of calcium silicate slag on highly weathered Humic Ferruginous Latosols (Ultisols). On Humic Ferruginous Latosols (Ultisols) in the high rainfall area of Mauritius where cane had shown "leaf freckle" and low levels of silica in the leaves, particularly in winter, Wong and Halais (1969, 1970) used a finely ground calcium silicate slag in fertilizer trials. Neither coral sand, to correct acidity, nor a nitrogen–phosphorus–potassium fertilizer had succeeded in giving good yields on these soils, but 7.5 tons/ha of calcium silicate increased yields of cane from about 42 to 67 tons/ha. This experimental work in Mauritius is recent, and the literature does not indicate the extent of the area on which silicate responses may be expected. Although Hawaii and Mauritius are the only confirmed areas of responses of sugarcane to silicate, there are some suggestions that sugarcane and also maize may respond to applied silicate in South Africa and Puerto Rico.

Apart from rice and sugarcane, there is little information on the silica needs of tropical crops. Wong and Halais (1969) reported yield responses from sorghum in pot experiments in Mauritius, and Grant *et al.* (1967) reported that on Rhodesian soils, calcium silicate doubled the yield of millet in pots in the absence of phosphorus, though responses to silica alone were not as good as from phosphorus alone. Some tropical grasses accumulate large quantities of silica; Miller and Blair-Rains (1963) reported over 20 percent ash, probably mostly silica, in *Hyparrhenia rufa* grass in northern Nigeria. Other reports of the amount of ash found during leaf analysis indicate that the levels of silica, in the same species, vary greatly from area to area and from soil to soil.

SILICA IN PLANT NUTRITION

It has been suggested that the beneficial effect of silica may be due to its ability to control manganese toxicity or partially substitute for

phosphorus where levels are low. Samuels and Alexander (1968) showed that the manganese uptake of the cane plant was suppressed as the silica supply was increased; as the manganese content of the plant dropped, the silica content increased. They also reported that in the absence of silica, production of sucrose diminished in the leaves as the concentration of manganese increased. Localized accumulation of manganese in the leaves caused "freckling," which reduced the photosynthetic area.

The interaction of silica and phosphate has long been of interest. Yields of barley increased by use of silicate in the absence of phosphate were recorded at the Rothamsted Experimental Station nearly a century ago (Russell, 1961), and more recently (Rothamsted Experimental Station Report, 1968) an increase in barley yield of 35 cwt/ha was recorded where no phosphorus had been applied. The reason for these responses is not understood, and the suggestion that silica depresses the activity of the aluminum in the soil solution is not supported by the evidence discussed later, nor would it be expected in the neutral soils at Rothamsted.

PLANT-AVAILABLE SILICA IN SOILS

Colorimetric methods for rapidly and precisely determining monomeric water-soluble silica have provided a basis for a new approach to the study of the silica cycle in ecosystems and their associated soils (Iler, 1955). From the extensive bibliography, much of it included in the excellent review by Jones and Handreck (1967) and from recent findings of our laboratory (Louvain), some of the more relevant new concepts are summarized in the following paragraphs.

Solubility of Silica

The solubility of silica in water devoid of other dissolved ions is nearly constant between pH 2 and 8 at approximately 120 ppm at room temperature. The silica in solution is almost exclusively monomeric and consists of undissociated silica (SiO_2) molecules (Krauskopf, 1959; Beckwith and Reeve, 1963).

Supersaturated solutions of monomeric silica can be prepared, e.g., by deionizing sodium silicate solutions over exchange resins, but after a few weeks their concentration reverts to the 120-ppm limit. Inversely, shaking pure silica gel with water gives solutions with

slowly increasing concentrations, tending toward the 120-ppm limit. This indicates the existence of a slow equilibrium reaction between monosilicic and polysilicic material.

When added to silica solutions, neither monovalent nor divalent cations depress silica concentration between pH 2 and 8. Above pH 8, magnesium is known to form insoluble magnesium silicates. When iron and aluminum ions are added at pH values too acid for their hydroxides to precipitate, depression of silica concentration is very slight. However, as soon as these hydroxides can form, dissolved silica is very strongly adsorbed.

When pure saturated silica solutions are percolated through, or shaken with, soil material or known mixtures of potential soil constituents, adsorption always causes a considerable decrease in soluble silica concentration. Systematic studies have shown that free hydrated sesquioxides, particularly those of aluminum, are the most active silica adsorbers, especially when they are freshly precipitated (Miller, 1967). Thus a new set of equilibrium reactions, between free monomeric silica and monomeric silica adsorbed on the various internal soil surfaces along the soil solution stream, is introduced. In contrast to the monomer–polymer equilibria, these are strongly dependent on environmental factors. Thus,

- Increasing temperature lowers adsorption.
- Higher solid-to-liquid ratios result in more efficient retention.
- Acidity determines the nature and constitution of the surfaces of hydrated sesquioxides: between pH 4 and 8, silica adsorption is strongly pH dependent, i.e., it decreases strongly with increasing acidity (McKeague and Cline, 1963).

None of these environmental factors influences the solubility of silica; they merely regulate the equilibria between free and adsorbed silica. Silica does not combine with, and thus immobilize, toxic aluminum or iron ions but is merely adsorbed by their hydroxides when acidity is favorable to their formation. Should aluminum hydroxides dissolve through increased acidity, adsorbed silica would be liberated.

A reciprocal relation exists between soluble silica and soluble phosphorus in soils. As the amount of phosphorus applied is increased, release of water-soluble silica is increased, and vice versa. The nature of this interaction, often erroneously attributed to anion exchange, is not well known but probably takes place at the free sesquioxide adsorption sites.

Sources of Available Silica in Soils

The primary origin of available silica in soils is the chemical weathering of their parent materials; some silicate-bearing minerals decompose easily, and none are absolutely inert. During the process, considerable amounts of hydrated sesquioxides may be liberated, favoring silica adsorption and occlusion. This may retard crystallization of sesquioxides and at the same time prolong their silica-adsorbing action (Herbillon and Tran Vinh An, 1969).

Silica-to-sesquioxide ratios in these amorphous mixtures may, of course, vary widely; low values may result in a tendency towards fixation; high values may indicate better availability of retained silica. Some of this silica may pass into the crystal lattice of secondary minerals, and the presence of 2:1 clay minerals may indicate an abundance of potentially available silica. Some may precipitate as opal, or even crystallize into chalcedony or secondary quartz.

Large amounts of amorphous, gel-like aluminum–silicon compounds may be present in the soil. They may then retain potassium rather strongly, especially after drying out (Reeuwijk and Villiers, 1968), and depress availability of heavy metal micronutrients (Tiller, 1968). On the other hand, addition of small amounts of soluble silica, less than 1 percent, to sand cultures significantly increased their moisture-holding capacity (Ganssmann, 1962).

Considerable soluble silica may be lost from the soil by drainage (Eaton *et al.*, 1968) or into an ecosystem that is regularly harvested or burned (Lovering, 1958). Inversely, soluble silica may be introduced by runoff or seepage, by capillary ascension from the water table, or by aeolian, alluvial, or colluvial deposition at the surface.

Monomeric silica is also the only soluble silica form in vascular solutions, animal sera, and other biological liquids. Certain lichens and bacteria are able to extract their constitutional silica directly from crystal lattices. Inside the living matter, equilibrium reactions between monomeric and polymeric silica and between free and adsorbed monomeric silica may also be expected. Development of shells, spicula, and opal phytoliths is, therefore, in a way comparable to the formation of opal and chalcedony in rocks and of amorphous silicon–aluminum and iron compounds and duripans in soils. Decomposition of vegetable or animal tissues returns most of the silica in readily soluble form, with the exception of the phytoliths, spicula, and shells which may serve as paleopedological indicators (Twiss, 1969). Such decomposition may even enhance liberation of soluble silica from adjoining weatherable minerals (Kutuzova, 1969).

Silica-Responsive Soils

Experimental evidence for defining silica-deficient soils is limited and, apart from Japan, Mauritius, and Hawaii, few references are available. In soil surveys, soil analysis does not include the determination of soluble silica, so that areas of possible deficiency cannot be located from soil maps.

From a consideration of the chemistry of silica, deficiency would not be expected in soils with considerable weatherable mineral reserves, 2 : 1 clay minerals, abundant amorphous aluminosilicates with high silica-to-sesquioxide ratios, limited external drainage, or enrichment by incoming drainage water or surface additions by windborne material.

On the other hand, silica deficiency might be expected in soils that contain no weatherable minerals, have clays with low silica-to-alumina or low silica-to-sesquioxide ratios, and have clays containing only kaolinite and gibbsite, goethite, or hematite.

Within this grouping, soils with a high percentage of hydrated oxides would be expected to have less available silica than those with a low percentage of oxides and more kaolinite. Soils with low cation exchange capacity and a low base saturation might also be included. Low silica-supplying power has been reported for soils developed on acid peats, granite, quartz porphyry, coarse-textured material derived from sandstone and coral sand, and for Humic Ferruginous Latosols (Ultisols), gravelly lateritic soils, and allophane-rich soils under high rainfall. Much better supplied are heavy-textured soils, saline soils with pH values higher than 6.6, basalt-derived soils, and soils on recent volcanic ash rich in allophane under low rainfall (Fox *et al.*, 1967; Halais and Parish, 1964; Imaizumi and Hoshida, 1958; Lian, 1963; Shiue, 1964).

Apart from the well-weathered, highly leached volcanic soils of Hawaii and Mauritius, very low levels of "available" silica have been reported from Krasnozems (Oxisols?) in Australia by Jones and Handreck (1967). Whereas silica responses for sugarcane, reported so far, are confined to volcanic soils, the Japanese work on rice appears to refer more to soils of the old alluvial terraces—for example, the hydromorphic variants of the Paleustults in Southeast Asia—which have a low cation exchange capacity, are siliceous, and are very low in nutrients. The volcanic soils would probably be classified in the Ultisols or Inceptisols, and the old terrace soils would probably be the hydromorphic members of the Ultisols.

