July 1973 Tech. Bul. No. 219

A Review of Soils Research in Tropical Latin America

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Foreword

North Carolina State University, through the Soil Science Department, entered into a contract on June 30, 1970, with the Agency for International Development, through its Technical Assistance Bureau, to implement a program on "Agronomic-Economic Research on Tropical Soils". (Contract AID/csd 2806). The broad objective of this five-year contract is to provide relevant information to supplement and complement the programs of another activity of the University that is supported by AID, The International Soil Fertility Evaluation and Improvement Program.

Recognizing that the first step in any soundly developed research program is a thorough knowledge of the existing information on the subjects under consideration, the first phase of the program was designated for a review of the pertinent literature. The specific objective of the review was to provide a factual base for an analytical interpretation of the present information and future needs relevant to the characteristics and management of tropical soils for crop production.

The details gleaned from published research reports and supplemented by personal experience in Latin America have enabled the reviewers to prepare summaries related to various topics in soil science that are making useful contributions in developing plans for specific research projects in the region. We believe the report can be useful also to others with a similar interest.

C. B. McCants, Head
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Preface

The purpose of this publication is to compile the available literature on soils research in the American Tropics. This area comprises all countries of Latin America and the Caribbean excluding Argentina, Chile and Uruguay. Through an arrangement with the North Carolina Board of Science and Technology, a search was made of Biological Abstracts for work in the region. Approximately 1,000 abstracts were obtained on research published since 1960. These abstracts were coded according to a keywork list previously prepared and entered in a computer-based storage and retrieval system. Additional materials were obtained from Tropical Abstracts, the Latin American Bibliography of Agriculture and the authors' personal files.

The format adopted consists of citing only representative or crucial references in the body of the review, and citing all the reviewed materials in the bibliography.

The authors are aware that many worthwhile research publications are not included because these are not readily accessible to libraires and abstracting journals.

Emphasis was placed on the main food and feed crops of Tropical America grown in small and medium-size farms. Whenever possible, the literature was reviewed by the generalized soils areas outlined in the first chapter. Literature from other tropical regions and elsewhere was cited where considered relevant.

It is the hope of the authors that this publication results in an adequate synthesis of the present status of soils research in the region, and that the suggestions for future research priorities will be of use to Latin American soil scientists. A Spanish version of this bulletin is also available.

Pedro A. Sanchez, Editor
June, 1972

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CHAPTER 1
Soil Genesis, Morphology and Classification

Stanley W. Buol[1]

The multifacited approaches to soil characterization that have been used in various parts of the world create problems in ascertaining data usable for over-all evaluation.

Whereas, generalized theories relating soil morphology and composition in gross terms of the climate, parent material, age, etc. are vital for the growth and development of the science of pedology, such generalizations are of limited help in understanding the agronomic-economic problems associated with the existing soil conditions. However, when relationships of soil properties to soil forming factors are understood and correctly related to the situation to be studied, they offer savings in analytical costs because of the extrapolation afforded by these associations. However, some "ground truth" data must be gathered in almost every situation in order to validate extrapolation via genesis theory.

A continuing need is seen, both to generate more soil characterization data in conjunction with maps and other devices for associating this data with areal distribution on the landscape and to continue research to establish associations of cause and effect in the governance of soil properties therein facilitating extrapolation of results at minimum cost.

Generalized Soil Areas in Tropical America

When the tropics are defined as those points on the earth lying between the tropics of Cancer and Capricorn, there is only one characteristic that is totally applicable. This is the nearly uniform temperature of the soil profile, at depth, throughout the year. Simply, the variation of temperature taken at 50 cm below the top of the ground is less than about 5°C from summer to winter. This temperature will be within a few degrees of the mean annual air temperature and thus may be very hot, near 30°C in lowlands and very cool in permanent frost environments on the intertropical mountain peaks of the Andes in Central and South America. But, whatever the temperature, it has little seasonal variation in contrast to temperate zone soils.

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The following general areas are delimited in an attempt to illustrate the major areas of concern in tropical Central and South America.

Savannas of infertile soils

This condition is best characterized in the Cerrado of Brazil and the upland Llanos of eastern Colombia. Soil conditions of low fertility, often complicated by high iron and aluminum contents are prevalent. A dry season of at least 2-3 months or more is experienced in these areas. These areas have smooth topography and deep friable soils. The limited use of these areas may be attributed to almost total inadequacy of these soils, except for scattered high base status areas, to support primitive (no fertilizer) agriculture. Thus there is low intensity of inhabitation in most areas except for local occurrences of high base status soils such as the Eutrustox areas of the Brazilian Cerrado.

Tropical rain forests

Vast areas of sparsely populated jungle exist in the Amazon Basin. Infrastructure of transportation has been limited almost entirely to rivers, although major road building efforts are currently underway. Soil conditions in these areas are not well documented. Conflicting reports and personal examination in part of this area in eastern Peru leads us to hypothesize that some of these soils are relatively fertile. Since almost all reports are confined to areas of close proximity to rivers, there is a strong probability of bias in the information.

Mountainous areas with soils of volcanic ash origin

The central chain of Andean mountain extending throughout Central America and near the west coast of South America typifies this general area. Climatically these areas vary according to altitude and also according to rather dramatic "rain shadow" effects. In general, the soils are fertile enough to support primitive agriculture. This condition can be traced to a genetic background of young age due to the recent nature of volcanic parent material and/or rapid geologic erosion of the steep slopes that exposes relatively unweathered minerals to exploitation by plant roots. These areas are densely populated, usually by small farmers with limited management ability and are not attractive to agronomists because the steep topography precludes implementation of mechanized modern agriculture. Modern agriculture is also inhibited by the difficulty in managing phosphates in these soils with high contents of active, amorphous clay minerals.

Seasonally flooded plains

Large areas of nearly level plains characterized by the western plains of Venezuela and that part of the Colombian Llanos north of the Meta river present unique problems. In general, the soils are quite fertile and free of complicating components such as high Al, Fe, and amorphous concentrations. The monsoon type climate causes these areas to be alternately extremely dry or flooded. The magnitude of these areas taxes the imagination for possibilities to control the water. Population is sparse and transportation is limited. It appears that except for areas where water control is practical, little can be done to increase agricultural development.

Desert areas

A number of desert areas with low total annual rainfall exist at all altitudes and over a wide range of temperatures. These soils are often quite fertile and the only outstanding need is for irrigation systems to transmit water. Some salinity and alkalinity problems may be noted as well as some fixation of fertilizer can be expected when free carbonate is present. These areas are sparsely populated except for the irrigated valleys, many of which support modern intensive agriculture.

Formation of Soils in Tropical America

Factors affecting and processes involved in the formation of soils in the tropics are the same as those familiar to pedologists from temperate areas. Although some quantitative differences do exist these are often of a small magnitude. Genesis studies appear prone to seek out the extraordinary or dramatic occurrences and further case them as universally present and unique in the tropics.

Most of the research and experience in technology upon which our textbooks and other educational materials are derived at this time, have been from temperate areas. Indeed there is probably no soil scientist who has been devoid of temperate zone experience either directly or indirectly, whereas, many soil scientists have no experience in tropical areas and many have only limited acquaintances with minute parts of the tropics. Thus it is probably inadvertent that we must attempt to relate conditions in tropical areas to those more familiar to our experience in temperate zones.

Perhaps the most straight-forward approach to soil genesis is to view all soil forming processes as continuous functions. The activity of each is determined by the environment present in which it can proceed. In

order to proceed, each process has need for raw or primary material upon which to inflict change; the necessary energy capable of causing change in the primary material; and either a secondary product inert to further change or capable of serving as a primary material for another process. In order that a process be measured and reported by pedologists, the change from the primary to the secondary material must be measurable. Therefore, to evaluate soil formation at any point, it is necessary to know the nature of the initial material and the secondary material. This is further complicated because the rate of the reaction can not be measured except as averages where definite time spans can be discerned.

Only one factor difference is discernible in all tropical areas versus temperate areas. This is the lack of seasonal fluctuation in the temperature component of climate. Thus, tropical soils at some mean annual temperature above freezing are continually exposed to liquid water and do not encounter physical mixing (cryopedoturbation) by expanding ice crystals. (Smith, 1965).

Influence of vegetation

It is also noted that there is a similar pattern in type of vegetation in the tropical areas and temperate areas with respect to organic matter distribution in the soil profiles. Perennial trees leave all, or almost all of the annual organic matter production in the soil surface whereas in grasslands annual decomposition of root systems places a much greater proportion of the vegetative growth in the subsoil where decomposition is not speeded by high surface temperatures. Thus, organic matter distribution in savannas like the Cerrado of Brazil and Llanos of Colombia is similar to that of the Midwest of the U.S. (Moura, 1968; Guerrero, 1971).

Age differences

As a point of debate, it can be said that time in itself does not actively cause any difference in soil. Time only provides a dimension in which the processes operate. With this in mind, we must observe that at least on an areal basis there are more old soils in tropical America than in temperate America (Smith, 1965). With the notable exception of the volcanic areas, the tropics are composed of many areas, of relatively level topography thus low erosion rates, that predate the Pleistocene. The temperate zones are greatly influenced by continental glaciation and sea level fluctuation as recent as 10,000 years ago. By its very act, continental glaciation brings to the surface material not previously weathered. In contrast, surface erosion and deposition in most cases moves soil material, after it has undergone weathering in

one place, and redistributes the weathered material on another surface for still further alteration. We can assume that of the transported parent materials those in tropical America were much more severely weathered prior to present soil formation than those in equivalent positions of temperate America.

Parent materials and mineralogy

Volcanic ash. Genesis of soils formed from this type of parent material, as opposed to other better studied parent materials, appears somewhat unique. Some confusion exists since the chemical composition of volcanic material is quite variable.

Martini (1969) reported general agreement that certain soil features could be related to the andesitic, basaltic and rhyolitic nature of the ash. Andesitic ash, which has a high content of volcanic glass and a low content of quartz, silica, iron and bases, tends to form soils high in amorphous material and low in quartz, silica and iron. Stable organic matter—amorphous complexes are formed and the soils have dark colors and high exchange capacities.

Basaltic ashes have greater contents of plagioclase, pyroxene and amphibole minerals. Thus iron, calcium and magnesium contents are high in the clayey, low quartz content soils that quickly evolve.

Rhyolitic ash is higher in content of quartz and feldspar. Sandy, gray colored acid soils tend to form such deposits.

Extreme variation is reported to exist with respect to CEC and base saturation of volcanic ash derived soils. Bornemisza and Morales (1969) report CEC values of <2 meq/100 gram in recent volcanic ash while Kobo (1964) reports a range of 30-60 meq/100 gram. Martini (1970) reports that there is a decrease in CEC with age in volcanic soils. This is in agreement with Besoaín (1964) who reports high concentration of amorphous material (allophane) in the early stages of volcanic ash weathering that generally weathers to kaolinite or halloysite with time (Vicente and Besoaín, 1961).

Montmorillonite is frequently associated with arid and semi-arid climates where the ash has a high silica/alumina ratio (Besoaín, 1969).

Allophane as a distinct mineral is not well understood. The conclusions of Ross and Kerr (1934) that "Allophane has no definite atomic structure or chemical composition, and is a mutual solution of silica, alumina, water and minor bases and accessory acid radicals" is still valid despite numerous studies (Kitagawa, 1971). Such lack of uniformity even in the ability to define and characterize such a widespread and important component of soil developed from volcanic ash is one of the major unresolved problems facing pedologists and soil mineralogists (DeVilliers, 1971). Empirical techniques such as Alexiades and Jackson's (1965) provide some basis with which to evaluate the pres-

ence of allophane but better techniques are needed to advance evaluation of such soils.

Martini (1969) has shown that many of the propertie of volcanic ash soils associated with external factors of soil formation in much the same way as they do in other soils. However, it should be noted that Bornemisza and Pineda (1969) found that when there was more than 15 percent allophane present in the soil, mineralization of organic nitrogen was retarded.

Igenous rock derived soils. There appears to be two distinct types of situation in these areas. Low CEC values associated with kaolinitic mineralogy is the general rule. The proportion of bases on the exchange sites decreases as the weathering intensity increases and since kaolinite is a more stable mineral in soils than is montmorillonite, there is a general tendency to find soils with low CEC, of kaolinitic type, with low base saturation. Conversely soils with high components of montmorillonite, high CEC, are generally higher in base status. In the Amazonia of Brazil, Fassbender *et al.* (1970) described two groups of soils. Those low in CEC and high in Al (exchange acidity) and those with high CEC and >65 percent base saturation. Similar observations have been made in the Amazon Basin of eastern Peru by Sanchez and Buol (1971).

Such a relationship is not universally true however. For example, Moura (1968) reported 93 to 99 percent base saturation in a Eutrustox from Central Brazil where the predominant clay was kaolinite and CEC values were quite low. In this regard, it is important to remember that the type of clay mineral, i.e. CEC, may be the relic of a past clay formation environment and the present ion population reflects the immediate history of the soil. Ion populations are drastically influenced by such management practices as liming and fertilization. Also, in the soil studied by Moura, microstructure appears to play a major role in retaining basic ions.

Climatic influence on soil composition

Differences between tropcial and temperate areas, aside form the isotemperature nature of the tropics, are site dependent. It would hardly seem pertinent to subject the reader to lengthy reruns of desert and humid conditions etc. to emphasize the climatic factors. One study on this point does seem very pertinent to this discussion, however. Jenny *et al.* (1948) found that in a comparison of Colombian soils and North American soils with the same temperature and moisture values, the Colombian soils have a much higher nitrogen and organic matter content than North American soils. These authors expressed surprise at not being able to see nitrogen content expressed in soil color and expressed agreement with Vageler (1930) who said tropical humus

was colorless.

It is only conjecture as the part of this writer but it appears reasonable that this phenomenon is explainable when you consider that the temperature comparison were made on a mean annual basis. Thus, to have comparable mean annual temperatures in temperate and tropical settings much higher temperatures are experienced at some time of the year in the temperate zone than in the tropical zone. Since biological and chemical reactions follow the often quoted Van't Hoff rule of 2-3 times the velocity for each 10° C temperature rise, the following reasoning seems in order.