Analytical Assessment of Plant-Available Silica in Soils

A first approach toward assessing plant-available silica in soils, though rather crude, is the total silica determined by fusion. The mean total silica content of 1,300 Hawaiian soils, in which several cases of silica deficiency have been described, is only 28 percent, some soils having less than 10 percent.

From the preceding discussion, it appears that the greater part of the potentially soluble but not immediately available silica resides mainly in the amorphous aluminosilicates. These may envelop the weathering minerals, may partly coat the walls of soil voids, or may merely be precipitated as concretions. This silica is mainly in the polymer form, but fair amounts of monomeric silica may be adsorbed. Loss of soluble silica will obviously be compensated for first by desorption, then by depolymerization, and ultimately by enhanced chemical weathering. Determination of amorphous aluminosilicates may therefore be considered as a means of roughly estimating the silica-supplying power of a soil. Suitable methods have been described (Hashimoto and Jackson, 1960). Quantities of silica thus extracted may amount to several percent.

Although there is no universally accepted method of determining "available" silica directly, the methods of extraction proposed are similar to those in use for the extraction of "available" phosphorus: water, dilute mineral acids, neutral or slightly acid salt solutions, and buffered citrate or acetate solutions (Imaizumi and Yoshida, 1958; Shiue, 1964). Japanese workers have used the amount of silica extracted by normal acetic acid buffered to pH 4 with sodium acetate as a measure of "available" silica. Kawaguchi and Kyuma (1969) stated that silica values of less than 10.5 mg/100 g soil in the plow layer indicate deficiency for rice, and that more than 13 mg/100 g indicates sufficiency.

Systematic studies in Hawaii have shown good correlations between the trichloroacetic-acid-soluble silica in the leaf sheath of sugarcane and the water-extractable or acid–phosphate-extractable silica in soil. This was used to establish standards of "adequacy" of silica in soil and cane leaf sheaths (Fox *et al.*, 1967).

Other more elaborate ways would be the study of soluble silica concentrations in soil solutions extracted at given matric suctions (Jones and Handreck, 1967), or the establishment of cumulative extraction curves indicating the speed at which the available silica reserves of the soil, adsorbed, polymerized, or lattice-bound, restore the silica concentration in the leaching solution.

CONCLUSIONS

It is now well established that in certain soils and for certain crops, especially rice and sugarcane, addition of silicates increases yield. Though some of the increases have been recorded where phosphorus was inadequate, most of the responses have been in the presence of adequate supplies of other nutrients.

There is considerable scope for further research into the role and need for silica in tropical agriculture, but it was rather neglected in the past because deficiencies of other nutrients have limited crop growth and because the large quantities required (the recommended usage is about 7 tons/ha of calcium silicate slag, though not needed every year) would be very expensive to transport. Transport costs may be considerably reduced in the future if manufacturing plants are set up in the countries needing the material, since the raw materials for manufacturing calcium silicates are usually easily available.

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O. P. ENGELSTAD

Fertilizers

Many of the problems of tropical agriculture that relate to fertilizer effectiveness are basically the same as, or similar to, those in temperate regions. The differences are mainly in the degree of severity; that is, the problems that affect the effectiveness of fertilizers in the tropics are often more serious and restricting than their counterparts in temperate regions. In many cases, conventional fertilizers should be satisfactory, in others, new fertilizers or modifications of existing ones may be needed to attain high yields.

Higher cost is a very important obstacle to adoption of any fertilizer modification. This is especially critical in countries where cost of conventional fertilizers is high relative to the price received for the crop. However, this factor is not given priority here, since a "forward look" into the future is desired. Several examples in fertilizer development have shown that costs usually decrease as production increases.

The main objectives of this chapter are to discuss possibilities for new fertilizers or fertilizer modifications of special interest for the deeply weathered soils of the humid tropics and to offer possible solutions to soil fertility problems of importance in those areas. Background information on the historical development of fertilizers

and the chemical characterization of phosphate fertilizers is given in an appendix.

FERTILIZERS FOR SOIL FERTILITY PROBLEMS

Nutrient Losses via Leaching

One of the most serious problems limiting the effectiveness of fertilizers in the humid tropics is the potential for high losses of nutrients through leaching. Heavy rainfall coupled with high percolation rates and low base exchange capacities of the soils would be expected to produce especially serious losses of nutrients.

The chief characteristics of fertilizers that relate to losses of nutrients are initial solubility and reactivity. All conventional nitrogen and potassium fertilizers are water-soluble; the compounds involved are dissolved almost immediately upon application, and the nutrients are then subject to losses, with the exception of forms that are attached to charged sites of clay or organic matter. Whereas losses of ammonium, nitrogen, or potassium are low in most soils of temperate regions, the deeply weathered tropical soils often possess such low cation exchange capacity that significant losses can occur. To reduce the rate of initial dissolution, several approaches have been tried. One is to use a nitrogen or potassium source that has a low rate of dissolution in water. The rate of dissolution of such compounds decreases as the amount of surface area exposed decreases; hence, large particles have a lower rate of dissolution than finer particles. Examples of nitrogen compounds are oxamide (DeMent *et al.*, 1961) and isobutylidene diurea (IBDU) (Hamamoto, 1966). One potassium compound that has some agronomic potential is potassium calcium pyrophosphate (Engelstad, 1968). Of these, only IBDU is being produced in commercial amounts at present.

Another method of lowering the rate of dissolution is to coat soluble nitrogen or potassium compounds with materials that slow or delay the release of the nutrient source. An example is sulfur-coated urea, developed by the Tennessee Valley Authority (TVA) (Rindt *et al.*, 1968). The soluble urea prill is coated with a combination of elemental sulfur, conditioner, microbicide, and wax to reduce the rate of dissolution. The actual rate of dissolution is affected by such factors as soil temperature, placement, coating weight, and imperfections in the coating. Granular potassium chloride has also been

coated in the same process to form a slowly soluble source of potassium.

Other types of coatings that have been tried are plastics or asphalt applied to the prill and the use of perforated plastic bags.

In the process of lowering the release rate by these means, seed or seedling injury and luxury nutrient uptake are minimized. Also, a more uniform supply of nutrient to the crop can be attained; this may, however, require an admixture of uncoated material to provide some initial supply of nutrient.

Another approach to reducing losses of nitrogen is to restrict the process of nitrification—that is, to prevent the biological transformation of ammonium nitrogen to nitrate. In soils where there is substantial cation exchange capacity, this should reduce leaching losses. Several nitrification inhibitors seem fairly effective in small or closed systems. However, in the field it is often difficult to determine any effects in reducing the rate of nitrification. This seems to be a result of high vapor pressure in certain cases. Also, in the tropics, there is some evidence that the relatively high temperatures quickly inactivate these inhibitors (Private communication, National Institute of Agricultural Sciences, Tokyo).

Ammonia Volatilization via Topdressing to Upland Crops

It is a very common practice in the tropics to add some nitrogen at planting time and the remainder as topdressing during the growing season. Topdressing of materials such as urea can result in substantial losses of ammonia to the atmosphere. Such losses can be especially serious when urea or ammonium–nitrogen fertilizers are applied to calcareous soils during periods of high temperature and when the soil is undergoing drying (Terman, 1965).

One precaution that could be taken where irrigation facilities are available is to add water soon after application. This will move the urea into the soil before hydrolysis or ammonia release.

Another approach is to use a source such as ammonium nitrate for topdressing. This source usually suffers relatively little loss of nitrogen as ammonia when applied in this way. Ammonium nitrate has been used infrequently in developing countries because of its potential explosive hazard and possible use by dissident groups. Use of ammonium sulfate or calcium ammonium nitrate may be feasible alternatives that have little or no explosive hazard. Also, these carry secondary nutrients that may be needed.

An additional approach could be that of adding some coated nitrogen fertilizer at planting to supply nitrogen for later crop needs. This would be incorporated, and losses would thus be minimized. Also, there would be less need for later topdressing.

Solubility of Phosphorus Fertilizers

A number of variables influence the effectiveness of phosphorus fertilizers in addition to solubility in water or citrate solutions, or both. Therefore, it is difficult to generalize regarding needed levels of solubility for various crop–soil combinations in the tropics. Soluble phosphorus fertilizers undergo rapid reaction with soil components, forming less soluble precipitates. Some tropical soils "fix" large amounts of phosphorus in less soluble forms–an important problem in many areas. Also, in areas where fertilizer phosphorus is rapidly fixed in unavailable form, higher rates may be needed before crop response occurs.

Research in temperate regions indicates that phosphorus fertilizers applied at planting time should have at least 40 to 50 percent of phosphorus in water-soluble form. This assures an adequate concentration of soluble phosphorus for rapid uptake and early growth stimulation in cooler climates and on alkaline soils. However, in the tropics where the soil pH is quite low, phosphorus fertilizers of lower solubility seem to be effective for many crops. For example, the more reactive rock phosphates with at least part of the phosphorus in citrate-soluble form have been effective in Malaysia, Thailand, and Vietnam.

The TVA has characterized in some detail most of the important rock phosphate deposits of the world. Considerable variation exists in terms of chemical characteristics, citrate solubility, and reactivity with soils. Agronomic research is needed to compare the various rock phosphates found or marketed in the tropics in relation to that of a water-soluble standard such as triple superphosphate. Once adequate agronomic data are available, it should be possible to determine which source would be the most feasible investment in light of transportation costs, delivery price, and other economic considerations.

Other possibilities that might be considered for acid soils are partially acidulated rock phosphate, rock-phosphate–sulfur mixtures, and rock-phosphate–urea mixtures. These can be granulated for convenient handling if they are sufficiently reactive.

Among phosphates of intermediate solubility that could be con-

sidered are the polyphosphates (also called metaphosphates) of calcium and potassium, fused magnesium phosphates, basic slag, and nitric phosphates. Naturally, nutrient content should be considered where transportation distance is considerable.

Some new water-soluble sources of phosphorus may be of interest in relation to tropical soils; these are ammonium polyphosphate and urea ammonium polyphosphate. These sources carry about half of their phosphorus content as orthophosphate and the remainder as polyphosphate. In the United States, they are at least equal in effectiveness to ammonium orthophosphates. They should be tested in tropical soils to determine whether any agronomic advantages over conventional sources might be found.

Efforts to Improve the Effectiveness of Phosphate Fertilizers

Since water-soluble fertilizers react readily with iron and aluminum in acid soils to form less soluble compounds, greater effectiveness from the fertilizer results from reducing its contact with the soil. Thus, banding or spot placement of the fertilizer near the seed provides greater effectiveness per unit of phosphorus. This might be of real importance in those areas where fertilizers are relatively costly.

Another problem is that of approach to application; this might be identified as the question of "crop versus soil fertilization." The banding or spot approach might be called crop fertilization, that is, where relatively low rates are added near the row as a localized placement to restrict contact with the soil. Fertilization of the soil involves much heavier rates of application where the objective is to satisfy the phosphorus-fixing capacity of the soil. The feasibility of this approach would depend on the capital position of the farmer and his particular planning horizon. Agronomic information should be made available to the farmer to help him make such a decision.

Addition of silicate to the tropical soils of Hawaii has been reported to enhance the uptake of fertilizer phosphorus by sugarcane. Apparently, silica can substitute for phosphorus on the reactive sites in the soil, freeing phosphorus for plant uptake. It might be well to test various silica–phosphate combinations in the effort to enhance the effectiveness of phosphate fertilizers. The TVA tested a reaction product of silica and phosphoric acid several years ago and found it to be a satisfactory source of phosphorus.

Research should be conducted in the tropics to ascertain residual effectiveness of various phosphates. It might be that the less soluble

phosphates have a greater residual effect in the soils than the water-soluble phosphates. The citrate-soluble phosphates (water-insoluble) and the rock phosphates might be of interest in this connection.

Secondary and Micronutrient Deficiencies

In many of the highly weathered soils of the tropics, secondary and micronutrient deficiencies are important limiting factors for crop production. In addition to the problem of diagnosis, suitable methods of applying the needed nutrients to correct the deficiencies are involved.

Where calcium and magnesium deficiencies occur, the soil pH is probably low, and applications of ground limestone or dolomite can correct the acidity and supply calcium and magnesium. Naturally, care must be taken in liming tropical soils that are subject to "liming injury." For the most part, addition of ground limestone or other amendments via fertilizers does not supply enough liming material to correct soil acidity. There have been instances in which fertilizers have supplied sufficient calcium and magnesium to correct deficiencies where low soil pH *per se* was not a problem. In fact, part of the benefit of calcium phosphates may be to add needed calcium in addition to phosphorus.

Sulfur may be supplied by adding at least part of the nitrogen or phosphorus requirements by means of ammonium sulfate or ordinary superphosphate. The latter contains a substantial quantity of calcium sulfate, a satisfactory source of sulfur. These fertilizers are low in nitrogen or phosphorus, however, and exclusive use of either would not be recommended in areas where transportation costs are high. Sulfur-coated urea, ammonium-nitrate–sulfate, urea–ammonium-sulfate mixtures, ammonium-phosphate–sulfate, and rock-phosphate–sulfur mixtures are other possibilities; elemental sulfur can also be applied alone or added to fertilizers lacking sulfur.

The micronutrients are a special case. Usually, the amounts required for correcting deficiencies are so low that it is difficult to apply sources evenly. However, micronutrient sources can be incorporated with certain macronutrient carriers. The result is that only a single application of fertilizer is required and the micronutrients are added much more uniformly than if added alone. More details regarding incorporation of micronutrients in macronutrient fertilizers are in the literature (Mortvedt and Giordano, 1967; Young, 1969).

Availability to the plant of the micronutrients when added with macronutrient fertilizer is related not only to their distribution but also to a combination of reactions between the respective sources and between the fertilizers and the soil.

Zinc should receive special mention here. Deficiencies in this nutrient are becoming more common each year in both the developed and developing areas of the world. Both flooded and upland crops are showing response to additions of zinc. More attention must be paid to supplying this nutrient if high crop yields are to be attained.

OTHER SOIL FERTILITY PROBLEMS

Low pH of Subsoils

In many deeply weathered tropical and subtropical areas, low pH in the subsoils is seriously limiting crop yields. The effects of low pH may be expressed as toxic aluminum or manganese or both and possibly as calcium deficiency. The addition of most nitrogen fertilizers aggravates the acidity problem. Since the use of nitrogen fertilizers is increasing generally in the tropics, the associated problem of subsoil acidity can be expected to become more serious over time.

Multiple Nutrient Deficiencies and Imbalances

In many of the developing countries of the tropics, nitrogen fertilizers are being applied almost exclusively, even where multiple nutrient deficiencies occur. This is a result of (1) more immediate, visual response to nitrogen in many cases, (2) the construction of nitrogen-production facilities in-country, (3) importation of phosphorus and potassium fertilizers based on scarce foreign exchange.

Improvement of this situation depends on several factors:

- Indigenous sources of phosphorus and potassium should be found and developed.
- Importation procedures of fertilizers should be improved, to increase efficiency of handling and reduce costs.
- Soil testing services and an up-to-date research program should be developed.
- A well-trained agricultural extension service should be established.

Fertilizer-Variety Interactions

Development of new crop varieties has changed markedly the nature of the yield response to fertilizer nutrients. The yield response curve is now positive in slope over a much wider range in fertilizer application than was true for the older native varieties. Much of this increase in yield can be attributed to greater lodging resistance; thus, heavier rates of fertilizer nitrogen can be applied without causing serious lodging problems.

The development of new varieties and new management systems renders much of the older crop-response data obsolete except in a qualitative way. New experimental programs are needed to obtain data relevant to the changed situation. While farmers' fields will no doubt be used in most cases, modern experimental techniques should be employed for all operations. Improved statistical designs should also be used; these should involve complete replication on each site and at least two nonzero rates of application in addition to a proper control for each nutrient.

Such studies can also be used for economic analysis, thereby extending the usefulness of the data. Where fertilizer cost is high relative to the price of food crops, the economics of fertilizer use will continue to be a very important consideration.

Tests of New Fertilizers

A number of new fertilizers are being developed. It is customary to test these new materials under local conditions to ascertain their effectiveness compared with that of a standard or known nutrient source. To do this properly, several conditions are required:

- A yield response to the nutrient in question should be obtained.
- In addition to a proper control plot, at least two nonzero rates of the nutrient in question should be employed.
- Modern statistical design should be used; this involves at least complete replication on each site—incomplete or partial replication is not satisfactory.
- Good management should be employed in all phases of the experiment. Yields or responses limited by extraneous factors will be of little value. Adequate levels of other nutrients should be assured.
- Provision for measuring residual effects should be made where

nutrient sources are of low solubility or where losses during the off-season are minimal.

- Statistical analysis of the data should be employed; where relevant, economic analysis of data should also be conducted. The most economic source of a particular nutrient for a given area or country might be determined, based on agronomic performance and delivered prices.

Further details on fertilizer evaluation have been published by Terman and Engelstad (1971).

Transportation Costs

In many areas of the tropics, the farm-to-market road system will be inadequate for some time to come. In fact, fertilizer and other inputs must yet be carried in by head load in many areas. Then, too, the cost of transporting fertilizer to the final distribution point is often prohibitive on a per-unit-of-nutrient basis. The nutrient content should be increased toward the theoretical limit as a means of offsetting these difficulties.

The TVA has developed laboratory-scale amounts of some experimental fertilizers of very high nutrient content. Typical grades are 55-92-0 and 11-58-39. Some of these could serve as shipping intermediates, but may require some processing at the market area. Others can also be used in direct application, as their performance is equal to that of conventional materials on a per-unit-of-nutrient basis. While these are still only in very early stages of research and development, the potential for tropical regions is marked.

APPENDIX

Fertilizer Development in the Temperate Regions

Solid Fertilizers

The nutrient content of fertilizers used in all countries was low until relatively recent years. In the United States, for example, a significant increase in nutrient content occurred only after 1930. As a re-

sult of the joint efforts of the TVA and the fertilizer industry in the United States, the average nutrient content ($N + P_2O_5 + K_2O$) of U.S. fertilizers rose from 18 percent in 1930 to over 40 percent in 1968.

Another recent change in fertilizers is improved storage and handling properties. One of the initial obstacles to the use of high-analysis solid fertilizers was the tendency to "set-up" or "cake" during storage. However, with the development of granulation and the use of conditioning agents and moisture-proof bags, these problems were overcome and products are now "free-flowing" in field-application equipment. This aids in a more uniform application in the field and a marked reduction in "dustiness"—a disagreeable problem associated with powdered or semigranular fertilizers. Also, farmers who apply fertilizers by hand prefer granular materials.

Granulation is a fairly recent development in the United States, beginning in the early 1950's (Slack, 1966). Since that time, the shift to production of granular fertilizers has been dramatic, largely as a result of new technology and consumer preference. Single-nutrient and multinutrient materials used for bulk blending or direct application are now almost exclusively granular.

Various clays or other absorbent earths are used as conditioners to improve fertilizer handling and storage properties. These conditioners are coated on granule surfaces and serve as anticaking agents. This prevents the formation of intergranular crystals that seem to be responsible for much of the caking problem (Slack, 1966).

Historically, solid fertilizers have been transported in bags. Recently, however, handling and transport in bulk form have become important. One aspect of handling solid fertilizers in bulk form is the blending or mixing of granular materials at local distribution points or at seaports. This approach to formulating mixed fertilizer is called bulk blending and usually results in both high-analysis mixtures and flexibility to meet consumer demands. The fertilizer can then be applied in bulk form or bagged for further handling.