When one considers that many of the savanna grasslands of South America are dry for 3-5 months a year, thus inhibiting decomposition as in the winter of the temperate zones, and then the remaining months are usually lower in temperature than the summers of temperate zones of the same mean annual temperature one may have somewhat less energy available for decomposition in the tropical area.

If one compares the amount of organic carbon within the top 1 m of several well-drained profiles from Iowa, U.S.A. (SSIR, 1966), Southeastern U.S. (SSIR, 1967) and Brazil (Ministério da Agricultura, 1966; Ministério da Agricultura, 1970) some striking contradictions to common beliefs are observed. Organic carbon contents of 0.3 to 0.42 percent are present in the top meter of Red and Yellow Sands, Red-Yellow Podzolics and Dark Red Latosols in Mato Grosso, Brazil. From 0.5 to 1.0 percent O.C. is present in Latosols from Brasília while common well-drained upland soils in the Southeastern U.S. range from 0.1 to 0.3 percent O.C. and Prairie soils (Mollisols) in Iowa range from 0.6 to 1.0 percent O.C. in the top 1 m.

Thus, although at this time extensive calculations of such values have not been made, it appears clear that there is a much greater organic matter content in many of the well-drained tropical situations than is present in our common southeastern U.S. soils. Although the soils appear quite red and devoid or organic matter, there appears to be a deceptive amount of O.M. and since C/N ratios are usually 10-15, a great deal of N is potentially available. One possible source of error, not considered likely because of the reasonable C/N ratios, is that high Mn contents may create an errorously high %C readings by the oxidation methods used.

Topographic influences

Two distinct relationships of clay mineral suites seem to be associated with poorly drained soils. Further, these relationships appear best understood when the geomorphic position of the poorly drained soil is considered rather than only the profile characteristics of low chroma mottles. For those poorly drained soils associated with high

water tables the mineralogy tends to be about the same as the surrounding well drained soils (Martini, 1969). However, when the poor drainage is the result of anaerobic conditions engendered by impermeable subsoil horizons the mineralogy is likely to be montmorillonitic (Sánchez and Buol, 1971). This relationship is understood if one views the presence of montmorillonite, especially in high quantities in clayey horizons, as a zone that because of its expanding nature restricts leaching thus protecting itself from weathering. Such soils take on the characteristic grey colors of poor draingage but in reality little water is leaching and the potential to remove weathering products is low.

Latosols and Laterite—"Special Tropical Soils"

Latosols and laterite are frequently erroneously taken to mean the same thing. "Laterite is a highly weathered material rich in secondary oxides of iron, aluminum, or both." "It is nearly devoid of bases and primary silicates, but it may contain large amounts of quartz and kaolinite." "It is either hard or capable of hardening on exposure to wetting and drying" (Alexander and Cady, 1962). Thus, it is a material, not really a soil.

Latosols are a group of soils high in secondary oxides and low in silica that may or may not contain laterite material in part of the profile. Presently, Latosol is the name used by some soil taxonomists, notably the Brazilians, for those soils that have a latosolic B horizon as opposed to a textural B or argillic horizon.

Modern nomenclature. Because of long standing confusion surrounding these terms and lack of uniformity in defining laterite, they have been dropped from taxonomic usage in the present United States system. (USDA, 1970). The term plinthite, defined as sesquioxide-cemented material that is hard, or capable of hardening upon repeated wetting and drying, replaces the name for much of the material once covered by the term laterite. The taxonomic order Oxisol replaces many but not all Latosols and the oxic horizon definition has a definition comparable with and still being refined in conjunction with, the latosolic B horizon of the Brazilians.

To many, this may seem as a confusion factor perpetrated by soil taxonomists to mystify non-taxonomists.

Numerous edifices to the confusion and erroneous interpretation of the old terms exist, and, one bears special attention (McNeil, 1964). From her interpretation, one can conclude that no modern agriculture is possible in much of Florida, Georgia, Alabama and Louisiana as well as nearly all of Hawaii, Puerto Rico or Cuba because upon cultivation the soil will harden.

Personal experience has seen a noted geologist refer to soils in southern Arizona as lateritic or relic Latosols because they were "red" where analysis showed them to contain less than 5 percent free iron oxide, have pH values near neutral, and clay mineral suites with high concentrations of illite and other easily weathered minerals. Any usage of the older terms demands close scrutiny by the modern research worker.

Hardening process of Plinthite (laterite). The property of a soil material to harden upon wetting and drying is no small item of consideration in planning potential use of an area. Plinthite is present where either there are high concentrations of iron in the parent rock or where iron is translocated into an area. It usually forms in conjunction with a fluctuating water table (Daniels *et al*, 1970; Alexander and Cady, 1962). Thus, such practices as the installation of drainage may cause significant drying, followed apparently by sesquoxide crystal growth, and the formation of an indurated layer. This can easily be tested for by removing suspected material, wetting it to saturation and allowing it to dry. If after repeating this for five to ten times, the material is still friable enough to be broken in one hand, the material will not qualify for plinthite and probably will afford no induration problems. In most areas of any civilization, the natives will frequently have identified such material and be using the plinthite (laterite) as a road building material because of its indurating property.

Distribution of Plinthite (Laterite). Laterite, Latosols and Laterization (the ambigous processes ascribed by many to this formation) are terms that occupy a great deal of visibility in the literature. Although Plinthite is a rather common feature in subsoils in some Ultisols of the U. S., its occurrence was not recognized for some years in the U. S. It is apparently not present in much of Europe, thus was the new and different feature found in early tropical studies. As such, it was much discussed and grossly exaggerated in both word and deed.

Because quantification of the term plinthite is rather recent, it is not possible to give a quantitative evaluation of its areal extent. Personal visitation has found definite occurrences in Brazil, Mexico, and Colombia. In all cases, however, it occurred in minor proportions, and in definite geomorphic relationships similar to those described in the U. S. (Daniels *et al*, 1970).

Classification of Soils in Tropical America

It is probably best to ascribe the want to classify to human nature. Aside from this natural desire, the act of classification allows like things to be associated for purposes of comparison, study and extrapolation. If the properties used to group soils in a classification system are the same as the properties affecting a particular use of soils, it follows that the groups created in the system will have similar responses for similar uses. For example, if the aluminum content of the soil affects growth of corn, soils grouped for similar aluminum content will have corn growths that compare, assuming Al is the only causitive difference in growth. This assumption of a single factor variable is usually not valid in the case of soil-fertilizer-plant growth-economic analysis. Nor more simply, is it entirely valid in soil-plant growth relationships. Moreover a soil classification system should be useful for more than one crop so many soil properties are used in delimiting group criteria.

Types of classification systems

Classification systems for soils can themselves be classified into at least two types. One type is for the particular use of the soil. Many examples are available of this dating back to ancient Chinese attempts to classify land for tax purposes. Similarly such classes as corn soils, blueberry soils, cotton soils and garden soils fall in this category.

The more common image of soil classification is as a vehicle for arriving at a knowledge of how different soils are related in nature and affording some hope of associating features that various soils have in common.

More simply, one could say the approaches to soil classification in the first case involve the use of criteria related to the use man can make of the soil for specific purposes and in the second case, criteria of how man thinks the soil developed its properties is used to define categories. In either case, it is important to point out that classification is man-made. Thus it is safe to say that as long as man finds either new uses for soils or new methods of measuring soil characteristics and thus can hypothesize new theories of soil formation he will continue to revise soil classification systems (Smith, 1965).

With the exception of some purely empirical systems of the first type, namely the engineering classification of soil material, all of the present soil classification systems have an element of both approaches directly or indirectly built into the criteria they use to differentiate soil groups or taxa. The most extensively used systems of classification in Latin America are the Brazilian system (Bennema and Camargo, 1964; Lemos, 1968), which is patterned after the 1938 U. S. system, the New 7th Approximation system (Soil Survey Staff, 1960, 1964, 1967, 1970)

of the U. S. introduced in 1960, and the FAO Map unit and sub-unit naming system (Dudal, 1968a, 1968b, 1969). Each system is to some extent, related in certain important criteria thus translation is not too involved. Since each system was designed at a different time by different people and intended to serve somewhat different needs, some comparison of this background is necessary to understand what may appear to many as unresolved differences.

The 1938 U. S. system (Baldwin *et al*, 1938) as revised in 1949 (Thorp and Smith, 1949) adherred to a strong genesis bias. It had developed primarily from European and U. S. data and experience and left broad groups for tropical regions. In effect, this system of grouping soils of tropical regions into one or two categories by climate criteria has given students of soil science an erroneous impression of uniformity and singularity of tropical soils. The Brazilian modifications of this system have elaborated on the kinds of soils most prevalent in the American tropics and established subgrouping in that area.

The U. S. 7th Approximation published in 1960 and since revised (Soil Survey Staff, 1960, 1964, 1967, 1970), for internal U. S. use diminished the genesis criteria bias of the 1938 system and focused attention on properties of the soil profile. Further and most important, it established quantitative limits on the variation of composition within each category so that all groups, at any level in the system, were mutually exclusive. By so doing, it brought together soils from tropical regions into the same higher categories as like soils of the temperate zone. This permits an earier transfer of information from one area to the other. The system usually separates tropical equivalents of information from one area to the other. The system usually separates tropical equivalents of temperate soils either at the third level (Great Group) or the fifth level (Family). Again, however, the grouping of some extensive soils found in tropical areas are grossly treated because of their limited occurrence in the U. S. Provisions are being made for an orderly improvement of these groups, as in all other groups, when new data is available.

The FAO system was not designed as a classification system but rather as a two level system for use in correlating small scale maps. It encompasses almost an entirely new nomenclature designed to pacify all the leading nations of the world (Dudal, 1968b). Since it is designed for use in naming units of general maps, it is not nearly as detailed as the U. S. system which serves the detail required on detailed maps of a scale of 1:15,000 (about 4" per mile). Thus, while the U. S. system contains about 10,000 categories for soils in the U. S., the FAO system has only 103 categories (Dudal, 1970) for all the soils of the world. In general this is about comparable to the third level of the U. S. system.

The FAO system, like the U. S. system and the Brazilian modifica-

tions of the 1938 system, have elements of quantification and attention to profile characteristics not common to earlier systems or some present European systems. Further, much of this quantification has developed while in communication; thus the systems are fairly easily translated. For example, the latosolic B of the Brazilian system, a criterion for their Latosols is defined in a fashion similar to the oxic horizon of the U. S. system, a requirement of the Oxisol order in that system. The FAO system contains quantitative criteria for its units and sub-units that parallel U. S. criteria in almost every respect (Table 1 and 2). Where parts of the Brazilian system do not fit with the present U. S. system, it relates to the older 1938 U. S. system readily understood by most U. S. soil scientists: (Tables 3 and 4).

Unfortunately, many soil surveys are done only on a series basis with no attempt to relate the series to a hierarchical taxonomic system. In such cases it is necessary to study the soil profile descriptions in detail, if provided, to glean any comprehension of the soil properties.

Value of soil classification

The exercise of classifying soils into any system is of value only if (1) it forces people to study soil characteristics, (2) it produces a better understanding of the relationship of soil properties, (3) it provides a sound basis for extrapolation of information from one area to another. Obviously item 3 is of prime concern in the over all agronomic-economic endeavor of our involvement in tropical soil fertility research. Thus an interpretive classification is better suited than multi-faceted systems designed to study the soils themselves. Recognizing this need in the area of resource planning most of the soil survey programs in every country use a land capability on land economic system to classify their lands. This type of system, although quite qualitative in practice fills a very definite need. Based on various criteria of slope, depth of soil, texture, and adverse chemical properties the soils are rated in a I, II, III etc. order to depict those that have no limitations to agriculture, to those having severe limitations. Insofar as possible, specific limitations and potentials are pointed out for each class by the personnel making the soil survey. While serving a very worthwhile purpose such systems are for interpretation within limited geographic, and social-economic confines and usually correlation from area to another is difficult. Also, since these interpretations have rather specific management interpretations in mind they are subject to invalidation as management and economic charges take place. Their major omission in many cases is in not presenting quantitative soil characteristics for a research worker to research. They essentially map and classify an interpretation.

It appears to this writer that there is no, and never can be a perfect or even best classification system for soils. The quality of any classification system is determined solely on its ability to be useful for some particular need. As long as there is more than one use for soil there will be more than one set of criteria needed for a soil classification system or a need for more than one classification system.

A comprehensive, quantitative system utilizing all measurable soil properties as criteria with several technical subsystems that utilize only criteria of importance to individual soil uses is seen as the most promising solution. One may liken this to one big memory bank for all soil properties and a number of smaller systems that can recall characteristics for specific projects and not be concerned, and confused, by properties extraneous to that use.

Summary

A variety of soil characteristics exist in tropical areas. With the exception of the annual soil temperature variation solely typical of tropical conditions, no other property appears commonly shared by tropical soils. In most cases, characteristics in tropical soils have a counterpart in temperate soils; however, several properties are areally more significant in the tropics than in temperate areas. This is especially true with characteristics of low cation exchange capacity and fine granular oxic horizon structure which is rare in temperate soils. The high free iron oxide concentrations and the presence of indurated iron formations in some tropical areas are rare in the geologically younger parts of the temperate areas but similar to those found in older temperate areas. Organic matter contents are higher in many tropical grassland areas than in older humid temperate soils.

The concepts of soil genesis expressed for tropical areas are best summarized as being the same as those held for temperate zones. This writer best likes the summary of soil genesis in the tropics stated by Carter and Pendleton (1956):

> Why, if things are as simple as we present them, has there been such confusion? The concept of a tropical process came to be focused about the term "laterite". Laterite was and is a feature, a specific thing, and not a process. The process was invented by those who had never seen the feature and who, even worse, applied it to all sorts of phenomena supposedly, but not really like laterite as originally described.

Most features of tropical soils are similar or the same as those in temperate zones and can be predicted and interpreted by genesis theories to the same degree as can temperate soils.

Classification of soils in Tropical America is fragmented but not as drastically as it would appear at first glance. Officially three major

systems are of major use in tropical America but since these have a high degree of correlation, information can be extrapolated with minimum difficulty. Also, there has been, and is, an intense effort on the part of most Latin pedologists to become knowledgeable in the U. S. system. They are hindered by lack of rapid translation and transmittance of recent amendments to the U. S. system.

There is an abysmal lack of communication between fertility-economic research and the soil classification and mapping work which affords such research the sound areal extrapolation it needs. A need is apparent for improved understanding and cooperation. It appears that a technical soil classification kept simple by using *only* soil morphology and composition *known*, and *demonstrated*, to have economic influence on soil-plant-fertilizer interactions will help bridge this abyss.

Table 1. Comparison of FAO—7th Approximation Diagnostic horizons (after Buol *et al*, 1973)

FAO/UNESCO	USDA 7th Approximation
melanic A horizon	mollic epipedon
distinct A horizon (sombric)	umbric epipedon
weak A horizon (pallid)	ochric epipedon
peaty A horizon	histic epipedon
natric B horizon	natric horizon
argilluvic B horizon	argillic horizon
planic B horizon (abrupt textural change)	described but not named
glossic B horizon (tongued upper boundary)	described but not named
plinthic horizon	plinthite
cambic B horizon (except gley horizons not included)	cambic horizon
gleyic horizon	(unique to FAO/UNESCO, for horizons with indications of pronounced wetness within 50 cm from the surface)
spodic B horizon	spodic horizon
oxic B horizon	oxic horizon
calcic horizon	calcic horizon
gypsic horizon	gypsic horizon
salic horizon	salic horizon
gibbsitic horizon	(unique to FAO/UNESCO, a layer with 30% or more gibbsite or 20% or greater by by volume of gravel-size aggregates containing 30% or more gibbsite)

Table 2. FAO—7th Approximation Correlation table (after Duda[1], 1969)

Soil Map of the World (Units, December 1968)	USDA 7th Approximation (Units, March 1967)	
FLUVISOLS		
Dystric Fluvisols	Fluvents	acid (1)*
Eutric Fluvisols	Fluvents	non acid
Calcaric Fluvisols	Fluvents	calcareous
Gleyic Fluvisols	(Fluventic) Aquents (2)	
RHEGOSOLS	Orthents (3) Psamments (except oxic Quartzipsamments and alfic Psamments)	
Dystric Rhegosols		acid (1)
Eutric Rhegosols		non acid
Calcaric Rhegosols		calcareous
ARENOSOLS		
Dystric Arenosols	Oxic Quartzipsamments	
Eutric Arenosols	Alfic Psamments	
GLEYSOLS (4)		
Tundric Gleysols	Pergelic Cryaquepts Pergelic Cryaquolls	
Thionic Gleysols	sulfureous families of Aquents & Aquepts	
Haplic Gleysols	Haplaquepts non Flueventic Aquents (2)	
Humic Gleysols	Humaquepts (except Histic ones) Haplaquolls (except Histic & Calcic ones)	
Calcic Gleysols	Calciaquolls (5) Calcic Hapaquolls	
Plinthic Gleysols	Plinthaquepts	
Histic Gleysols	Histic Humaquepts & Histic Cryaquepts (except Pergelic ones) Histic Cryaquolls & Histic Haplaquolls	
Rendzinas	Rendolls	
RANKERS	Entic Haplumbrepts (normally also lithic)	
ANDOSOLS		
Haplic Andosols	Dystrandepts (6) Eutrandepts Hydrandepts	
Vitric Andosols	Vitrandepts	
Gleyic Andosols	Andaquepts	

continued

* The figures in brackets refer to the explanatory notes.

Table 2 (Continued)

Soil Map of the World	USDA 7th Approximation
VERTISOLS	Vertisols (7)
YERMOSOLS	
Haplic Yermosols	non Mollic Camborthids
Calcic Yermosols	non Mollic Calciorthids with calcic Horizon
Gypsic Yermosols	non Mollic Calciorthids with gypsic horizon
Luvic Yermosols	non Mollic Haplargids
XEROSOLS	
Haplic Xerosols	Mollic Camborthids
Calic Xerosols	Mollic Calciorthids with calcic horizon
Gypsic Xerosols	Mollic Calciorthids with gypsic horizon
Luvic Xerosols	Mollic Haplargids
SOLONCHAKS	
Haplic Solonchaks	Salorthids
Humic Solonchaks	Salorthidic Calciustolls Salorthidic Haplustolls
Takyric Solonchaks	Salorthids (3)
Gleyic Solonchaks	saline phases of Aquepts or Aquents (9)
SOLONETZ	
Haplic Solonetz	Natriboralfs, Natrudalfs, Natrustalfs, Natrixeralfs
Humic Solonetz	Natralbolls, Natriborolls, Natrustolls, Natrixerolls, Natragrids, Nadurargids Natric Paleargids, Natric Palexerolls
Gleyic Solonetz	Natraqualfs Natraquolls
PLANOSOLS (10)	
Haplic Planosols	Albaqualfs (and some abruptic aquic Paleoolls) (1)
Humic Planosols	Argialbolls (and some abruptic aquic Paleoolls) (1)
Solodic Planosols	(11)
CASTANOZEMS (12)	
Haplic Castanozems	Haplustolls (except salorthidic ones)
Calcic Castanozems	Calciustolls (except salorthidic ones)
Luvic Castanozems	Arguistolls

continued

Table 2 (Continued)

Soil Map of the World	USDA 7th Approximation
CHERNOZEMS (12)	
Haplic Chernozems	Haploborolls
	Vermiborolls
Calcic Chernozems	Calciborolls
Luvic Chernozems	Argiborolls
Gleyic Chernozems	Calcic Argiaquolls
PHAEOZEMS (12)	
Haplic Phaeozems	Hapludolls
	Vermudolls (in part, 13)
Calcaric Phaeozems	Vermudolls (in part, 13)
Luvic Phaeozems	Arguidolls
Gleyic Phaeozems	Argiaquolls (except calcic ones)
CAMBISOLS	
Haplic Cambisols	Dystrochrepts (except andic ones)
Eutric Cambisols	Eutrochrepts (without carbonates in the cambic horizon, (except the andic ones)
Calcaric Cambisols	Eutrochrepts (with carbonates in the cambic horizon)
Vertic Cambisols	Vertic Eutrochrepts
Humic Cambisols	Haplumbrepts (except andic ones)
Andic Cambisols	Andic Dystrochrepts, Eutrochrepts and Haplumbrepts
LUVISOLS	
Haplic Luvisols	Hapludalfs
	Agrudalfs
Chromic Luvisols	Haploxeralfs
	Haplustalfs (except oxic ones)
	Rhodoxeralfs (except oxic ones)
	Rhodustalfs (except oxic ones)
Ferric Luvisols	Oxic Haplustalfs
	Oxic Rhodustalfs
	Oxic Rhodoxeralfs
Albic Luvisols	Eutroboralfs
Plinthic Luvisols	Plinthoxeralfs, Plinthustalfs
Gleyic Luvisols	Ochraqualfs, Umbraqualfs
PODZOLUVISOLS	
Haplic Podzoluvisols	Glossudalfs, Ferrudalfs
	Glossoboralfs
Gleyic Podzoluvisols	Glossaqualfs

Continued

Table 2 (Continued)

Soil Map of the World	USDA 7th Approximation
PODZOLS	
Humo-Ferric Podzols	Orthods (except placic ones) (in part, 14)
Ochric Podzols	Orthods (in part, 14)
Ferric Podzols	Ferrods
Humic Podzols	Humods (except placic ones)
Placic Podzols	Placorthods
	Placohumods
	Placaquods
Gleyic Podzols	Aquods (except placic ones)
ACRISOLS	
Haplic Acrisols	Hapludults, Rhodudults
	Haplustults, Rhodustults
	Haploxerults, Rhodoxerults
Humic Acrisols	Humults
Plinthic Acrisols	Plinthudults, Plinthaquults
Gleyic Acrisols	Aquults (except Plinthaquults)
NITOSOLS	
Dystric Nitosols	Oxic Palehumults, Oxic Paleudults, Oxic Paleustults
	Oxic Palexerults
Eutric Nitosols	Oxic Paleudalfs
	Oxic Paleustalfs
FERRALSOLS (15)	
Haplic Ferralsols	
Ochric Ferralsols	Haplorthox, Acrorthox, Gibbsiorthox
Humic Ferralsols	Humox
Plinthic Ferralsols	Plinthaquox
HISTOSOLS	
Dystric Histosols	Histosols, acid
Eutric Histosols	Histosols, non acid
LITHOSOLS	
Dystric Lithosols	Lithic subgroups, very shallow classes
Eutric Lithosols	

Table 2, Explanatory Notes:

(1) The dystric and eutric groups within the Fluvisols and the Rhegosols are separated at pH KCl 4.2. This is somewhat lower than the limit between the USDA acid and non-acid reaction classes separated at pH water 5.5. The figure of pH KCl 4.2 has been adopted in analogy with the separation made between Dystric and Eutric Histosols which is used in the Canadian soil classification. Unlike for the Psamments, the reaction classes are also applied here to the coarse textured Rhegosols and Fluvisols for the sake of uniformity.

(2) Though the Aquents do not have fluventic subgroups, an attempt is made here to use the (fluventic) distribution or organic matter in the Aquents to distinquish Gleyic Fluvisols. (Non fluventic Aquents are grouped with the Haplic Gleysols).

(3) The separation between Orthents and Psamments ia made by using textural classes. Arents are grouped with the units.

(4) Halaquepts are not shown separately; they are mapped as sodic phases. Neither do the Hydraquents have a specific place; part of them fall into the Thionic Gleysols. Psammaquents are shown as a coarse textured class of one of the other Gleysols.

(5) For the Calcic Glaysols the depth limit of the calcic horizon has been set at 100 cm, so that both Calciaquolls and Calcic Haplaquolls fall into this unit.

(6) The need has been felt to make a further subdivision within the Haplic Andosols in order to reflect the separation between Dystrandepts, Eutrandepts and Hydrandepts. It appeared, however, that not enough information was available to make such a subdivision at the scale of the map.

(7) It has been attempted to make a further subdivision between Pell- and Chrom- Vertisols. Here again, it seemed that at a world scale it is difficult to obtain the necessary information to do so.

(8) Takyric Solonchaks cover the Takyrs of the USSR (Saline soils of heavy texture, which form surface crusts and show polygronal cracking). They are likely to correlate with Salorthids.

(9) Saline soils being saturated with water for more than one month a year cannot be classified as Salorthids. Gleyic Solonchaks therefore probably correlate with saline phases of Aquepts or Aquents.

(10) No specific place is forseen in the Soil Map of the World outline for the Pale-groups. Those which show abrupt textural changes and aquic or albaquic features may fit the Planosol definitions.

(11) The Solodic Planosols are meant to cover what has been called Solods. Many of these soils fit the Argialbolls but are separated here on a sodium saturation which exceeds 6 percent in some part of the B horizon. Some

albaqualific natric or some argialbollic natric subgroups (e.g. within the Xeralfs or Ustalfs) may also fit the Solodic Planosols (natric being understood here as subgroups with high sodium saturation but not having a natric horizon).

(12) The non-calcic subgroups of the Xerolls correlate as a climatic variant of the Phaeozems. The calcic subgroups, however, fall within the Chernozems or Castanozems, depending on the color of their surface horizons.

(13) Only the calcareous Vermudolls correlate with the Calcaric Phaeozems. The other Vermudolls are grouped with the Haplic Phaeozems.

(14) With the Ochric Podzols it is attempted to separate within the Orthods the soils formerly called "Brown Podzolic". A definition is being tried out on the basis of the Fe/Al ratio which in "Brown Podzolic" soils seems to be much higher than for other Spodosols.

(15) The definition of the Ferralsols matches the one of the Oxisols. The subdivision of the Ferralsols, however, follows a different outline. The Rhodic Ferralsols, normally formed on basic materials, cover most of the Eutrothox The Haplic and Ochric Ferralsols cover the Haplorthox, Acrorthox and Gibbsiorthox. The Ochric Ferralsols cover part of the kaolinitic families generally occurring under conditions of permanent humidity in equatorial regions.

Table 3. 7th Approximation—1938 Correlation (after Soil Survey Staff, 1960).

Present order	Approximate equivalents (Baldwin et al, 1938)
1. Entisols	Azonal soils, and some Low Humic Gley soils.
2. Vertisols	Grumusols.
3. Inceptisols	Ando, Sol Brun Acide, some Brown Forest, Low-Humic Gley, and Humic Gley soils.
4. Aridisols	Desert, Reddish Desert, Sierozem, Solonchak, some Brown and Reddish Brown soils, and associated Solonetz.
5. Mollisols	Chestnut, Chernozem, Brunizem (Prairie), Rendzinas, some Brown, Brown Forest, and associated Solonetz and Humic Gley soils.
6. Spodosol	Podzols, Brown Podzolic soils, and Ground-Water Podzols.
7. Alfisols	Gray-Brown Podzolic, Gray Wooded soils, Non-calcic Brown soils, Degraded Chernozem, and associated Planosols and some Half-Bog soils.
8. Ultisols	Red-Yellow Podzolic soils, Reddish-Brown Lateritic soils of the U. S., and associated Planosols and Half-Bog soils.
9. Oxisols	Laterite soils, Latosols.
10. Histosols	Bog soils.

Table 4. Higher level soil classes recognized in Brazil (after Bennema and Camargo, 1964).

1. Soil with Latosolic B horizon (includes Latosol Roxo; most other normal Latosols with CEC of clay below 6.5 meq/100g.).
2. Soils with textural B horizon with plinthite.
3. Soils with textural B horizon without plinthite (includes Rubrozems, Terra Roxa Estruturada, among others).
4. Soils with natric B horizon.
5. Soils with incipient B horizon.
6. Soils with hardpan below A horizon.
7. Grumusols
8. Lithosols
9. Regosols
10. Sands
11. Podzols (including Hydromorphic Podzols).
12. Other Hydromorphic soils (including Organic).