Distribution in bags has been facilitated by significant improvements in bag construction since about 1945. Moisture barriers of the asphalt type have been improved, and barriers in the form of plastic films or coatings have been introduced. At present, there is a trend toward the use of all-plastic bags that offer almost complete resistance, even to rain, and are competitive in price with multiwall paper bags.

Fluid Fertilizers

Use of fluid mixed fertilizers in solution (commonly called liquid) or suspension form involve variations of the bulk-handling concept. Advantages of these fertilizers are primarily the greater convenience of handling and application as compared with solids, rather than a price advantage. Such problems as caking, dustiness, hygroscopicity, and segregation—common for solid mixed fertilizers—are avoided with fluids. Significant savings in labor costs may be realized.

The nutrient content of fertilizer solutions has generally been low, since most components have limited solubility in water. However, use of highly concentrated superphosphoric acid has permitted substantial increases in the analysis of the resultant solutions. Because of sequestration properties of the pyrophosphates in superphosphoric acid, its addition to relatively low-cost wet-process phosphoric acid prevents precipitation of impurities that would otherwise occur when this acid is ammoniated.

In suspension fertilizers, at least part of the ingredients are not in solution but are suspended with the aid of a small amount of clay. Suspension fertilizers are higher in analysis than are the corresponding solutions. Various micronutrients and pesticides may be incorporated into and applied with suspensions, provided that the ingredients are physically and biologically compatible. Most suspensions, however, should not be stored for long periods because of crystal growth and settling out of the solids.

Development of Fertilizer Use in Tropical Regions

Historically, the total fertilizer tonnage used in the developing countries of the tropics has been very low by temperate region standards. Most of this was imported and used on the so-called estate or tree crops. In view of the recent concern for population growth and food supplies, many developing countries are building fertilizer plants within their borders. Several of these countries are approaching self-sufficiency in nitrogen. While much of the phosphorus and potassium material will be imported for some time to come, it is reasonable to expect that most of the fertilizer requirements of the tropics will eventually be produced there. Urea is rapidly replacing ammonium sulfate as a source of nitrogen in much of the developing world. This shift in sources represents an increase in nitrogen content from 21 to 45 percent. The interest in production of urea in develop-

ing countries stems from its high analysis, low raw material cost, and transportation savings, as compared with other nitrogen sources.

Similar trends are taking place in phosphorus sources. Developing countries have begun importing large amounts of ammonium phosphates; however, as they develop their domestic nitrogen supplies, concentrated superphosphate may become the leading imported source of phosphorus. These sources represent substantial increases in phosphorus content, as indicated in the following tabulation:

Sources of Phosphorus	P_2O_5 Content (%)
Ordinary superphosphate	18–20
Concentrated or triple superphosphate	45–48
Ammonium phosphates	46–48

In addition to an increase in phosphorus content, the ammonium phosphates carry substantial amounts of nitrogen—11 and 18 percent for the monoammonium and diammonium phosphates, respectively. These figures indicate the increases in nutrient content now being realized in many developing regions.

Naturally, these increases in nutrient content represent substantial savings in transportation and handling costs per unit of nutrient, especially important for countries importing most if not all of their requirements. In addition to savings in overseas shipping charges, however, the savings in internal distribution costs must be recognized, especially where highways, rail systems, and storage facilities are inadequate.

Thus, it appears that most of the plant nutrients required in tropical countries in the next decade will be supplied by urea, ammonium phosphate, triple superphosphate, potassium chloride, and various combinations of these.

The grades and ratios of mixed fertilizers should be limited to those that can be justified on agronomic grounds. Low-analysis grades generally should be discouraged. It is easier to control the grades and ratios in the early stages of development of a fertilizer industry and use than after proliferation has taken place. Once grades become established, there is considerable resistance to dropping them. The primary consideration should be to keep the nutrient cost low for the farmer, rather than to provide him with a wide choice of ratios and grades.

The ratios must be decided according to soil and crop needs on a

regional basis. Some allowance should be made for shifts in fertility over time; grades should, therefore, be re-evaluated every few years.

Bulk blending of granular materials has real potential in tropical countries. Blends can be bagged or handled in bulk for transport and application. Any desired fertilizer ratio can be easily prepared near the final distribution point.

From an agronomic standpoint, it matters little whether the needed nutrients are applied separately or as a homogeneous mixture. One exception would be the well-known increase in phosphorus uptake that results from placement of nitrogen with banded phosphorus fertilizer. This is a phenomenon that is important only where phosphorus is banded and where phosphorus fertilizer rates are low. For farmers who are not knowledgeable about plant nutrients, the use of a complete fertilizer (i.e., containing all locally needed nutrients) is more practical than the separate purchase and application of two or more materials. For farmers who are knowledgeable about plant nutrients, separate materials may be a feasible choice, offering possible economic advantages and flexibility in application.

Chemical Characterization of Phosphate Fertilizers

Common nitrogen and potassium fertilizers are water soluble and therefore, pose no problems in initial characterization. Phosphate fertilizers, however, cover the range from zero to high levels of citrate or water solubility; hence, it might be well to describe here the chemical characteristics of phosphate fertilizers. These mainly involve their solubility in various solvents, an indication of the rate of dissolution when applied to soils.

Both water-soluble phosphorus and available phosphorus are used in describing phosphorus fertilizers. In the United States, these two terms are defined by standardized methods of analysis developed and published by the Association of Official Analytical Chemists (AOAC). These standard analytical methods are essential for the successful enforcement of fertilizer control laws.

In the United States, available phosphorus (expressed as P_2O_5) is defined as water-soluble phosphorus plus that fraction which dissolves in neutral ammonium citrate solution. Available phosphorus can also be determined directly by ammonium citrate extraction of the fertilizer sample without determining the content of water-soluble

phosphorus. Fertilizers in the United States are guaranteed according to available phosphorus content as determined by solubility in neutral ammonium citrate solution, but not by their water-soluble fraction.

The methods adopted by the AOAC in the United States for control purposes are also employed in certain other countries. Others determine phosphorus content by dissolution in water (particularly for superphosphates). Determinations in Japan and most European countries are based on dissolution in alkaline ammonium citrate solution. There is evidence that the last method provides a better guide to the agronomic effectiveness of phosphorus in ammoniated superphosphates than does the neutral ammonium citrate method.

Common phosphate fertilizers may be grouped into the following categories of solubility according to AOAC procedures:

1. Water-soluble phosphates—ammonium orthophosphates, ammonium polyphosphates, ammonium phosphate nitrates and sulfates, superphosphates, sodium and potassium phosphates, and phosphoric acids.
2. Citrate-soluble phosphates (water-insoluble)—dicalcium and tricalcium phosphates, basic slag, fused serpentine phosphates, and nonorthophosphates (such as calcium polyphosphate) that hydrolyze to water-soluble forms.
3. Mixtures of 1 and 2—nitric phosphates, ammoniated superphosphates. The water-soluble phosphorus content of nitric phosphate fertilizers varies from 0 to 60 percent of the total, depending on the process and formulation used. Most of the water-insoluble phosphorus is citrate-soluble.
4. Citrate-insoluble phosphates—the bulk of phosphorus in phosphate rocks, "colloidal" phosphates, and some precipitated apatites.

The lines of distinction among these classes are not absolute; sample size, sample-to-extractant ratio, and time allowed for dissolution affect the degree of dissolution.

The degree to which phosphates dissolve in water and citrate solutions indicates to a considerable extent how they react in the soil and how effective they are as sources of phosphorus for plants. However, chemical tests are largely empirical and are not of equal value for all phosphates. Also, they do not reflect soil, crop, and climatic conditions that may affect the use of phosphorus by plants.

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J. K. COULTER

Soil Management Systems

Very broadly, agriculture in the tropics can be divided into a modern sector and a traditional sector. The modern agricultural sector is confined largely to the growing of industrial crops, and only in an indirect way are food crops, e.g., sugar, produced. Plantation crops have been extensively developed in both the equatorial and the monsoon regions. In the modern sector, perennial crops have given annual dry-matter yields as high as 50,000 kg/ha, thus illustrating that there are no ecological barriers to high levels of dry-matter production; such farming systems produce dry matter and utilize solar energy as efficiently as the best agricultural systems in temperate regions.

Traditional agriculture, i.e., the systems with traditional social structures that have not been greatly influenced by scientific advances, supplies much of the food and a substantial proportion of the cash crops of the tropical regions. It includes many types of farmers, from those in a society with virtually no cash income and often with very poor food standards, to those with some innovation and cash cropping, to those who are almost completely cash farmers (Allan, 1965; Jurion and Henry, 1969; Miracle, 1967; Schlippe, 1956; Tothill, 1948; Wills, 1962). Where the soils are very poor, nearly all

the farmers' efforts may go into providing the basic food requirements.

Traditional agriculture includes the systems of continuous cultivation of the irrigated lands of Asia and the Middle East as well as the systems of bush or grass fallowing. Though the term "traditional" may imply a resistance to change, the farmers in this sector do indeed change—for example, by introducing new crops like coffee and cotton in Uganda and cacao in Ghana and by accepting improved varieties of existing crops (Schultz, 1964). Resistance to change appears to be greatest where there is a possible interference with the food supply, obviously the first requirement of the farmer. Thus it has been difficult to persuade farmers to plant cash crops at the optimum date if this conflicts with planting food crops. Farmers are naturally reluctant to introduce expensive new techniques, e.g., the use of fertilizer where the vagaries of rainfall may largely neutralize the benefits. New crops and new systems may be accepted more readily in areas where the rainfall is reasonably well assured or where there are two wet seasons, as in Ghana and Uganda, or, of course, where there is irrigation.

SHIFTING CULTIVATION

Shifting cultivation, the system of farming on many of the soils in the humid tropics, relies on periodic reversion of the land to natural fallow for restoration of soil fertility. It supplies most of the food and many of the other necessities of life for much of the population of Africa south of the Sahara, a considerable part of South and Central America, parts of Asia, and most of the Pacific Islands (Nye and Greenland, 1960). The system has been described by some as the greatest obstacle not only to increased agricultural production, but also to the conservation of forest and soil resources. This is an uninformed judgment of a system that has supplied its practitioners with a modest diet, adequate in starch but deficient in protein; in the past, protein was often supplied by hunting and fishing, but these sources are now greatly depleted by the greater population densities. It would be difficult to substantiate the hypothesis that any better system could have been developed by the cultivators, considering the resources and technology available.

Although the term "shifting cultivation" is used here to cover all the traditional forms of agriculture in which the land is not farmed

continuously, intensities within the system vary greatly. In general, the cultivation period is shorter in forest areas than in savanna areas. Where villages do not shift, for example, there is an element of permanent cultivation in the form of compound or kitchen gardens, which are fertilized by various forms of refuse. The fertility of these compounds is recognized by some farmers, who periodically shift their villages in order to make use of the residual fertility at the old village sites. Rapid urban growth has resulted in areas of permanent cultivation with very dense populations around the periphery of larger towns. An often-quoted example is Kano, in northern Nigeria, where the farming belt, extending for many miles around the town, has a population density of about 500/km^2. Animal manure, household refuse, and night soil are used in this area to maintain a rather low level of fertility.

Thus the term "shifting cultivation" covers a wide range of subsystems (Phillips, 1966). Detailed descriptions by sociologists and geographers in several parts of the tropics indicate that even in similar ecological zones different methods may be practiced by different tribes; the crops may be the same, but the sequence, particularly the length of the resting period, may vary greatly. In Zambia, the Chitemene system needs resting periods of at least 20 years, but in other areas of this country, cultivation is reported to be almost continuous, though this depends on the individual cultivator, his age, the availability of land, and many other social factors. Even so, reports on intensity of cultivation may be misleading; aerial photographs of areas in Malawi, reported to be under permanent cultivation, showed that, in fact, only about half the area was cultivated and even in the most densely populated zones there were uncropped areas.

It is worth emphasizing that, in shifting cultivation, the farmer uses a series of crop sequences, often with a large variety of interplanted crops, and that the system is far more complicated in this respect than the rice-producing system in Asia. Apart from economic and social considerations, there are a number of questions about the system that we cannot answer. For example, is the common habit of planting a mixture of crops primarily a policy of keeping the soil covered, of insuring against adverse weather, or of controlling weeds? Uncertain rainfall also encourages the family to plant the maximum area of food crops, as extensive rather than intensive cultivation insures a more certain return in times of drought.

Because natural fallows are an extensive rather than an intensive way of exploiting soil resources, the system depends on relatively

low densities of population. Such a system has been adequate in the past, but there is no doubt that rapidly expanding populations are bringing it under increasing pressure, relieved to some extent by large-scale migration to the towns. This migration and a change from shifting cultivation toward a cash economy lead to the breakdown of the cohesive community.

A comparison of old and recent aerial photographs show clearly that much of the agricultural production needed by growing populations has been obtained by expansion into new areas, previously little used, or by more intensive use of existing agricultural areas, mainly by reducing the length of the resting periods. The settlement of new areas has been stimulated by disease control and by providing facilities for processing agricultural products and roads for transport. In most countries, however, new areas suitable for settlement are limited and most of these will be used up in the next 20 years, many probably before that. Some of these "reserve" areas may have such poor soils that their retention under the original forest is highly desirable. On removal of the forest, they provide at most 1 or 2 years of cropping before reverting to pernicious rhizomatous grasses that cannot be eradicated by the cultivators' primitive tools (Thomas, 1956).

SOIL FERTILITY UNDER SHIFTING CULTIVATION

Soils in the tropics have a major influence on the agricultural systems, the strongly weathered and well-leached soils usually having low population densities compared with the volcanic and alluvial soils. The largest absolute increases in population have been on the already thickly inhabited soils, but some of the areas have now reached saturation, and even with the aid of modern technology, it is unlikely that they can cope with the foreseeable population increase (Gourou, 1966). Consequently, improvement of marginal lands will assume greater importance in the future, though many of them are reaching a critical population density for their systems of agriculture.

There has been little research to discover what happens to soils under shifting cultivation and, in particular, to find out what part soils play in determining the cropping systems, the length of the fallow periods, and the methods of cultivation. In the forest areas, the organic cycle, which plays a significant role in the behavior of leached and weathered tropical soils, is drastically changed when cultivation is initiated. In these areas, rainfall is abundant, vegetation

is lush, and a high percentage of the nutrients in the ecosystem is cycled through the vegetation; in such areas, the vegetation rather than the soil is the major buffer against leaching losses. In savanna soils only a very small proportion of the plant nutrient reserves is in the vegetation (grass) cycle. Thus, breaking the cycle makes only a minor change in savanna soils but a major one in forest soils.

It is popularly believed that the farmer shifts because of a decline in fertility, though he is not concerned with fertility in a strict sense, i.e., the ability of the soil to supply enough nutrients and moisture to fully utilize the energy at the site (Webster and Wilson, 1966). He is, in fact, concerned with productivity, i.e., yield. Nutrients supplied by the soil obviously play a part, since some sites may be cropped for many years, while others may be cropped for only a year or two. However, the level of nutrients at one site, when abandoned, may greatly exceed that at another site newly opened up. For example, in West Africa, the base status in some areas is higher at the end of the cropping cycle than it is in others at the beginning. If nutrient losses are responsible for the introduction of the fallow period then perhaps low levels of nitrogen and phosphorus are mainly responsible for fallowing (Nye and Greenland, 1960). However, the source of nutrients, particularly nitrogen, in tropical agricultural systems is not well understood. In rice fields, much of the nitrogen may be fixed by blue-green algae, and the average yields, about 800 to 1,000 kg/ha of grain, are close to those of medieval agriculture in Europe and of modern experiments with continuous cultivation on unfertilized plots. The evidence from these experiments suggests that the natural systems are capable of supplying about 20 to 30 kg/ha of nitrogen per year.

In fallow systems, leguminous trees or weeds could supply nitrogen, though the amount of legumes in savanna areas appears to be small. Whether sulfur deficiency, so widespread in savanna soils, plays a part in this is not known. Because there have been so few long-term experiments with continuous cropping, it is very difficult to get an evaluation of the level to which yields will fall. The few experiments that have been done suggest that the fall-off is not particularly dramatic, but soil erosion has been prevented in the small plots, often with some form of grass strip boundary. Control of soil erosion is obviously a major virtue of shifting agriculture; in areas where cultivation has become more or less continuous, erosion may be a serious problem.

Though a decrease in nutrient supply may be one of the reasons, it

is certainly not the only reason and perhaps not always the major one for abandoning land (Jurion and Henry, 1969). Weediness may play a major role; in many communities weeding is done by the women, an already overburdened section of the society, and when this task is beyond them, the area may be abandoned. Felling and burning forest, on the other hand, is done by the men and though regarded by many observers as needing excessive labor, it does in fact appear to be a relatively popular form of work. Determination of fertility of a soil must also take into account biological factors and water-supplying power. There is very little information on the biological changes, e.g., the buildup of soilborne pests and diseases. It is known that monoculture of some crops, sugarcane and bananas, for example, can lead to serious nematode problems, and the sequence of crops and the resting periods in shifting cultivation undoubtedly help to control them.

Physical properties of the soil—its ability to resist erosion, to supply moisture, and to permit good germination—are improved by fallow periods. The resting period, especially under forest, leaves the soil in a very friable state, which is little disturbed by felling and burning since the seeds are usually planted without cultivation. The stumps and boles of fallen timber and the patchwork pattern of the felling protect the soil from serious erosion. Any system of permanent cultivation would eliminate these advantages and must provide alternative means of performing these functions.

Though shifting cultivation has been gradually improved in the Congo, for example, it remains an inefficient system on which to superimpose modern soil management techniques. However, a better understanding of the reasons for shifting is needed in the search for a more efficient replacement. In this respect, it contrasts with irrigated agriculture, particularly rice, where fertilizers, new varieties, and weed control can be imposed upon a comparatively efficient system to make it more productive.

Introduction of Fertilizers

Though many factors must be considered in the development of better farming systems, the nutrient status of soils is one that can be rather easily changed, and it has received perhaps most attention. Fertilizers have obviously made a great contribution to changes in temperate farming, for without an outside source of nutrients, improved varieties and improved husbandry would have had much less

effect. Improved management techniques have brought about the biggest yield increases on the poorer soils and, in general, the greater the productiveness of the farming system, the less the dependence on soil type. At the moment, however, fertilizers are little used in the traditional agriculture sectors of Africa and South America, and even the most optimistic projections suggest that large areas will receive little or no fertilizers within the next decade.

Fertilizers could be imposed on shifting agricultural systems and have been in experiments, but they have not been used much by farmers. Undoubtedly, a more efficient system of agriculture must be developed, probably in stages. There is little information on what constitutes the appropriate stages for the introduction of fertilizers. Spectacular improvements of some agricultural systems have been brought about by the introduction at a strategic time of a single factor that appears to have broken the vicious circle of poor farmers, poor farming, and poor yields, e.g., the introduction of new rice and wheat varieties. Perhaps fertilizers could do the same for shifting agriculture if they could be supplied to the farmer at a cost comparable to that for new varieties. Nevertheless, it has taken even sophisticated farmers a long time to accept fertilizers in adequate quantities, compared with the acceptance of herbicides, for example. This is possibly because the latter is a simple concept. Building up the fertility of the soil is not a simple concept, and it is very difficult to persuade the tropical farmer to look beyond the current year's return, something that is necessary if the vagaries of climate are to be taken into account.