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CHAPTER 2

Soil Physical Properties

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Some soil physical properties are distinct; others are so interrelated with the chemical, mineralogical, and fertility aspects that they cannot be considered independent insofar as plant growth is concerned. Likewise, fundamental principles know no political boundaries. For example, the forces and physical principles involved in water movement and in evapotranspiration are the same in Central and South America as in the United States. The magnitude of the values might vary from place to place, but the fundamental principles remain the same. The variation in magnitude might be due to differences in climate, parent material, topography, drainage, etc., and it is important to document in this review data obtained under specific conditions. As Liebig said, "Facts are like grains of sand which are moved by the wind but principles are these same grains cemented into rocks."

For the most part, the review will cover work done in Central and South America but with reference to work done elsewhere, particularly with reference to basic principles.

The review will cover four general areas: 1. climate; 2. water; 3. other physical properties; and 4. soil and water conservation. Insofar as possible, these will be related to each other and to other soil properties.

The amount of water present in a soil at any particular time or place is a function of the amount applied minus the losses. The amount applied may be by precipitation or by irrigation. The losses may be by surface or subsurface runoff, by drainage to deeper layers, or by evapotranspiration. Precipitation varies tremendously in tropical America. In certain sections of Colombia, Venezuela, Ecuador, and Peru, the annual rainfall is less than 10 inches per year. In other sections, particularly in the upper Amazon Valley, and on the headwaters of the Amazon, it is more than 200 inches per year. In some sections the soils are too dry for agriculture without irrigation and in others they are too wet a large part of the year, particularly for the use of heavy agricultrual equipment. In areas where climatic data are available, the potential evapotranspiration can be calculated from the formulas of Penman, Thornthwaite, or Van Bavel. Schoch and Dancette introduced a coefficient "alpha" in the modified Piche

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formula for calculating potential evapotranspiration at the crop level. The value of alpha varied considerably with the aridity of an area. However, a good correlation was found between alpha and aridity. The value of alpha also varied with the type of shade covering any particular area. For estimating evapotranspiration in humid areas, the statistical relations developed by Mustonen and McGuinness can be used. Other pertinent information on the measurement of evapotranspiration in the tropical regions is given by Eldin and Daudet and by Oliver.

Lack of available soil water may limit plant growth even in areas of high annual rainfall. This may be due to poor distribution of rainfall throughout the year, to low infiltration, or to deep seepage in soils with low water-holding capacity.

Many investigators in the United States and elsewhere have shown that the rate of infiltration usually decreases as the duration of rainfall increases. Lugo-Lopez, *et al* (1970) presented data from 740 field infiltration tests in Puerto Rico showed a declining rate of infiltration after the initial hour. They found highly significant correlations between the eighth hour infiltration rate and the preceding one hour interval rates. Because of the highly significant linear correlation between the third and eighth hour rates, they suggested use of the third hour rates for predicting infiltration under prolonged rainfall. Further discussion on evapotranspiration in the humid tropics is given by Williams and Joseph. In fact, they gave a fairly comprehensive discussion of soil-water-plant relations in humid tropical conditions. They pointed out that certain tropical crops are adversely affected when soil moisture tensions rise to only slightly above field capacity. Crops strongly affected by low to intermediate moisture stress conditions are cacao, coffee, tea, bananas, sugar-cane, pineapples, coconuts, oil palms, and rubber. No explanation was offered for the supersensitivity of these crops. Obviously, the leaves were transpiring water faster than the roots could absorb it. This could be due to a small root surface area, to a low hydraulic conductivity in the root zone, to excessive transpiration under the existing climatic conditions in time of drought, or to a combination of all these. Williams and Joseph presented data which showed that additions of readily available nitrogen increased water efficiency tremendously, even in the humid tropics. This effect of nitrogen on water use efficiency has been demonstrated many times in temperate regions.

Other work has shown wide variation in the wilting point of various crops. Sykes determined the tension of water in soil at the wilting point of five species growing in soils of low and high hydraulic conductivities. He found that the wilting point varied from 7 atmospheres for *Helianthus annus* to 39 atmospheres for *Agropyron intermedium*.

There were highly significant differences among soils, species, and environmental conditions. Sykes concluded that the main factor determining wilting point was the rate of water movement in the soil.

Other workers have studied moisture tension-plant relations. Gavande made moisture tension curves of six Costa Rica soils and found that texture, organic matter, and compaction were the principal factors affecting the shape of the curves. Volcanic ash soils had high organic matter, high clay content, a high total porosity, and a high water-holding capacity. Such information is valuable in planning soil management systems and especially in irrigation. Fernandes and Sykes made extensive soil-water tension and soil-water movement studies on soils from three regions of Minas Gerais in Brazil. Gonzalez and Gavande made physical measurements of a number of soils used for sugar can production in Costa Rica. The properties studied were depth, texture, bulk density, particle density, total porosity and water-holding capacity. They stated that such data were extremely valuable in selecting new areas for sugar cane production. Cornejo prepared a bibliographical review of the main water-soil-plant relations concerned with cotton production on the coast of Peru. He included information on irrigation principles, water requirements, irrigation systems designed for efficient water use, and salinity problems. Forsythe and Diaz-Romeu made bulk density determinations of a number of soils and from them prepared a series of conversion factors for expressing laboratory chemical analysis in field equivalents, such, for example, as kilograms per hectare.

Burgas used rainfall and temperature data from 167 localities in Venezuela to prepare balance maps according to Thornthwaite's method. He presented maps showing annual rainfall, potential evapotranspiration, areas of water surplus, and areas of water deficit.

Garay selected four different topographic conditions and, hence, presumably four different drainage and aeration conditions, to study carbon dioxide and oxygen in soils used for coffee production. In spite of the difference in topographic position, he found no differences throughout the full depth of the profile in total porosity, in infiltration and percolation rate, or in the composition of the soil air. He did find differences in total volume of air. Gavande studied the relation between soil moisture tension, aeration porosity, and oxygen diffusion in six soils used for coffee production in Costa Rica. He found a linear relation between aeration porosity and oxygen diffusion ratio. Over a wide range of soil moisture conditions the oxygen diffusion ratio appeared to be a sensitive measure for soil aeration. He recommended the method as a means of characterizing the aeration status of soils when drained.

Plá stressed the importance of a knowledge of soil physical and hydrological characteristics, particularly soil mositure tension curves, in irrigated agriculture.

In the dry areas of South America, particularly in Venezuela, Colombia, and the coast of Peru, irrigation is necessary for crop production. One of the main problems is the salinity of the irrigation water. Zavaleta pointed out that the salinity of the cultivated lands among the coast of Peru has been steadily increasing to the point that large areas are going out of cultivation every year. A study of the occurrence and nature of saline and alkali soils in the area showed that nearly all of the irrigated soils of river valleys are saline-alkaline and that of the nonirrigated desert soils only 8 percent are unaffected by salts, the majority being saline-alkaline. Such information on the salinity of the soils, and of the water available for irrigation, is of considerable importance in the development of large irrigation projects similar to the one near Sullana in northern Peru, the Chimbote project along the Santa River, and the Majes-Siguas project in southern Peru. As pointed out by Israelson and Hansen, a knowledge of the characteristic properties of soils to be irrigated is essential to deriving maximum benefits from the irrigation. Without a knowledge of certain soil physical properties, efficient water use is impossible. In addition to physical characterization of the individual soils basic fundamental principles of water movement in soils must be understood.

Another important aspect of water is its conservation. Runoff, and the accompanying soil erosion, are major problems in all humid regions. Likewise wind erosion is a problem in arid regions. According to Fogling large areas of agricultural land in the Ecuadorian highlands have been destroyed or seriously damaged by erosion. In some cases remnants of the old Inca terraces still offer some protection but in others they increase the damage by channeling and, hence, accumulating the water at certain places where it is released in large masses producing serious gullying. This same situation exists throughout the Andes. Relatively little basic research has been done on runoff and erosion in Central and South America. Bertoni and Pastana studied the relation between rainfall and erosion losses on several soil types at four localities in the state of São Paulo, Brazil. The soils used were all cropped continuously to cotton. They found that both runoff and erosion increased with total rainfall per shower and with maximum rainfall intensity but the relations were not statistically significant with respect to rainfall characteristics, slope of the land, or soil types. Soil and water conservation programs have been underway in Jamaica (McMorris), in Guatemala (Marcos), and in the West Indies (Twyford and de Freitas).

Work by Pinto[2] in Venezuela on the Maracay soil series has shown that phosphorus increased the degree of aggregation, and the water holding capacity, but, decreased the modulus of rupture and the viscosity of clay suspensions. All of these changes improved the soil for plant growth. Other studies in Venezuela have shown that many of the savanna soils have a hard layer of gravel and conglomerates at various depths. This layer serves as a mechanical barrier to root penetration and apparently has been one of the principal factors in causing the savanna type vegetation. Studies on the aggregation of two soils in Puerto Rico have shown that organic matter was the principal cementing agent between clay particles. The organic matter content of these well-drained upland soils was as high as that usually found in temperate zones.

As stated in the introduction, basic principles know no political boundaries. It is not surprising, therefore, that many of the research findings in Central and South America are not greatly different from those reported elsewhere. The data do indicate several fruitful avenues for research in the area of soil physics. One of these is concerned with the relatively low wilting point of many tropical plants. The questions that should be answered are: Is this due to the inbalance between root surface area and leaf transpiring area? Is it due to a shallow, poor root system? Is it due to slow water conductivity in the soil?

Another major problem that needs considerable research is the interrelation of soil physical properties (porosity, bulk density, hydraulic conductivity, moisture content, etc.) with soil chemical properties in relation to plant growth. It is inconceivable that 139 years after establishment of the Rothamsted Experiment Station, and after all of the other field research that has been conducted throughout the world, we are still conducting, in the latter third of the twentieth century, soil fertility field experiments in which no effort is made to control, measure, or in any way evaluate the effects of other factors such as soil physical properties, climatic environment, etc.

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[2] Personal communication.

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CHAPTER 3

Soil Management Under Shifting Cultivation

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Shifting cultivation can be defined as a continuing agricultural system in which temporary clearings are cropped for less years than they are allowed to remain in fallow. It is the predominant practice in approximately 44 percent of the potentially arable and grazing land in the tropics, as well as the means of subsistence of over 200 million people (FAO, 1957). Even the most densely populated tropical area, Southeast Asia, has about one third of the total farm land under shifting cultivation (Dobby, 1950).

Shifting cultivation is also the predominant agricultural system in terms of total area in Tropical America. It occurs in sparsely populated lowlands where plowing implements and fertilizers are not available. This practice is the main form of agriculture found in the Amazon Basin which covers about 45 percent of Brazil, 70 percent of Bolivia, 32 percent of Colombia, 40 percent of Ecuador and 60 percent of Peru. Significant portions of the Antilles, the Atlantic slope of Central America and the Pacific coast of Colombia are also under this system. Haney (1968) estimated that about 72 percent of the total farmed area of Panama consists of shifting cultivation plots.

This practice is known by a variety of local names such as milpa in Mexico and Central America, conuco in Venezuela, roza or monte in Colombia, chacra in Peru, roça in Brazil and chaco in Bolivia. In English it is also known as slash-and-burn agriculture and as swidden farming.

Throughout the world, however, a remarkable similarity of shifting cultivation practices exists. In Tropical America small fields are cleared by ax and machete during periods of least rainfall and burned shortly before the first rains. Without further removal of debris, crops such as corn, rice, beans, cassava and plantains are planted in holes dug with a planting stick. Intercropping is very common. Some degree of manual weeding is practiced. After the first or second harvest the fields are abandoned to rapid forest regrowth. The secondary fallow may grow for 4 to 20 years before it is cut again.

Most soil types are used regardless of fertility status. Shifting cultivation is practiced in areas with annual rainfall ranging from 750 to 7500 mm. In the highest rainfall areas where burning is not possible,

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such as in the Pacific Coast of Colombia, the cleared vegetation is used as a mulch instead of burning (Snedaker and Gamble, 1969). Good descriptions of shifting cultivation practices in Latin America can be found in articles by Haney (1968), Popenoe (1960), and Watters (1966, 1971).

The literature on this subject is extensive. Conklin (1963) has compiled over 1,300 references, most of which are not relevant to soil management. Extensive soils research has been conducted in Africa most of which is summarized in two excellent publications: Nye and Greenland (1960) and Jurion and Henry (1969). Much of the African experience is relevant to Latin America. Studies of soil under shifting cultivation have been conducted in several countries of this hemisphere. Most of the observations are semi-quantitative at best except for studies by Popenoe and associates in Guatemala, and certain studies in Bolivia and Peru. The following is an attempt to digest most of the available data from the region and relate them to concepts developed in Africa and Asia.

Soil-Forest Nutrient Cycles

The existence of a nearly closed nutrient cycle between a mature tropical forest and the soil was first recognized by Hardy (1936) in Trinidad. Since then, many studies have attempted to quantify this phenomenon as a means for obtaining an understanding of the mechanism responsible for lush forest growth in otherwise infertile soils. The nutrient cycle has two main nutrient storages: the biomass and the topsoil, which are connected by several pathways.

Vegetation Storage

The total biomass of mature tropical forests usually ranges between 200 to 400 ton/ha of dry matter. Studies conducted in the Congo (Bartholomew *et al.*, 1953), Ghana (Greenland and Kowal, 1960), Panama (Golley *et al.*, 1960), and Puerto Rico (Ovington and Odum, 1970) indicate that the proportion of the main forests parts is fairly constant. Approximately 75 percent of the biomass consists of branches and trunks, 15 to 20 percent roots, 4 to 6 percent as leaves and 1 to 2 percent as litter. Studies in Guatemala (Snedaker, 1970) show that the rate of secondary forest regrowth is about 10 ton/ha per year during the first 9 years. Studies in the Congo indicate that about 90 percent of the maximum biomass is attained during the first eight years of regrowth.