The potential for fertilizers has obviously been well recognized by soil scientists in the tropics, and much time has been spent on fertilizer trials on both experimental stations and farmers' fields. The Food and Agriculture Organization Freedom from Hunger Campaign did some 65,000 demonstrations and simple trials on farmers' fields between 1961 and 1966. In addition, many trials have been done by national organizations in most tropical countries. These experiments have generally confirmed the expectation that, where other conditions—weeds, pests, diseases, variety, and rainfall—are not limiting, nitrogen and phosphorus increase yields of many crops on many soils. More than 90 percent of the Freedom from Hunger experiments have shown responses to nitrogen or phosphorus or both, and sometimes to potassium, although potassium has not always been included in the trials. Though the variability in response has been greater than in the temperate region, a useful picture has emerged

that is valuable at the national level for planning fertilizer production and useful at a regional level for advisory services but that is of little value for advising individual farmers. In some instances, expected responses to fertilizers were not obtained, and this has been attributed to a need for trace elements, to phosphate fixation, and to nonnutrient factors. Such reasons, however, are usually speculative.

Although some of the fertilizer trials have been accompanied by soil analyses, these have generally been devoted to the development of soil testing techniques rather than to basic studies of the effect of fertilizers on the soil, particularly the long-term effects. The attention devoted to soil testing programs by tropical soil scientists is perhaps illustrative of attempts to transfer techniques developed for temperate agriculture to very different agricultural systems, with insufficient attention to the underlying principles. In developed countries, soil testing has been reported as one of the largest single factors in making farmers fertilizer-conscious, but it is doubtful if it could have the same impact on peasant farmers. Though a valuable tool, its application to the promotion of fertilizer use in tropical soils requires a much improved understanding of these soils.

Fertilizers presently available have been developed almost entirely for nontropical farming. But the leaching of soluble nitrogen and potassium fertilizers, the fixation of phosphate, the need for organic matter, the need for trace elements, and the ease with which deficiencies of major or minor elements can be induced by fertilizers—all emphasize the difference between nontropical and tropical soils. These problems require a great deal of adaptive research before satisfactory systems can be evolved for tropical soils.

Obviously the productivity of many tropical areas can be improved, even without fertilizers, but soil fertility will limit yields without an input of fertilizers. For social and political reasons, development of new management systems for the marginal soils of many parts of the tropics is of high priority, and it is the soil scientists' task to provide the concepts on which these systems can be based.

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Soil Testing and Soil Fertility Evaluation Services

Soil testing programs and services for the purpose of advising farmers about soil management are widely used in many countries. An increasing emphasis is being placed on many of these programs, which vary markedly in organizational structure and in services rendered. They may function as an agency of government, as an arm of industry, or as an independent service unit. Those that are concerned with soil fertility and crop production (soil fertility evaluation and improvement programs) serve to advise farmers in the proper use of fertilizers, lime, and other soil amendments. The Committee has discussed this topic at some length, and what follows is a consensus of the Committee's views on the subject.

PROGRAMS FOR SOIL FERTILITY EVALUATION

Soil fertility evaluation and improvement programs are essentially organizational vehicles that function to implement the practical use of an extensive body of soils research knowledge. Such programs are concerned with (1) the summarization, organization, and evaluation of existing information on soils and crop production in particular

service areas, (2) the techniques and procedures for evaluating fertility and productivity problems at specific field sites, (3) the development of correlation procedures to employ the general research information in the solution of individual site problems, and (4) the development of research, analytical, and educational services to implement the coordinated use of the information. Such programs make the best use of the accumulated knowledge when they direct its application to the solution of problems on individual field sites that include excesses as well as deficiencies. The program operations, therefore, eventually should provide techniques for making field site evaluations followed by systematic procedures to ascertain the site needs for management in the light of all relevant research information.

Soil fertility evaluation and improvement services need to give advice and make recommendations for fertilizer use and soil management that are site- and situation-specific, because soil fertility and productivity conditions vary considerably between geographic areas and among farms and fields in the same soil area. As a consequence of this situation, general and regional fertilizer-use recommendations result in the most profitable practices for not more than a small segment of the farm and field situations. For another segment, such general recommendations may be entirely unprofitable. For the remainder of the field situations of an area, general recommendations may result in some profit from the use of fertilizer but not nearly as much profit as could be obtained by site-specific practices. Formulating and employing soil management and crop production programs that are site- and situation-specific will result in the best and most profitable uses of the land and fertilizer resources.

SOURCES OF SOIL FERTILITY INFORMATION

The information on which soil fertility advice is based is generally obtained from two sources—site-specific information and general information. The site information is derived from the analyses of a soil or plant sample, or both, from the field site in question, along with a record of the relevant past management practices and an appraisal of the management capabilities of the farm operator. The general information comes from research experiences on similar soils and crops in the surrounding or similar areas that are applied to the specific site through systems of soil classification. The value of the services de-

pends in large part on (1) the quality of the soil sample obtained from the site, (2) the accuracy of the analyses made on the sample, (3) the excellence of the supporting research, and (4) correlating procedures employed to relate the general research information to the problems of the specific site.

For soil fertility services to be useful in improving the productive capacities of soils and in making maximum economic use of the soil resources, they must be parts of broad programs that contain adaptive research as well as educational components and service functions. The research components are essential for several reasons. First, the results from soil and plant analyses are meaningful and useful in making fertilizer use and soil management recommendations only after they have been correlated with actual crop responses to fertilization under field conditions. Second, many factors in soil management and crop production are experiencing continual change, which results in the creation of new problems that need attention and in new and progressively higher levels of expected production. Third, developments in methodology and in instrumentation require research and testing in order for the analysis services to be most efficient and accurate and to keep pace with a rapidly changing agricultural technology.

OPERATION OF SOIL FERTILITY SERVICES

The service and educational phases are interrelated and are frequently handled or coordinated by a single agency. For purposes of discussion and evaluation, these phases can be divided as follows:

A. Service phases

1. Sampling field soils, the logistics of transporting and processing samples, and sample information and procedures to efficiently expedite the flow of reports from the advisory agencies to the farmers
2. Analyzing soil and plant samples, which includes methodology and laboratory organization and management
3. Interpreting the results of soil and plant analyses and making fertilizer and other soil management recommendations based on laboratory results, other specific field site information, which includes management history; the crop to be grown; the anticipated maximum yield; the kind of soil and research experience on similar

soils elsewhere; the management capabilities of the farm operator; and the local economics of production of the crop to be grown

B. Educational phases

1. Conveying information to farmers and other users of the services on how the program operates, on the importance of good soil sampling and handling techniques, and on the technical and economic impacts on crop production of fertilizer use and other soil management practices
2. Keeping the administration and other officials informed about the operation and functions of the program
3. Training technical personnel in the several phases of program operation

Sampling of soils and plants is still a major problem in the operation of a soil fertility assessment service. This phase could probably be improved more by education than by research. However, some research in sampling is still needed.

While instrumentation and laboratory operations in soil analyses need to be improved, they are far better developed than other phases of the program. There is not much need for a major research input into the analysis phase until such time as the other phases have been improved.

Calibration of data from soil analyses with field responses to the addition of nutrient elements needs much more research attention. Likewise, experimentation that permits an evaluation of the economics of fertilizer use is required. These kinds of research need to be stressed in tropical regions in order to implement soil fertility assessment services effectively.

USE AND LIMITATIONS OF SOIL FERTILITY EVALUATION SERVICES

In research relating to soil fertility assessment services, it is important to understand the relative value of soil analyses and how they may be properly used in assessing the fertility needs of farmers' fields. Soil and plant analyses are only one source of information and, in general, are of maximum value when combined with a wide spectrum of other information and research data. The yield of a crop is a function of the soil, the crop, management practices, and the en-

vironment for growth (chiefly climate). Analyses of soil samples only provide some site-specific information on the soil in question. Other essential information on the crop, management, and the environment would determine what modifications could profitably be made on the soil site in question.

Soil fertility evaluation services are essential to good fertilizer use practices in all areas where fertility and productivity factors vary among local soil sites. These areas include most arable soil regions of the world. Very few soil areas in the world have uniform fertility. In most instances, fertility and productivity vary among farms and fields and between contiguous soil mapping units. Also, productivity often varies markedly among sites within soil units because of management and other factors. Under these conditions of soil heterogeneity, soil fertility evaluation services have and will continue to have widespread utility in helping farmers adopt good soil management practices.

At the onset of establishing a soil fertility evaluation program, only a small percentage of farmers may use the services. In situations where service programs are initiated with a minimum of facilities and supporting research, the program should contain provisions to develop and acquire the necessary background and correlation research data.

The success of soil analyses as a tool for advising farmers on fertilizer management depends heavily on efficient educational services that can reach significant segments of the farmers. These educational services may come from extension organizations, from agricultural credit agencies, from agents of industry, or from other rural service organizations. Usually, several agencies perform educational functions in any single agricultural area.

Reliable soil and plant samples can be obtained if the educational services function properly; results of the analyses and the accompanying fertilizer management recommendations can be rapidly and effectively conveyed back to the farmers. It is difficult for soil fertility evaluation programs to make a significant impact on farmers of an area in the absence of educational and advisory services.

Appendix: Summaries of Country and Regional Reports

Members of the Committee and professional associates prepared reports on the status of tropical soils research in selected countries or regions. Since it was not feasible to publish the complete reports, the Committee has included in this volume brief summaries that were either prepared by or approved by the authors. A limited number of copies of each report have been reproduced and may be obtained upon request to the author of the report.

Summaries of the following reports are presented:

Soil Studies in Tropical Latin America
Soils of Malaysia
Soil Studies in French-Speaking Tropical Africa
Soils Research in Nigeria
Soils Research in Tanzania
Soils Studies in the Republic of the Congo (Kinshasa)
Soils of Central Africa
Soils Research in Hawaii

SOIL STUDIES IN TROPICAL LATIN AMERICA

A. Van Wambeke

The review is divided into three parts. Part 1 describes the soil survey methods currently being used in tropical South America, Central America, and the Antilles. The descriptions of classification and mapping procedures include coordinate systems (symbolization of soil properties), subdivisions into Great Soil Groups, and surveys based on soil landscapes. Use of the USDA soil series system is discussed. The various types of soil survey interpretations for direct agricultural purposes, as used in Latin America, are explained. Several types of maps are shown, and a list of 125 references classified by countries completes the first part of the report.

Part 2 summarizes soil fertility investigations conducted between 1960 and 1970; most relate to the low humid tropics. The results of experiments in Brazil, Bolivia, Central America, Colombia, Peru, and Venezuela are reported. A review is presented of nitrogen studies, including the effects of clearing and the cultivation of virgin lands. Responses to nitrogen fertilization under different soil and climatic conditions are reviewed. The work on symbiotic and nonsymbiotic nitrogen fixation is discussed, as is the use of organic residues and the effect of legumes in supplying nitrogen to the crop that follows. Various studies on soil phosphorus are summarized, including fractionation, fixation, and effect of liming. Investigations are being conducted on responses to different sources of fertilizer phosphorus, including residual effects. Methods of diagnosing phosphorus needs with different crops on different soils are being tested. The work on responses to potassium fertilization, liming, and sulfur is reviewed.

Part 3 reports on investigations related to soil physics. Effects of clearing the natural vegetation on the temperature of the surface soil have been measured in a few locations. The effects of temperature on nitrogen fixation and root growth are discussed. Soil-moisture measurements at 1/3 and 15 atmospheres have been made on a number of Latosols. The effects of cropping with machinery on the physical properties of soils are reviewed, and studies on the effects of organic matter, iron content, and liming on different soils are cited. Water intake and infiltration as affected by cultivation are discussed. It is suggested that the combination of very high erosion index, low erodibility, and steep slopes calls for adaptation of the soil-loss equation of Wishmeier and Smith to tropical conditions.

Evapotranspiration balances according to Penman-Bavel, Thornthwaite, and Blaney and Criddle have been calculated for several tropical stations. Provisional tables for certain regions assist in predicting the suitability of a particular soil-moisture regime for a particular crop.

The three parts of the report total 134 pages and have 261 references.

SOILS OF MALAYSIA

J. K. Coulter

A reconnaissance soil survey of the whole of West Malaysia and parts of East Malaysia has provided the framework into which more detailed soil surveys have been fitted and has stimulated work on such surveys for agronomic use. A land-use survey of West Malaysia, based on aerial photographs, has given the country an accurate inventory of the areas of important crops.

Research in Malaysia has shown that the fertility stored in forest soils, mostly in the organic matter, in areas of highly weathered and highly leached soils is extremely important for rubber and oil palm in the first planting cycle. The need for additional fertilizers in subsequent planting cycles has been amply demonstrated. With fertilizers, dry-matter production by permanent crops shows about the same efficiency of use of solar energy as is shown by annual crops in temperate areas, though it not as good as some forest crops in temperate areas. Well-grown legumes can fix considerable quantities of nitrogen, of the order of 200 kg/ha/yr. However, growth is possible throughout most of the year in Malaysia, so the efficiency of fixation appears to be about half that of legumes grown in temperate areas, which fix around the same amount over a much shorter growing period.

Compared with temperate soils, many Malaysian soils can be described as "fragile," and experience with fertilizer use on rubber and oil palm illustrates the great importance of the interactions of nutrients on poorly buffered soils. Thus, magnesium is necessary where ammonium sulfate and potassium are being applied to such soils and may be more important than calcium for several crops where other fertilizers are used intensively. Similarly, trace elements ordinarily are needed only when other fertilizers are being used. In the poorly

buffered soils, leaching is related to the type of anion in the fertilizers. Acidification by ammonium sulfate and loss of calcium are pronounced, so the use of other fertilizers that will supply calcium, for example, rock phosphate, is important.

Crops in Malaysia appear to differ greatly in their tolerance of different levels of soil fertility. Tree crops like rubber and oil palm and also legumes can grow at phosphorus levels at which maize makes no growth. Retention of phosphate varies, but laboratory measurements do not always agree with field experience. Laboratory measurements may not indicate the residual values of phosphorus fertilizers.

Malaysia has considerable areas of peat and acid sulfate soils, and the agronomic problems of the former and the chemistry of the latter require further investigation. Investigations already completed have indicated that with proper management, especially of the water table regime, they can be made productive.

The report is 82 pages long and has 135 references.

SOIL STUDIES IN FRENCH-SPEAKING TROPICAL AFRICA

J. Boyer

Most of the cultivated soils in French-speaking tropical Africa are either Sols ferrallitiques (Oxisols) or Sols Ferrugineux tropicaux lessivés (Paleustalfs). Some other soils, generally fertile, are Sols bruns eutrophes tropicaux (Eutropepts) and Andosols (Andepts), which occur in limited area in Guinea, West Cameroon, Madagascar, and the northeastern part of the Ivory Coast. Vertisols occur in Upper Volta, Mali, and Chad. Hydromorphic soils (Aquepts) are found in the Ivory Coast and Madagascar, where they are primarily used for rice; sometimes when drained they are satisfactory for banana culture.

The physical properties of the soils are important in determining soil fertility, particularly in relation to soil moisture and root penetration. Among the major problems is the large textural difference between the surface and subsoil horizons (at a depth of less than 80 cm). Subsoiling or deep plowing is a possible remedy for this problem. Another possible reason for poor fertility in the Sols ferrugineaux tropicaux lessivés is the very fine texture, not clayey, of the surface horizon. Deep plowing, which forms a cloddy structure, gives good temporary results. The massive structure of Vertisols may be

improved by incorporating organic matter, thus facilitating root penetration.

Nitrogen fixation by legumes and nonsymbiotic nitrogen fixation have been investigated in only a few studies. Ammonification is more limited than nitrification in dry areas or in very acid soils. Responses to applications of nitrogen fertilizers are favorable in most cases. However, the response depends on the crop, the level of soil nitrogen, and the soil pH. Ammonium sulfate often has a more favorable effect because of the sulfur deficiency of the soils but has an undesirable acidifying effect when large amounts are used. The acidifying effect can be corrected by liming where the soil is excessively acid. This has not been studied much, but it is essential to emphasize that these possible problems have been overestimated. In African cultivation systems, the advantages of liming are due in part to the upward movement of bases during the long fallow period. Liming is not recommended except for certain crops such as bananas or cotton or where excess acidity results in manganese or aluminum toxicity or a deficiency of calcium or trace elements.

From research studies in tropical French-speaking Africa, it appears that the level of available potassium is adequate for the usual crops. However, some sandy ferrallitic soils (psammentic Haplustox, Hapludox, and oxic Psamment) are very deficient in potassium. Under cultivation, leaching of potassium from the soil is increased; in ferrallitic soils (Oxisols) 50 to 60 percent of the applied potassium can be leached. The acidifying effect of the chloride and sulfate anions is not negligible.

The effect of soil phosphates on soil fertility seems to be related to other factors, such as pH and the amount of total nitrogen. In ferruginous soils (Paleustalfs) and ferrallitic soils (Oxisols), iron is largely free and can fix phosphorus in a form less available to plants. No satisfactory solution has yet been found to the problem of selecting the most effective phosphate fertilizer to apply to major crops that have exacting requirements for this element (for example, cotton, cacao, rubber, corn, and rice). French-speaking pedologists and agronomists have stressed the importance of the equilibrium in the soil between phosphorus and nitrogen and, secondarily, the interactions between phosphorus and sulfur and between magnesium and potassium. Soluble phosphate fertilizers appear to be effective, principally in ferrallitic soils (Oxisols). Their residual action (2 years) is measureable.

Studies of French-speaking researchers indicate that the soils of

the tropical regions of Africa often are deficient in sulfur. This is particularly important in tropical leached ferruginous soils under savanna (Paleustalfs). A sulfur-to-nitrogen equilibrium of 1:10 seems satisfactory in these cases.

Very little is known, in spite of some recent work, especially by ORSTOM workers, on the amount of trace elements in tropical soils and their dynamics. Certain studies are under way. A few investigators have studied the effect of the interactions of some of the trace elements on crop yield chiefly in the case of deficiencies: boron in palm tree culture as well as with cotton and banana; molybdenum with legumes; copper and zinc with banana on peat soils (Histosols) after liming. Manganese toxicity has been studied in very acid soils in the Ivory Coast, Chad, and the Congo. Direct toxic effects of excess levels of aluminum and iron are rare. Deficiencies of silica have seldom been described, except in Madagascar and Polynesia.

Agricultural methods modify soil characteristics by changing the soil climate, soil physical properties, decomposition of organic matter, dynamics of mineral elements, and leaching and erosion conditions. Some long-term studies are in progress in tropical French-speaking countries, including Senegal, the Ivory Coast, Chad, and Madagascar. These studies are cumbersome but indispensable. International cooperation for this type of research, which is essential for worldwide efforts in the conservation and rational use of natural resources, would be desirable.

The report has 175 pages and 535 references.

REVIEW OF WORK ON NIGERIAN SOILS

H. Vine

A comprehensive and detailed presentation of soil research related to oil palm and cocoa production is given in this report. The analytical values of 27 soil profiles are some of the most complete that have been made on tropical soils. The manuscript is divided into two parts: (1) soil studies related to oil palm research, and (2) soil studies related to cocoa production.

Soil Studies Related to Oil Palm Research

There are 100 pages devoted to the descriptions and analyses of 18 individual soil profiles. A general description is given of the different

horizons of most of the profiles. Several profiles are described in more detail. The analytical values of the different horizons of each profile consist of the following: mechanical analysis, organic matter and nitrogen, pH, cation exchange capacity, and exchangeable bases.

Variations in the surface layer, which ranged from 5 to 10 cm deep, were as follows:

Mechanical analyses. Most of the soils were coarse-textured. The clay and silt contents of 11 soils ranged from 10 to 19 percent; 5 ranged from 20 to 30 percent; and one was 70 percent.

Organic carbon. Most of the soils were low in organic carbon. One soil contained less than 1 percent; 6 ranged from 1.0 to 1.5 percent; 5 from 1.6 to 2.0 percent; 4 from 2.0 to 4.0 percent; and one contained 4.68 percent.

pH Values. One soil had a pH value of 3.6; 10 ranged from pH 4.0 to 5.0; 4 from pH 5.0 to 5.7; and 3 from pH 6.0 to 6.6.