The first year of forest regrowth is similar to crop growth in terms of dry matter production. Tergas and Popenoe (1971) found the dry matter production of a 10-month-old forest to be 9.7 ton/ha while un-

fertilized corn produced 9.9 ton/ha near Izabal, Guatemala. When corn was adequately fertilized it produced 30 ton/ha during the same period. Results of longer term comparisons in Nigeria showed that the secondary forest produced 40 ton/ha after six years of regrowth while stargrass pasture established at the same time produced 17 ton/ha (Jaiyebo and Moore 1964). The biomass of mature forests in the Congo, Ghana, Panama and Puerto Rico provided the following nutrient ranges:

	kg/ha		kg/ha
N	701 to 2044	S	196 (one observation)
P	33 to 137	Fe	43 " "
P	600 to 1017	Zn	13 " "
Ca	653 to 2760	Mn	5 " "
Mg	381 to 3890	Cu	3 " "

The accumulation rates as a function of age of secondary forests vary substantially among nutrients. Most of the N, K, Ca and Mg is accumulated linearly (Bartholomew *et al.*, 1953).

These figures indicate that tropical forests accumulate more nutrients at a faster rate than temperate forests. Relatively young secondary tropical forests (18 years) accumulate more nutrients than 50-to 100-year-old temperate coniferous or hardwood forests (Greenland and Kowal, 1960).

Only about 40 or 50 percent of the total biomass is available to soil additions, mostly leaves, small branches and roots. The nutrient accumulation pattern in these parts is faster than in the rest of the vegetation. Leaves accumulate about 94 percent of their maximum uptake within two years of forest regrowth. About 80 percent of the maximum litter production and 64 percent of the maximum root production is achieved within the first five years in the Congo.

Soil Storage

The magnitude of the nutrient storage capacity of tropical soils in equilibrium with a mature forest was established by Greenland and Kowal (1960). The top 30 cm layer of a Latosol contained 2.6 times as much total N as the biomass and about the same amount of exchangeable Ca and Mg as the total plant Ca and Mg. The topsoil contained 75 percent of the biomass K as exchangeable K but only 9 percent of the biomass P as available P.

The African data also shows that 68 to 85 percent of the root system of mature forests is found within the top 25 to 30 cms (Greenland and Kowal 1960), which gives the subsoil a secondary role in the nutrient cycle.

Nutrient Transfer from the Vegetation to the Soil

The recognized mechanisms are rainwash (stemflow and thoroughfall), litter fall, timberfall and root decomposition. Although rainwash data varies considerably with seasons and species its contributions are considerable. Nye (1961) estimated it to be in the order of 12 kg N, 3.7 kg P, 220 kg K, 311 kg Ca and 70 kg Mg per hectare per year. Sollins and Drewry (1970) observed that the concentration of NO_3, K, Na, Ca, Mg and S in rain water increased from 2 to 6 times as it passed through a rain forest in Puerto Rico.

The annual rates of litter fall range from 5.5 to 15.3 ton/ha in the tropics as compared with 1.0 to 8.1 ton/ha in temperate forests (Ewell, 1968). The nutrient composition of the litter is similar between tropical and temperate forests except for a substantially higher N content in the tropics. The nutrient composition ranges in litter layers in Guatemala (Ewell 1968), Puerto Rico (Odum 1970), Ghana (Nye 1961) and the Congo (Bartholomew *et al.*, 1953) is as follows:

	kg/ha/yr		kg/ha/yr
N	74 - 199	Ca	45 - 220
P	1 - 7	Mg	10 - 94
K	8 - 81	S	9 - 10 (one site only)

The relationships between litter production, accumulation and decomposition have been studied by Jenny *et al.* (1949) and Suárez de Castro and Rodríguez (1955) in Colombia; Ewell (1968) in Guatemala; Weigert (1970) and Weigert and Murphy (1970) in Puerto Rico, as well as by Nye's and Bartholomew's groups in Africa. Although considerable argument exists about which are the proper parameters, litter decomposition rates vary from 50 to 500 percent per year (McGinnis and Golley 1967). Decomposition studies with time in the Congo (Bartholomew *et al.*, 1953) and Guatemala (Ewell 1968) show very similar trends. Approximately half the dry matter in the litter is mineralized within the first 8 to 10 weeks, after which the rate decreases. About 80 percent of the K is mineralized within the first month. P, Ca, Mg and S are mineralized at a faster rate than dry matter, but N is mineralized more slowly.

The only estimate in the available literature that includes all four sources of nutrient transfer is that Nye (1961). Assuming that 10 percent of the roots are decomposed per year the annual rate of nutrient transfer from the vegetation to the soil is as follows:

kg/ha/yr	Dry Matter	N	P	K	Ca	Mg
Rainwash	——	12	3.7	220	29	18
Litter fall	10528	199	7.3	68	206	45
Timber fall	11200	38	2.9	8	82	8
Root decomp.	2576	21	1.1	9	15	4
Total added	24304	268	15.0	303	332	75
% Total biomass	7	13	11	33	12	19

This extraordinary natural fertilization program is what keeps tropical forests so well supplied with nutrients.

Nutrient Losses from the System

The nutrient additions from the vegetation to the soil are nicely balanced with the nutrient uptake by the vegetation from the topsoil. Apparently the shallow nature of tropical forest roots provide a very effective means of maintaining a nearly closed nutrient cycle. (Nye and Greenland 1960). Nevertheless, nutrient uptake from the subsoil accounts for 20 percent of the total which undoubtedly contributes to the efficiency of the system. Data on leaching losses are almost non-existent. An analysis of Amazon river water provided the following leaching estimates: 0.5 kg NO_3, 4.4 kg K, 37 kg Ca, 5 kg Mg, and 5 kg SO_4 per hectare per year. (Russell, 1950)

The Cycle as a Whole

A quantitative study of nutrient cycling was attempted in Puerto Rico (Odum 1970, Edminsten 1970, Luse 1970, Jordan 1970). Unfortunately the quality of the data is questionable in many of their reports. The following generalizations, however, may be of value. The N cycle consists of an annual flow of 102 kg N/ha per year. This element is tightly held in the cycle. Additions from the rain wash and biological fixation plus possible denitrification losses in the soil are thought relevant (Edminsten 1970). The P cycle is restricted to the superficial soil layer. P^{32} release from decaying leaves is almost quantitatively held by the surface roots in the top 5 cm of soil and subsequently taken up by plants. P is strongly held in the cycle (Luse 1970). K is cycled at very high rates but it is loosely held. Ca, Mg, Mn, Fe and Cu are cycled slowly and bound very tightly (Jordan 1970, Odum 1970).

Changes in Soil Properties Under Shifting Cultivation

When the nutrient equilibrium described in the previous section is destroyed by clearing, the soil undergoes a series of changes caused by burning, cropping and regrowth.

Soil Physical Properties

Soil temperature. Air temperatures during the burning of a tropical forest may reach 450 to 650° C at 2 cms above the soil surface. Air temperatures decrease at the rate of 100 C per cm below the soil surface for the first 5 cm (Zinke *et al.*, 1970). Below this depth, Suárez de Castro (1957) found no changes in soil temperature during burning in Colombia.

After the burning process is over, cleared areas have higher mean air and soil temperatures than before (Budowski 1956). Maximum air temperatures increased from 25 to 32° C after a forest was cleared in Thailand (ASRCT, 1968), but no change was registered in minimum air temperatures. Maximum soil temperatures at 7.5 cm depth increased from 27 to 38 C when a forest was cleared in Ghana (Cunningham 1963) while the minimum temperatures remained at 24 C.

In a virgin forest of Guatemala only 4 percent of the total solar radiation reaches the soil surface (Snedaker, 1970). The first year of forest regrowth decreased incoming radiation to 35 percent of that of the cleared land. In older secondary forests only 5 to 10 percent of the solar radiation reaches the soil surface. The solar radiation and temperature data suggests that when a soil is cleared, the biological processes will be considerably stimulated but that after the second year of forest regrowth a situation similar to the virgin forest is attained.

Soil moisture. A mature 40-year-old forest canopy intercepts and evaporates about 16 percent of the total rainfall. It's leaching potential, therefore, increases by that amount.

Forested soils have a uniform soil moisture profile with deep water tables (if present) due to high transpiration rates from different soil layers (Budowski, 1956). After clearing a forest in Thailand, daily evapotranspiration increased eight times (ASRCT, 1968). Most of evapotranspiration losses then affect the top horizons which result in a disuniform moisture supply. Fluctuating water tables may be caused by clearing (Firth 1955, Budowski 1956). Soil moisture contents may increase in the B horizons with clearing (ASRCT, 1968). Budowski further believes that this is why iron pans, when present, are almost always found in savannas, rarely under forest and never in virgin forests.

Soil structure. It is widely believed that burning and clearing causes a deterioration of soil physical properties. Suárez de Castro (1957), however, observed that burning increased the infiltration rate and the soil aggregate fraction larger than 0.25 mm in a volcanic ash soil of Colombia. Popenoe (1957) observed that the bulk density of the 5 to 10 cm layer of Guatemalan soils increased from 0.56 to 0.66 g/cc after clearing and decreased from 0.74 to 0.70 after 3 or 5 years of forest regrowth in another observation. The overall low bulk density values also suggest the influence of volcanic ash. These differences are probably not significant enough to affect plant growth. Popenoe (unpublished) reports cases of irreversible dehydration in the soil surrounding long burning logs or stumps.

Watters and Bascones (1971) showed that bulk density increased from 1.08 to 1.14 g/cc and total porosity decreased from 59.5 to 57 percent in a yellow brown clay loam of the Venezuelan Andes with clearing. They did not consider these differences important. In Africa, Nye and Greenland (1964) observed visual soil compaction with clearing, but no change in bulk density within two years. Cunningham (1963) observed a decrease in total porosity from 52 to 43 percent and a similar decrease in water stable aggregates with three years of clearing in a latosol of Ghana without cropping. Friese (1934, 1939) reported that total porosity in some soils of southeastern Brazil decreased from 51 percent in a virgin forest to 12 percent in a savanna. He attributed the decrease to clay shrinkage and cracking, suggesting the presence of montmorillonite.

These results suggest that compaction occurs in mild degrees in volcanic ash soils and Latosols, but it may be an important factor in soils with less desirable physical properties.

Runoff and erosion. Popenoe (1957) found little surface erosion in cleared fields with steep slopes in Guatemala and attributed it to the low soil bulk density. He observed that most of the erosion takes place as land-slides during heavy rainfall. Suárez de Castro (1957) showed that runoff decreases after clearing in Colombia and attributed it to increases in permeability due to burning. Both sites were affected by volcanic ash. The effects of clearing on soil runoff and erosion losses may be severe in other soils.

Soil chemical Properties

Soil acidity. Ash additions containing large amounts of bases increase the pH of most soils after burning. Nye and Greenland (1964) estimated that the ash contained about 5.3 ton Ca/ha, 0.7 ton Mg/ha and 1.6 ton K/ha in Ghana. Leaching of these bases during cultivation results in a subsequent pH decrease. The magnitude of these changes varies with soil properties. In soils affected by volcanic ash, Suárez de

Castro (1957) reported pH increases from 4.6 to 5.4 after the first burning and smaller increases after burning crop residues after each harvest. Popenoe (1957) reported increases from 5.8 to 6.4 in the top 5 cm and back to the original levels after the second year of regrowth. No changes were detected in the 5 to 40 cm layer. Watters and Bascones (1971) also reported increases from 4.1 to 4.4 in the top 8 cms and no changes below in the Venezuelan Andes.

Cowgill (1962) observed no significant pH changes in calcareous soils of Petén, Guatemala. Urrutia (1967) reported slight pH decreases in a similar soil with secondary forest regrowth.

The last three studies were based on samples collected under forests of different age at the same time. Studies conducted on one site sampled at different times provide a more accurate picture. Nye and Greenland (1964) found that pH increases from 5.2 to 8.1 in the top 5 cm right after burning and a decrease to 7.0 after two years. The 5-15 and 15-30 cm layers increased from 4.9 to 6.2 with burning and decreased to 5 after two years. Popenoe (unpublished data) also observed pH increases down to 40 cms in Guatemala. These studies indicate that unlike commerical lime, ashes tend to move down the profile and increase the pH at substantial depths. Unlike lime, its mobility causes these pH increases to be short lived, but highly beneficial to the crops grown under shifting cultivation and perhaps to the initial forest regrowth.

Organic matter and nitrogen. Although burning volatilizes most of the nitrogen, carbon and sulfur present in the vegetation, it does not decrease the organic C and N contents of the topsoil. Both Nye and Greenland (1964) and Popenoe (unpublished) actually found that organic C and total N increased after burning, probably due to incomplete combustion of the vegetation. Organic matter contents decreased rather sharply in the top 5 cm of the soil possibly due to increased soil temperatures (Popenoe, unpublished; Nye and Greenland, 1964). Total N, however, remains constant in some cases (Suárez de Castro, 1957; Popenoe, unpublished) and decreases in others (Popenoe 1957, Cunningham 1963, Nye and Greenland 1964). The C/N ratios, therefore, drop sharply in some cases (from 16 to 8 in two months in high organic matter soils of Guatemala) and remain stable in others. Most studies agree that changes below the first few cms are negligible in terms of C, N and C/N ratios. When sharp drops in C, N or C/N ratios take place, they occur within the first few months and reach an equilibrium after one or two years (which is the extent of the data available). Regrowth of secondary forests reverse the above trend (Urrutia 1967). Jaiyebo and Moore (1963) observed annual increases in the order of 700 kg N/ha per year during the first three years of forest or kudzu pasture regrowth.

Organic matter decomposition rates under these conditions is a subject of considerable debate. A summary of African and Latin American data on the subject by Greenland and Nye (1959) show an average decomposition rate of 3 percent for organic carbon. They also found that soils under shifting cultivation maintain a C content of 75 percent of the equilibrium value, provided a crop:fallow ratio of at least 1 to 3 years, which is considerably shorter than the actual practice.