Cation exchange capacity. Most of the soils had relatively low exchange capacities. The exchange capacities of 5 soils ranged from 4.0 to 5.9 meq/100 g of soil; 4 ranged from 6.0 to 7.9 meq/100 g; 4 from 8.0 to 9.9 meq/100 g; and 5 from 15.6 to 18.1 meq/100 g.

Degree of saturation with bases. Only 3 soils were less than 10 percent saturated with bases; 5 ranged from 10 to 20 percent; 2 from 20 to 40 percent; 5 from 40 to 60 percent; and 2 had degrees of base saturation equal to 80 percent.

Selective mineralogical analyses indicated that kaolinite was the dominant clay mineral. Montmorillonite was present in moderate amounts in poorly drained soils and in small amounts in well-drained soils. Gibbsite was present in small amounts in only one profile. Illite was dominant in one profile.

The statement was made that the percentage of humus in the topsoils is strongly influenced by the protective action of clays, in that clay–humus complexes are formed that are relatively resistant to microbial attack.

The results of a number of fertilizer experiments with nitrogen, phosphorus, potassium, and magnesium are reported. Calcium–potassium interactions were found. Soil analyses of available nutrients were made. The available phosphorus was determined by five methods.

The effect of burning in the soil management system was studied. Cover crops and intercropping were studied in conjunction with

burning. Burning conserved the sodium and potassium in the soil but was responsible for losses of calcium and magnesium.

Soil Studies Related to Cocoa Production

Soil physical properties, including mechanical analyses, soil moisture values, bulk densities, and porosity relationships, are reported for 9 soil profiles. These data are some of the most comprehensive that have been reported for tropical soils.

The clay and silt content ranged from 9.9 to 50.3 percent, organic carbon from 1.86 to 2.62 percent, field capacity from 15.3 to 31.8 percent, available water content from 10.5 to 17.4 percent, and bulk density of the surface layer from 1.0 to 1.40 g/cc. In all profiles, the bulk density of the subsoil was as much as 0.5 g/cc more than that of the surface soil. In one profile, bulk density ranged from 1.36 in the surface layer to 1.86 in the subsoil, indicating a rather dense subsurface horizon. The aeration porosities exhibited similar trends. They ranged from 15.4 to 42.6 percent by volume. The differences between the aeration porosity of the surface layer and of certain horizons in the subsoil ranged from 8.8 to 35.1 percent.

The complete report has 130 pages and 72 references.

SOILS RESEARCH IN TANZANIA

P. H. Le Mare

Tanzania comprises the mainland country of Tanganyika and the islands of Zanzibar and Pemba. The review deals largely with Tanganyika and has 76 references.

The most important arable soils are nonlaterized red and yellowish soils derived from metamorphic rocks and granite. These soils cover much of the Tanganyika plateau at 900 to 1,200 m. They are acid and have low cation exchange capacities, and their primary deficiencies for crops are nitrogen and phosphorus. The more productive soils are immature soils on volcanic ash and lava in the north around Kilimanjaro and in the southern highlands.

Important food crops are maize, groundnuts, beans, sweet potatoes, cassava, rice, wheat, and bananas. Crops grown for export are cotton, coffee, sisal, cashew nuts, and tea.

Nitrogen deficiency occurs in most crops throughout the country. In sisal cultivation, a leguminous cover crop between the rows is

particularly effective in low-nitrogen soils. Phosphorus deficiency is widespread; a need for phosphate fertilizer has been demonstrated, particularly for maize and cotton. There is need for lime on many sisal estates. Elsewhere, there has been little experimental work on liming, but there is evidence of an increasing need in cotton production, especially as more ammonium fertilizer is used. Sisal is the main crop requiring potassium fertilizer. As productivity in other crops improves, potassium deficiency is likely, and some instances have been observed.

Boron deficiency is incipient in many areas, and it limits production in a few places. Sulfur deficiency is rarely a limiting factor but would be if sulfur-free nitrogen and phosphorus fertilizers were used.

In estate agriculture (mainly sisal), cropping and cultivation systems are well understood; but in peasant agriculture, soil erosion is not adequately controlled in many areas.

SOIL STUDIES IN THE REPUBLIC OF THE CONGO (KINSHASA)

A. Van Wambeke

The review of soil studies carried out in the Congo (Kinshasa) until 1960 deals with soil survey, soil survey interpretation, and soil properties that were considered important for plant growth. The report is limited primarily to research related to the production of food crops in the low humid tropics. No use was made of the extensive literature on plant nutrition of industrial tree crops not specifically related to soil factors.

One fifth of the Congo (50 million hectares) is covered by soil maps. A soil classification system has been developed by Sys and coworkers. The basic principles were summarized by Tavernier and Sys in 1965. Soil survey interpretation was based on soil properties and the characteristics of the vegetation. Generally, only broad land-use classes were considered.

The change in soil fertility after clearing and during cropping, the mineralization of organic matter, and the need for shifting cultivation as related to the nitrogen cycle are discussed briefly; the investigations of Laudelout were the main references. It was found that inoculation of legumes was beneficial, provided that the soil was deficient in nitrogen, that crops were adequately supplied with calcium and phosphorus, and that the specific *Rhizobia* were not pres-

ent before inoculation. Little work has been done on nonsymbiotic fixation. Investigations have been initiated on retardation of nitrification to avoid rapid leaching of nitrates. Ammonium sulfate increased the exchangeable aluminum content of soils.

Phosphorus in slowly soluble forms was less efficient than superphosphates in the highly weathered soils of the Congo basin. Residual effects of phosphorus fertilizers were observed. Manganese deficiencies occurred in volcanic ash soils high in organic matter, at a pH above 6.4. On forest Oxisols, crop response to liming that raised the pH only from 4.2 to 4.5 was good. Potassium deficiencies appear only 3 or 4 years after the forest has been cleared. Application of sulfate-containing fertilizers lowered the pH in the subsoil; calcium and magnesium suffer some losses through leaching; potassium was not fixed in a nonexchangeable form.

The report has 13 pages, 1 map, and 17 references.

SOILS OF CENTRAL AFRICA

J. K. Coulter

Small-scale schematic soil maps have been made of Zambia, Malawi, and Southern Rhodesia, but comparatively little of the area has been covered by detailed maps. The reconnaissance soil surveys indicate that Central Africa has extensive areas of highly leached, sandy soils with very low cation exchange capacity. Population density is still relatively low on these poor soils but has reached a high concentration on the better soils, some of which are now under almost continuous cultivation.

Maize, groundnuts, tobacco, and cotton are the more important crops of the region and time of planting was shown to be very important in determining production. Yields of late-planted maize and groundnuts may be only one third of those planted early, but the reasons for lowered yields have not been elucidated.

Applications of nitrogen produce large increases in yield; in most crops responses to phosphorus and potassium are less frequent. Sulfur deficiency is widespread, and maize and tea have given spectacular responses to added sulfur. Calcium deficiency in groundnuts leads to production of many empty shells. Deficiency of boron is the most widespread trace element deficiency, cotton and eucalyptus being the most susceptible.

Manganese toxicity is regarded as a potentially serious problem in some of the more acid soils with a high clay content. Mobility of manganese is accentuated by intense drying followed by wetting, by waterlogging, and by placing superphosphate in bands or pockets.

Many of the soils of Central Africa have a weak structure, easily destroyed by heavy rain, and they are thus very susceptible to erosion. Bulky organic matter, establishment of a good plant stand, and close planting can ameliorate this condition. Leaching is a problem on sandy soils, and nutrients applied in fertilizers, not quickly taken up by plants, are lost. Sulfur and calcium as well as nitrogen and potassium disappear rapidly from the topsoil.

On poor soils, fertility can be built up by using fertilizers and farmyard manure, but maximum yields may not be obtained for several seasons.

The complete report has 36 pages and 66 references.

SOILS RESEARCH IN HAWAII

L. D. Baver

The contributions of Hawaii are outlined in succinct form and are accompanied by 38 references that are relevant to the following topics:

Soil survey of the Hawaiian Islands
Soil morphology and development, mineralogy, and colloidal properties
Cation and anion adsorption and exchange
Extractable aluminum
Liming tropical soils
Phosphate availability in tropical soils
Potassium relations in tropical soils
Soil nitrogen
Trace elements
Soil analyses for fertilizer recommendations
Evapotranspiration and soil moisture

The major soils of Hawaii are the Low Humic Latosols (Oxisols), Humic Latosols (Inceptisols), Hydrol Humic Latosols (Inceptisols), and Humic Ferruginous Latosols (Ultisols). The important minerals

and oxides of the soils are given, along with the genesis of Low Humic and Humic Ferruginous Latosols. Allophane–kaolin transformation and the colloidal properties of the amorphous fraction are outlined. The cation exchange properties and degree of base saturations of the Latosols are presented. Specific attention is called to the impact of anion adsorption on colloidal properties. Liming is treated as it relates to extractable aluminum, phosphate uptake, leaching of potassium, mineralization of soil organic nitrogen, and calcium as a nutrient.

Phosphate fixation is related to clay mineralogy and the amorphous nature of soil colloids. The retention and leaching of potassium in soils are covered. The importance of mineralizeable nitrogen to the growth of sugarcane is emphasized.

Studies of trace elements have related to manganese, zinc, and silicon. The first experiments that suggest that silicon deficiencies occur in certain tropical soils are cited. Soil analyses for mineralizable nitrogen, available calcium, potassium, and phosphorus are used extensively by the sugar industry.

Both evaporation pans and the resistance of gypsum blocks have been used to pinpoint the water requirements of the sugarcane plant. Yields of sugar were highest when soils were irrigated at a moisture content equivalent to an evapotranspiration-to-pan evaporation ratio of 1:1.

This report is in outline format and contains 17 pages and 38 references.

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