Phosphorus. The C/P ratios and N/P ratios in the organic matter of tropical forested soils of Ghana are considerably higher than those of temperate regions and indicative of P deficiencies (Nye and Bertheux, 1957). In spite of the relatively low amount of P cycling, the tightness of this cycle prevents P deficiency under natural conditions. Upon burning, the Bray-extractable P in the top 5 cm layer of a Guatemalan soil increased by about four times and remained so for about six months. At the end of one year it was still twice the original value (Popenoe, unpublished). No changes in available P were observed below that layer. Suárez de Castro (1957) in Colombia and Watters and Bascones (1971) in Venezuela observed similar relationships.

Urrutia (1967) found that secondary forest regrowth increases the Bray-extractable P in Rendzinas of Petén, Guatemala. The low mobility of the P in the ash certainly favors its conservation in the soil unlike that of the exchangeable bases. Tergas and Popenoe (1971) observed drastic species differences in their P uptake after 10 months of secondary forest regrowth in Guatemala. At similar levels of dry matter production, *Heliconia* spp. and *Gynerium* spp. accumulated about 3 times the P of the average vegetation.

Exchangeable bases. About all the K, Ca and Mg in the vegetation after burning can be accounted for by the increase in exchangeable K, Ca and Mg in the topsoil (Nye and Greenland, 1964). Large leaching losses of K and Mg occur during the first year but Ca losses are small. Popenoe (unpublished) found that the exchangeable K contents in the top 0-5 cm layer tripled after burning, decreased to twice the original value within three months and to the original value within a year. K contents from 5 to 40 cm remained unchanged. He also observed that exchangeable Ca in the top 5 cm increased by 50 percent and exchangeable Mg by 75 percent with burning but both elements reverted to the original value in less than a year. Popenoe (1957) showed that Ca and Mg move down to the 20 to 40 cm layers, where they can still be recovered by crop roots before they move further. After two years, leaching, erosion, and crop removal of Ca and K from the soils accounted for only 50 percent of the gains incurred after burning in Ghana (Nye and Greenland 1964) implying that the beneficial effects of the ash may extend beyond the usual cropping period. Exchangeable K and Mg increased with regrowth of secondary vegetation in Guatemala (Urrutia 1967).

Soil Microbiology

Mieklejohn (1955) in Kenya observed that burning decreased the soil microflora and that aerobic N fixers are killed while anaerobic N fixers survived. Suárez de Castro (1957) on the contrary found no changes in the fungi, actinomycete and bacterial flora within one week after burning in the 0 to 10 and 10 to 20 cm layers of a Colombian Andosol. Fowells and Stephenson (1934) observed that nitrification is stimulated by burning and the liberation of basic ash in Oregon. Apparently, the detrimental effects observed by Mieklejohn were short lived.

Crop Performance Under Shifting Cultivation

The high supply of organic nitrogen (and probably sulfur) left in the topsoil after burning plus the large quantities of phosphorus, potassium, calcium, magnesium and probably micronutrients added in the ash almost insures no fertility limitations to the first crop grown in most tropical soils.

In Latin America, farmers' surveys indicate that the yields of the second crop are about half of the first and the yields of the third crop if grown, are half of the second (Cowgill 1962, Watters 1971). The plots are usually abandoned when the yield decreases to half the original.

A significant proportion of shifting cultivation plots are cropped to perennials such as plantains and papayas before finally reverting to the forest. In other areas pastures are established during or immediately after the harvest of the first crop and kept for several years. Haney (1968) points out that such pastures support a high carrying capacity for a few years in Colombia, provided that they are burned annually, but that eventually they are destroyed by overgrazing and the land becomes useless. In Yurimaguas, Peru, about 20 percent of the plots cropped to upland rice are kept in natural pastures for several years. One ranch has 20 year-old natural pastures with good carrying capacity which have not been fertilized. In Pucallpa, Peru, pasture production is limited unless fertilized.

Crop yields

Agronomic experiments in shifting cultivation systems are very scarce in Latin America. The high soil nutrient supplying capacity after cutting the forest prevented fertilizer responses in the first crop of upland rice in Peru (Sanchez and Nureña, 1972) and of corn in Guatemala (Urrutia, 1967).

Continuous cropping experiments have provided some surprising results. Cordero (1964) grew upland rice and sugar cane for five consecutive years on an Alluvial soil near Santa Cruz, Bolivia without fertilization. Rice yields were primarily dependent on rainfall and no fertility decline with time could be observed. Actually, the highest yields were obtained in the fourth year. With sugar cane, the original planting produced the highest yields but the four consecutive ratoon crops did not show significant yield differences. Sanchez and Nureña (1972) grew three continuous crops of upland rice on a Tropaqualf near Yurimaguas, Peru. No yield declines were observed and the third crop was actually superior to the previous ones, probably because of better rainfall distribution. With a total N application of 20 kg N/ha, the cumulative yields were 8.5 ton/ha. The fourth consecutive crop also yielded well but the fifth began to develop certain nutrient deficiencies which reduced yields considerably. The Bolivian and Peruvian experiments were conducted with adequate but probably uneconomical weed control.

Fertilizer Responses

After the second crop, responses to fertilizers are commonly observed. Urrutia (1967) obtained significant yield increases of corn in a Rendzina of Guatemala and Sanchez and Nureña (1972) with rice in the Selva of Peru with N applications during the third consecutive crop, but no responses to added P and K were found in either cases in spite of relatively low soil test levels of these nutrients.

These three studies suggest that the fertility decline after clearing these soils is relatively slow. In all cases none of the soils were highly weathered or of coarse texture. Pendleton (1954) observed that nutrient leaching is so fast in certain sandy soils of Trinidad that no second cropping is possible on them. Similar situations may exist in other well-drained sandy areas.

Management Practices

An interesting experiment was conducted for several years by Suárez de Castro (1957) in a volcanic ash soil of Chinchiná, Colombia on the effect of burning corn residues under continuous cropping. In a plot where corn yields did not decline for four years under conventional cultivation, the cumulative yield was 9.2 ton/ha. When corn stubble was burned, the cumulative yield increased slightly to 11.8 ton/ha. In another plot where the conventional treatment resulted in sharp yield decreases with time, a total of four crops yielded 5.4 ton/ha while burning the corn stubble yielded 8.9 ton/ha. Burning crop residues might be a feasible means for adding P and bases to the soil in places

where fertilizers are unavailable or expensive.

Land clearing methods have recieved keen attention from government planners and large private operations in shifting cultivation areas of the Amazon Basin. The effect of land clearing methods on costs, yields and soil properties was studied by Cordero (1964) in Santa Cruz, Bolivia. Clearing, burning and planting by hand was compared with mechanized clearing, vegetation removal, plowing and leveling with bulldozers and root rakes. Cordero found that the clearing costs tripled with mechanization while no significant yield differences were observed with four consecutive crops of upland rice or five crops of sugar cane, and that mechanized land clearing decreased the soil organic matter content from 4.6 to 3.6 percent as compared with the conventional way due to the topsoil removed by the bulldozers. A series of huge land clearing machines have been developed in Pucallpa, Peru (Abastos 1971) and used to clear large tracts of jungle. While there is no question about the effectiveness and thoroughness of their operation, crop and pasture production has been relatively poor because no successful soil management practices have been devised.

The African Experience

There is not a single reference in the available literature related to soil management studies on Ultisols and Oxisols under shifting cultivation in Latin America, even though the bulk of the shifting cultivation areas occurs on such types of soils.

This subject has been thoroughly researched by African scientists for over 50 years. Perhaps the most important finding is the extreme variability of results within regions or soil types. Vine (1953, 1954, 1968) summarized much of the work in Nigeria and concluded that crop yields can be maintained satisfactorily for long periods of time with small amounts of fertilizers or green manures. Corn yields fluctuated from 1.3 to 1.6 ton/ha during 17 years when a velvet-bean crop was planted, burned and incorporated every year (Vine 1964). No responses to N were observed in the first 8 to 10 years. Short term green manure crops were not sufficient when the soil N was considerably depleted. In savanna soils with C/N ratios greater than 12, N deficiency was common during the first year. The extensive experiments conducted by INEAC in the Congo and elsewhere (Jurion and Henry 1969) produced results so variable that led INEAC to recommend a systematic shifting cultivation system in long rectangular plots rather than continuous cropping. Other relevant African papers are included in the bibliography.

Conclusions

There is no doubt in this writer's mind that shifting cultivation is an efficient soil management system for subsistence farming in low populated tropical areas. Most of Latin America's population is concentrated in high-density coastal and highland areas. When governments act to relieve these pressures through road construction or colonization projects, other alternatives for soil management must be developed. Such is now happening with the Transamazonic highway construction in Brazil and similar road building and oil-drilling operations in other Amazon Basin countries. The knowledge of this subject in Tropical America is very limited and only parts of the puzzle have been developed in a wide variety of localities. What is badly needed is a systematic approach, measuring changes in soil properties as a function of time, coupled with parallel efforts in weed control and with the development of economically realistic fertilizer and management practices best adapted to specific areas.

This review raises some specific thoughts for research:

Since the primary productivity of tropical forests is much higher than temperate counterparts, why should not one be able to obtain high crop yields with adequate rotation schemes, fertilizers and weed control?

Most of the nutrients accumulated in secondary forests reach maximum values at early stages of regrowth (5 to 8 years). Is it necessary to wait as long as 15 to 20 years or is it mainly a question of ease of weed control? To maintain soil N at 75 percent of the equilibrium level only requires three years of regrowth per year of cropping—why wait longer?

Ash must supply substantial quantities of P and act as highly mobile lime. The Ca and K added in the ash stays in the soil longer than it is usually cropped. Can the cropping period be prolonged with new cultural practices?

Burning crop residues every year may be equivalent to burning a year-old secondary forest. Could this practice take care of a large portion of the fertilizer requirements?

Short term green manures have been successful in Africa as suppliers of nitrogen. This merits investigation in Latin America.

The large quantities of nutrients returned annually to the soil from the forest is probably too great to be applied economically as fertilizer and lime. The annual fertilizer requirements of crops could be reduced by stubble burning and green manure incorporations.

The soil should be covered by crops at all times to prevent possible physical damage and excessive increases in soil temperature. Multiple cropping could not only decrease compaction, erosion and runoff, but also reduce weed control efforts.

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CHAPTER 4

Soil Nitrogen in the Tropics

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Research on soil nitrogen and nitrogen transformations in soils of the tropics has been spotty. In some specific areas there has been a fair research effort in tropical environments while in others there is little or no information. Tropical agriculture appears to have depended heavily on research in temperate areas for fundamental information on soil nitrogen. This extrapolation of information appears in most instances to be both reasonable and appropriate.

However, there are some soil nitrogen and organic matter transformation processes in the tropics as well as some soil nitrogen movement and crop absorption patterns which are quite different from those commonly observed in temperate regions. These differences result largely from differences in climate and not from any differences in the fundamental biological processes. In fact, fundamental principles should apply in and all situations when due consideration is given to environmental factors.

In temperate regions, the annual cycle of growth of vegetation is restricted annually by cold temperatures. A variety of rainfall regimes are found in combination with the cold seasons. However, during the growing seasons the rates of evapotranspiration generally exceed the rates of precipitation. Also, in most temperate regions the growing season starts with the supply of available water in the soil.

In all but the wettest tropical regions, plant growth may be limited at one or more times during the year by drought. In seasons of heavy rainfall, excess water may move rapidly down through the soil and carry many soluble plant food elements with it. At the end of each wet season and during the onset of the dry season, the vegetation removes most or all of the available water within the range of plant roots. Consequently, the next cropping season starts without any reserves of water for the growth of the ensuing crop.

These basic differences in the rainfall and temperature regimes between temperate on tropical climates require important management innovations in the transfer of soil management technology from temperate to tropical agricultural systems.

Several technical areas relative to nitrogen have been examined in some detail. However, the literature search has not been exhaustive owing to the magnitude of the task.

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The literature examined has led to the generalizations which follow. The references consulted are grouped into subject categories in the literature reviewed sections.

Soil Organic Matter and Organic Nitrogen

The quantities of organic matter and organic nitrogen in soils of the tropics have been measured in numerous instances and have been reported in many diverse publications. An appraisal of the results indicate that the same general principles relative to accumulation and loss of soil organic nitrogen apply to both tropical and temperate regions when due consideration is given to climatic differences.

In general the quantities of organic nitrogen in soils of tropics are low. There are some notable exceptions, e.g., the volcanic ash soils, some altiplano soils, and some rain forest soils. Many of the soils in the tropics have been cropped for long periods of time; the organic nitrogen accumulated under virgin conditions has been dissipated; the organic matter has closely approached equilibrium under current management; and the net amounts of nitrogen supplied to crops from organic nitrogen are near zero. If nitrogen fertilizers have not been used, the crop yields on these soils closely reflect the quantities of nitrogen coming from rain water and nitrogen fixation.

On the other hand, there are yet large areas of land in tropical regions that have not been cleared and cultivated within the known history of the land. The clearing and cultivation of some of these areas is now underway. Additional areas will be cleared in the future. The inland regions of Brazil are examples. Following clearing and cultivation the soils would be expected to furnish some substantial amounts of nitrogen to the crops grown. The amounts furnished, the rates of anticipated declines in soil organic nitrogen, and the times of cultivation at which equilibrium will be essentially established are important factors about which there is little information in the research literature. Moreover, experience in temperate regions may not be helpful in evaluating the rates of changes of organic matter in tropical zones.

There have been some studies on rates of mineralization of organic nitrogen, but since most are laboratory and/or greenhouse experiments, extrapolation to natural field situations is beset with difficulties.

Mineralization of Organic Nitrogen

Several factors peculiar to the tropics influence the course of mineralization of soil organic nitrogen. Perhaps the primary factor is the temperature of soils of the tropics. The absence of a cold season permits mineralization to proceed at all seasons when moisture is not limiting.

Annual rates of mineralization therefore, should be larger than in temperate zones (Jenny, 1949).

A second factor is the dry season prevalent in most tropical areas. Desiccation of the soil followed by wetting tends to cause a surge of microbiological activity and of nitrogen mineralization (Birch, 1958; Soils and Fertilizers, 1948; Semb and Robinson, 1969). This flush in mineralization and thus in available nitrogen at the onset of a wet season is an important factor in nitrogen use management in many parts of the tropics.

A third factor is the mineralization reactions in volcanic ash soils. These soils tend to be rather high in organic nitrogen (Kobo, 1964), but also tend to supply nitrogen slowly even when high in organic matter. The organic matter tends to be rather stable towards mineralization (Fox, 1969).

Theron (1951) reports that plants have an influence on mineralization of organic nitrogen in the soil. He also suggests that grass may influence nitrification. However, these phenomena are controversial and need further investigation.

Nitrogen in Rain and Dust

Nitrogen additions to soil areas by rain are considered here because in many low producing areas of the tropics this source may be supplying an important part of the nitrogen for crop production.

The general magnitudes of nitrogen coming to the soil from this source range from 1 to in excess of 50 kg/ha/yr. The mean is from 6-8 kg/ha/year.

It is of interest to note that the largest quantities reported from rain have been from studies in tropical areas (Jones and Bromfield, 1970; Thornton, 1965; Gore, 1968).

Symbiotic Nitrogen Fixation

An evaluation of the literature indicates that symbiotic fixation of nitrogen in tropical regions is basically like that of temperate regions. The chief differences lie in the spectrum of host plants, the prevailing climatic regimes and the predominating soil conditions.

Much of the research on symbiotic nitrogen fixation in tropical environs has been done in Australia in relation to pasture problems.

Symbiotic nitrogen fixation contributes the large proportion of the nitrogen for plant growth in tropical areas. However, most of this incoming nitrogen comes into forested regions, savanna areas, and pastures and only a minor proportion comes by way of intertilled crops.

The literature examined covers a wide spectrum of topics relative

to symbiotic nitrogen fixation. These include: tropical host plants; symbiotic microorganisms; biochemistry of nitrogen fixation; inoculation procedures and evaluations of nodulation; methodology for evaluating fixation processes; influence of legumes and other host plants on associated plants; and soil and climatic factors influencing the growth of host plants and nitrogen fixation.

An appraisal of the status of progress in the field of symbiotic nitrogen fixation suggest that the problems of legume culture in pasture production may be of prime importance in tropical and semitropical agriculture. Some persistant problems apparently needing increasing attention have to do with inoculation and nodulation of legumes newly introduced into a region and the management and fertilization of leguminous and other host plant crops.

Non Symbiotic Nitrogen Fixation

There is a large collection of literature pertaining to non-symbiotic nitrogen fixation (fixation by free-living microorganisms). Several aspects of the subject have been covered extensively by review publications (Burris, 1969; Jensen, 1940, 1954, 1965; Stewart, 1969; Verdade, 1969).

The following generalizations provide summaries of several aspects of the subject:

1. The capability for nitrogen fixation is rather widespread among free-living organisms. It occurs among both the autotrophic and heterotrophic organisms. Present day methods of detection have demonstrated a much wider distribution of the capability than was considered possible a few years ago.
2. Organisms with nitrogen fixing capabilities are distributed over all of the land surfaces of the earth where plant growth is possible (Jensen, 1965; Stewart, 1969).
3. The biological mechanisms and control processes of non-symbiotic nitrogen fixation are very similar to the processes in symbiotic fixation. Biochemical information suggests similar enzymatic processes (Burris, 1969).
4. The fixation processes are closely related to and controlled by the physiology of the organism. Jensen (1940) states that, "The process is growth bound, i.e., it is only performed by cells in a state of multiplication and is thus correlated with a synthesis of new cell material . . . .".
5. The organisms which have this capability can absorb and use combined nitrogen. In fact, the preponderance of evidence

indicates that the presence of only small amounts of combined nitrogen in the growth medium will largely, if not completely, inhibit fixation. There is not general agreement relative to the critical concentration of combined nitrogen to inhibit fixation, but it is sufficiently low to lead to the frequent conclusion that this mode of fixation is very low in normal agricultural situations in soil.

6. The estimates of non-symbiotic fixation in average soils range from 1 or 2 kg/ha/yr to as much as 20 to 40. The general concensus put the estimates from 2 to 10 kg/ha/yr.

7. Almost all of the research on fixation by free-living organisms has been done in the laboratory or in the greenhouse. The few estimates of the magnitude of the process from field studies have been beset with large errors of measurement such as sampling the soil and making nitrogen determinations.

8. Under idealized conditions where environmental conditions have been optimized and energy material (light or carbohydrate) has been present in abundance, fixation rates have been very high. Such has been demonstrated in the laboratory, in the greenhouse, and under field conditions.

9. The importance of this process (non-symbiotic nitrogen fixation) to practical production agriculture is questionable. Under systems of low productivity where the nitrogen in the soil is persistently low and where a reasonable supply of carbohydrate energy material is returned to the soil, from 4 to 8 kg/ha/yr is a reasonable estimate of the magnitude of fixation per year. Where rice is grown and the soil flooded, algae may make a similar or greater contribution to the annual increment of nitrogen added to the soil. In situations where large crop yields are consistently grown, the available nitrogen in the soil would be sufficient to inhibit fixation and result in little or no nitrogen from this process.

10. In non-agricultural situations or in many soil areas which are grazed, non-symbiotic nitrogen fixation may furnish from 2 to 10 kg/ha/yr, depending on the area and the environmental circumstances. It seems very probably that this process may be important on a large segment of the earth's surface and be important to the total supply of fixed or combined nitrogen. The agricultural use of such nitrogen would result chiefly from grazing animals and/or from transfer of the nitrogen by animals, wind carried dust, or by volatile routes to other agricultural areas.

Nitrification and Urea Hydrolysis

An evaluation of the experience with nitrification reactions and with the transformations of urea in soils of the tropics indicates no essential differences from those obtained in soils of temperate regions. Much of the work in tropical areas has been concerned with transformations in paddy or submerged soils.

Nitrogen Movement in Soil and Loss Processes

Information from tropical zones relative to nitrogen movement in the soil is scarce. Most investigators have assumed the existence of extensive leaching during the wet seasons in the tropics. Actual measurements were found only for lysimeter studies.

Fluctuations in nitrate content of soils have been noted in a number of instances in tropical regions. These fluctuations generally have been related to the advent of the dry season or to the beginning of the wet season. The extent of net vertical movement of nitrogen under specified rainfall, cropping and soil conditions still must be determined. This would include downward displacement during the wet season and upward displacement during the course of the dry season.

No direct measurement on volatile loss processes was found in the literature review except from the temperate zones and from Austraila. In general, in temperate zones such losses have been constant but not large, except under some abnormal environmental situations. Since we have not developed any management techniques to prevent such losses, it is not likely that research in this area could be made to have a major impact on nitrogen use practices.

Shifting Cultivation and Burning

The practice of shifting cultivation to restore a measure of productivity to land and of burning to eliminate plant residues and weeds both have major impacts on crop growth through some modifications of the soil nitrogen supplies. For these reasons, some literature dealing with the subject was reviewed. Nye and Greenland (1960) provide a comprehensive review of shifting cultivation. The literature on burning in the tropics needs to be comprehensively reviewed and evaluated.

Microorganisms and Microbial Activity

Numerous publications are found concerning the kinds, numbers, and activities of microorganisms in soils of the tropics. Only a few are listed. They tend to show a rather universal distribution of common

soil organisms and that numbers and activity are very similar to those found in temperate zones.

Research Areas Needing Attention

Nitrogen is the element most likely to limit the crop growth in tropical regions. The nitrogen needs in these regions will eventually be met either by natural supply processes or through fertilization. The natural supply processes have many inherent limitations and it is unlikely that any process with the possible exception of biological fixation could be improved sufficiently through management research to warrant the research input.

The needs for research lie in the area improving the efficiency of use by crop plants of the so-called available nitrogen in the soil. General estimates place crop use at about 50 percent of the soluble nitrogen in the soil. The remainder escapes plant absorption either by loss processes which remove it from the field of action or by failure of the crop to absorb the nitrogen because of root-zone position, or because of unfavorable moisture situations. A better understanding of loss processes in tropical environments and of plant absorption processes from the root zones of tropical soils appears as the best avenue for improving crop production and for bettering the use of nitrogen resources. Some aspects of the nitrogen problem needing attention in tropical environs are listed below.

Position of nitrogen in the root zone

In temperate regions the position of nitrogen in the root zone of crop plants has been shown to have an important influence on the rate of plant absorption of the nitrogen. Data are sparsely available for the tropics, but similar influences would be expected. Since vertical movement patterns in soils of the tropics may be quite different from those commonly found in temperate zones, the direct transfer of soil management techniques from the temperate to the tropical zones is hazardous. The impact of vertical as well as lateral position of nitrogen on rates and extents of crop absorption needs to be known for major tropical soils and crops.

The influence of water on crop absorption of nitrogen

It is well known that water has a profound influence on plant absorption of nitrogen as well as on the absorption of other nutrient elements. As a guide in nitrogen management in tropical regions, it would be quite important to determine the physical status of water in the several depth horizons of tropical soils during both the wet and dry seasons and also to know the vertical zone from which crop plants use water.

Crop use of nitrogen

Actual crop of nitrogen at varying yield levels can be found for the cereal crops (corn, wheat, and rice) and for several commercial crops like sugarcane, pineapple, and bananas. For the cereals the information comes almost wholly from temperate zone research.

The quantities of nitrogen actually absorbed and used by crops in tropical regions needs to be known as a guide in planning fertilizer practices. Such information constitutes the standard by which fertilizer efficiency is evaluated. For most crops nitrogen use is constant and predictable and varies largely with crop yield.

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CHAPTER 5
Nitrogen Fertilization

Pedro A. Sanchez[1]

Starting with this chapter, most of this review consists of examining crop responses to fertilizers. It is appropriate to consider the relative importance of the major food crops in Tropical America. Table 5 indicates that the crops produced in largest quantities are cassava, corn, rice, potatoes, wheat and beans, in that order. Nitrogen is the most commonly applied nutrient in the region. The average application rate for Tropical America was 14 kg N/ha (Rodríguez, 1967), which indicates that the proportion of crops receiving nitrogen applications is still low. The following sections review the nitrogen fertilization research conducted on the major food or feed crops of the region.

Cereal Crops

Corn

Corn is the second food crop produced in largest quantities in Tropical America and the first in area planted. It is found in almost every farm under a wide variety of soils, climate and management.

Responses. Many recent field trials conducted throughout Tropical America indicate that corn responds positively to nitrogen rates between 60 and 150 kg N/ha (Berger 1962, DeGeus, 1967, CIMMYT 1967. 1960). Nevertheless, the actual nitrogen use is considerably lower. The factors affecting the response vary considerably between major soil groups. In areas where Oxisols and Ultisols predominate, there is a wide variability in nitrogen response by corn. Although positive responses within the range mentioned are common, in many instances corn does not respond to nitrogen both in recently cleared and in intensively cropped land. Gallo *et al.* (1968) for example, observed positive responses in 24 out of 31 experiments conducted in the State of São Paulo, Brazil. DeFreitas *et al.* (1960), Mikklesen *et al.* (1963), Gomez *et al.* (1963), Cornell University (1971) cite cases of no response while other investigations report only positive responses (Viegas *et al.*, 1963, Miranda *et al.*, 1964, IAEA 1970).

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Table 5. Production, area and yield of major food crops of Tropical Latin America[1] (Calculated from the FAO Production Yearbook 1970).

Crop	Production (million m. tons)	Area (million has.)	Yield (ton/ha)
Cereals:			
Corn	30.9	23.8	1.30
Rice	11.4	6.2	1.84
Wheat	4.3	3.0	1.44
Sorghum	2.8	1.3	2.17
Barley, oats, rye, millet	0.9	1.3	0.69
Total:	50.6	35.3	1.43
Root Crops:			
Cassava	34.5	2.5	13.80
Potatoes	6.6	0.8	8.25
Sweet potatoes and yams	3.7	0.4	8.50
Total:	44.8	3.7	12.11
Grain Legumes:			
Beans	4.1	6.8	0.60
Soybeans	1.9	1.4	1.35
Peanuts	1.1	0.8	1.49
Broadbeans, chick peas & peas	0.5	0.6	0.83
Total:	7.6	9.6	0.79
Bananas:	16.3	0.9	18.20

[1] Excludes Argentina, Chile and Uruguay.

The absence of nitrogen responses has been attributed to other limiting factors such as aluminum toxicity or phosphorus deficiency in cases where yields were low and to a high native nitrogen supply where yields were high. DeFreitas *et al.* (1960) failed to obtain responses in a Cerrado soil limed to pH 5.5 apparently because of other nutrient deficiencies. Mikklesen *et al.* (1963) observed an inverse relationship between nitrogen response and organic matter or clay content in three recently cleared Cerrado soils. Corn responded positively to 240 kg N/ha in Regosol low in organic matter but negatively to 60 kg N/ha in a Dark Red Latosol with 2.6% organic matter.

Recent work in Puerto Rico confirms that some Oxisols and Ultisols have very large amounts of inorganic nitrogen in their profile, but that these amounts are not necessarily related to nitrogen responses by

corn (Cornell University, 1971). No responses were observed in a clayey Oxisol with 381 kg/ha of inorganic nitrogen in the profile while a clayey Ultisol with 300 kg/ha produced a sharp response. There is a need for further research to clarify the processes involved, including the flushes of nitrogen mineralization at the start of the rains in Ustic environments, the pattern of nitrogen movement in the profile and landscape, and the residual effect of previous nitrogen applications.

The voluminous research conducted in the highlands of Mexico and Central America indicates that nitrogen responses are more consistent in this region than in Oxisols and Ultisols. Reports from Mexico (Laird and Lizárraga 1959, Laird and Rodríguez 1969, Turrent 1970) show that when no responses are obtained, they are due to drought, weeds, waterlogging, or other factors than high nitrogen supply or soil acidity limitations. Generalized nitrogen rate recommendations for attaining optimum yields have gradually increased in Mexico, from 40 to 50 kg N/ha in the 1940's to 80 kg N/ha in the 1950's and from 80 to 175 kg N/ha in the 1960's (Colwell 1946, Laird and Lizárraga 1959, CIMMYT 1967, Turrent 1970).

In the Cauca Valley of Colombia, Gómez (1968) conducted a continuous cropping experiment for 11 years with two crops per year. He observed no responses to nitrogen until the tenth crop. Afterwards, optimum yields were obtained with 80 kg N/ha until the sixteenth crop and with 120 kg N/ha up to the twenty-third. In the irrigated coastal areas of northern Peru, Seminario and Peña (1971) obtained linear responses and maximum yields at 180 kg N/ha. Their curves suggest that higher rates may have produced even higher yields.

The influence of cultural practices and weather on nitrogen responses by corn have been studied in several areas. The general increase in recommended rates in Mexico during the past 25 years is no doubt related with better varieties and cultural practices. Viegas *et al.* (1963) studied the effects of varieties, population and fertilization in 32 experiments on a wide range of soils in São Paulo State. They observed no interactions between these factors and obtained the highest yields with hybrids seeded at 50,000 plants/ha and fertilized with the highest nitrogen rate. The need for higher plant populations to obtain maximum yields at high nitrogen levels has been confirmed by Ramírez (1964) in Venezuela, Laird and Lizárraga (1959) and Turrent (1970) in Mexico. The optimum population at optimum nitrogen levels ranged from 45,000 to 57,000 plants/ha while for unfertilized corn 20,000 to 38,000 plants/ha was sufficient.

Perhaps the most fruitful research approach on this subject has been developed by Turrent (1970) in the Puebla Project of Mexico. During the first year, 27 experiments were conducted in farmers' fields to determine the extent and variability of nitrogen and phosphorus

responses to corn. In the next two years the interactions between nitrogen rates and timing, phosphorus rates, and plant populations were studied in several soils. The soils were then grouped according to factors related to corn yields which in this case were subsoil texture and depth of root penetration. The recommendations were given to farmers by soil group in terms of nitrogen rates and timing, variety and plant population.

The effects of drought and excess moisture on nitrogen responses have been established for the Bajío region of Mexico. The number of drought days during the tasseling stage directly reduced corn yields at high nitrogen rates (Fernández and Laird 1958). The depressions in yield response due to drought or excess moisture reduced maximum yields by about half of those where rainfall distribution was adequate (Rockefeller Foundation 1963-64).

Sources, timing and placement. A series of trials in Brazil, Colombia, Mexico and Peru coordinated by the International Atomic Energy Agency served to evaluate the efficiency of several management practices with radioisotopes in the field (IAEA 1970). The results show no differences between ammonium sulfate, urea and ammonium nitrate as sources of nitrogen for corn in the sites studied. Orihuela and Espinoza (1968) reached similar conclusions in Venezuela but Gil (1959) obtained superior performance with ammonium sulfate in the Cauca Valley of Colombia. No differences between ammonium sulfate and anhydrous ammonia were observed by Gargantini *et al.* (1968) in Brazil. Preplant applications of sulfur-coated urea resulted inferior to postplant applications of commercial urea but equal to preplant urea in an Ultisol of Puerto Rico (Cornell University, 1971).

Research on nitrogen placement and timing has been conducted in many locations. As expected in this type of work, the results vary among sites due to differences in soil type, rainfall and leaching. Basal applications either plowed-in or banded were more efficient than sidedressing in an irrigated experiment at La Molina, Peru (Lugo, 1969). No differences due to timing and placement of ammonium sulfate were observed by Miranda and Freire (1964) in ten experiments in São Paulo. Experiments coordinated by IAEA (1970) in Brazil and Colombia, by Laird and co-workers in Mexico and by Cornell University (1971) in Puerto Rico show that either split or sidedressed applications are more efficient than basal applications because the leaching losses or weed competition are reduced. Turrent (1970) studied the variability in sites and with seasons and concluded that sidedressing at first cultivation was the method that gave the most consistent results in Puebla, Mexico.

Rice

Rice is the third food crop produced in largest quantities in Tropical Latin America. It is grown under upland conditions (direct seeded, rainfall dependent) in about 75 percent of the total acreage, mainly in areas or seasons with high temperatures, monthly rainfall greater than 200 mm, and in soils with good water holding capacity. Irrigated rice is grown on relatively fertile valleys near population centers. Most of the rice fertilization research in Latin America has been conducted in irrigated areas.

Responses. Rice responds to nitrogen almost universally, except in recently cleared land. There is no clear relationship between response pattern and major soil groups as in some other crops. Organic matter content, cation exchange capacity and potential leaching losses are the main soil properties associated with nitrogen responses in rice. Other factors, such as plant type, solar radiation and water management exert a greater influence on rice responses than soil properties.

With traditional tall-statured *indica* varieties and cultural practices, positive responses up to 30 or 60 kg N/ha are commonly reported, as they have in other parts of the world (Oliveira *et al.*, 1964, 1965, 1966; Penny 1965, Ten Have 1967, Kawano *et al.*, 1972, Sánchez and Nureña 1972). A large quantity of data from certain areas of Peru, Mexico and Brazil report optimum rates in the order of 120 to 160 kg N/ha for traditional varieties and cultural practices (Calzada *et al.*, 1959, Vasconcelos and Almeida 1966, Schmitt and Gargantini 1966, Carmen 1968, Jarrero and Ortega 1968). These higher rates seem due to high solar radiation levels, low efficiency of applied nitrogen, or both.

Experiments on variety-nitrogen interactions show that the new short-statured plant types now widespread in Latin America, respond positively to higher rates and produce much higher yields than the traditional varieties in either upland or irrigated conditions. Grain yields in the range of 5000 to 7500 kg/ha have been obtained with varieties such as IR8 at rates of 90 to 180 kg N/ha in upland conditions in Costa Rica and Peru (Cordero 1970, Cordero and Romero 1972, Kawano *et al.* 1972). In irrigated conditions, maximum yields of 10,000 to 11,500 kg/ha have been obtained consistently with short-statured varieties at rates of 100 to 400 kg N/ha (Rosero and Moreno 1970, Sánchez and Calderón 1970a, Sánchez 1972a, Riccio and Gavidia 1972).

The higher yields and responses observed with short-statured varieties under either upland or irrigated systems are associated with higher tillering capacity, higher pancile production, higher grain:straw ratios and resistance to lodging (Sánchez 1972a). In many cases the

responses were linear, suggesting that higher rates are needed to arrive at the optimum levels. In most of the references cited, the IR8 variety was used. It has limited grain quality for the Latin American taste. Recently released short-statured varieties with improved grain quality such as CICA-4, Naylamp, Chancay, Huallaga, Sinaloa A-68 and INIAP 6 produce similar response curves as IR8 but seldom attain IR8's maximum yields.

In most rice-growing areas in Latin America, there is enough research available to recommend nitrogen rates for short and tall varieties. Information about other factors affecting nitrogen response and about how far can results be extrapolated to farmer fields is very limited. Ten Have (1967) compiled the results of 197 trials in Surinam and established that the differences in yield response could be grouped according to the check treatment yields. Such information is useful in estimating site and season variability. Several studies conducted in the Peruvian coast have evaluated the effects of solar radiation, temperature regimes, planting date, plant spacing, growth durations and water regimes on nitrogen response (Sánchez 1972ab). These results permit establishing more reliable recommendations as well as estimating the risks associated with weather and management differences. Similar research is badly needed in other areas, particularly in upland conditions, where the relationship between water stress and yield responses needs to be studied.

Sources, placement and timing. The poor performance of nitrates in intermittently flooded rice has been known for 25 years in Peru (Calzada *et al.*, 1959). The same reference summarized 23 experiments comparing nitrogen sources in high pH soils of the Peruvian coast. The results indicate that ammonium sulfate and urea perform almost equally and that both are superior of guano (bird manure) and nitrate sources. Recent investigations provided the same results in acid clays of Surinam during seven seasons (Ten Have 1967) as well as with new varieties and higher yield levels in Peru (Ramírez and Sánchez 1971). Under upland conditions in Costa Rica, Cordero (1970) found no differences between urea, ammonium sulfate and ammonium nitrate, probably due to the absence of reduced soil conditions.

Slow-release nitrogen sources have received some attention recently. EAP (emulsified asphalt parafin)-coated ammonium sulfate was compared with conventional sources in Costa Rica, Trinidad and Peru (Cordero 1965, Ahmad and Whiteman 1969, Estación Experimental de Lambayeque, 1967). Under upland conditions in Costa Rica and flooded conditions in Trinidad, this source resulted superior to ammonium sulfate. No beneficial effects were observed in Peru. Basal applications of sulfur-coated urea were superior to basal or topdressed applications of conventional urea in intermittently flooded Peruvian

soils, particularly those with very poor water management (Ramírez and Sánchez 1971, Sánchez 1972a).

There is a surprising agreement in the results on timing of nitrogen applications in Tropical America, in spite of the wide variety of conditions on which rice is grown. Results from Brazil (Schmitt and Gargantini 1966), Costa Rica (Cordero 1970, Cordero and Romero 1972), Mexico (Jarrero and Ortega 1968), Peru (Calzada *et al.*, 1959, Sánchez and Calderón, 1970b, 1971, Ramírez and Sánchez 1971) and Surinam (Ten Have 1967) indicate that delaying nitrogen applications until the tillering or panicle initiation stages is superior to a single application incorporated at planting. This is in sharp contrast with Asian data, which generally recommends a basal application at transplanting. The differences are probably due to the higher initial nitrogen leaching losses in Latin America caused by less soil puddling and more alternate oxidation-reduction conditions.

Efficiency. Fertilizer nitrogen is lost easily by leaching and denitrification rice soils due to the presence of alternate redox conditions and the larger amounts of water used in this crop. Under constant flooding, recoveries in the order of 40 to 60 percent of the added nitrogen are considered good. Studies in Peru under intermittent flooding show that the apparent fertilizer recovery at harvest time fluctuated between 20 and 30 percent with conventional sources and timing practices. With improved timing of applications of conventional sources or with basal applications of slow-release materials recovery values were increased to 30 or 40 percent (Ramírez and Sánchez 1971, Sánchez and Calderón 1971).

Wheat

This crop is grown in three main regions of Tropical America: the arid Mexican northwest under high solar radiation and calcareous soils, the Andean highlands from Mexico to Bolivia at high elevations on Andepts and non-volcanic soils, and in Southern Brazil on Ultisols and Inceptisols. In the last two regions wheat is not irrigated and the short-statured Mexican varieties are not widely adapted.

In northwestern Mexico, wheat responds strongly to nitrogen at rates between 60 and 100 kg N/ha needed for maximum yields of 3 tons/ha in 1955 (Arvizu and Laird, 1958). New varieties require about 200 kg N/ha to achieve yields of over 5 ton/ha (CIMMYT, 1969).

The information from the Andean highlands is quite variable. In the Bajío region of Central Mexico, Fernández and Laird (1958) studied the effects of moisture stress on nitrogen response in two clayey Alluvial soils. They found that the maximum yields were obtained at 50 and 150 kg N/ha respectively but were reduced by half when substantial water stress occurred. Laird *et al.* (1969) observed that burning

or removal of previous crop residues decreased the rates needed for optimum yields by 20 percent. A series of experiments conducted on Andepts in the Central Plateau of Guatemala showed that maximum yields of 2.3 ton/ha were produced with 75 to 140 kg N/ha. Lodging was observed at high rates as well as a positive interaction with phosphorus (Ramírez *et al.*, 1971). In 16 trials conducted in Bolivia, linear responses were observed in rates up to 80 kg N/ha, some of which yielded as much as in northwestern Mexico (Manzano *et al.*, 1969).

In yellow latosols of southern São Paulo, Brazil, Jorge *et al.* (1965) and Blanco *et al.* (1965) observed little or no nitrogen responses in areas with maximum yields of 1 to 2 ton/ha.

Attempts to relate nitrogen responses with soil parameters have been made in all areas. Torres *et al.* (1963) observed that a content of 750 ppm NO_3 in 45 day-old wheat plants represented the critical limit for obtaining responses in northern Mexico. No relationships with organic matter or total soil nitrogen were found in the same area by Arvizu and Laird (1958), while only soils with less than 0.1 percent total N responded in São Paulo (Blanco *et al.*, 1961).

No studies on the effects of sources, placement and timing were found in the available literature.

Root Crops

Cassava

This crop (known also as yuca, manioc, mandioca, tapioca) is the food crop produced in largest quantities in Tropical America. Unfortunately, cassava has received little attention by Latin American soil scientists. It is generally considered a crop suited to infertile soils because of its ability to remove nutrients at considerable depths in the profile. Nevertheless, cassava can remove about 60 kg N/ha with moderate yields of 17 ton/ha and over 200 kg N/ha with yields of 60 ton/ha (Normanha and Pereira 1950).

The only long term study available is the work of Normanha and associates in São Paulo, Brazil. These studies show that significant or economical nitrogen responses were less frequent than those of phosphorus and potassium. In some cases, the top:root ratios increased with nitrogen rates of 40 to 80 kg N/ha with no increases in root yields (Silva and Freire 1968b). In other instances, root weights and protein contents increased but not the starch yield (Malavolta *et al.*, 1953). The Brazilian data emphasize the importance of N:K balances. Most responses to N were obtained in the presence of ample phosphorus and potassium supplies. Response studies from other regions are few. A study in Colombia showed that an application of 45 kg/ha of N and P_2O_5 increased yields by 250% (DeGeus 1967).

Placement and timing studies have been conducted in São Paulo (Normanha 1951, Normanha and Freire 1959, Normanha *et al.*, 1968, Silva and Freire 1960a). They show that nitrogen sources alone or in combination with other materials when applied to the planting furrow can significantly reduce sprouting and plant vigor. They recommend that half of the nitrogen and all of the phosphorus and potassium be applied to the side of the planting furrow and that the rest of the nitrogen be sidedressed at later stages.

Some studies on sand and water culture have been conducted in Trinidad and Brazil. Dry matter and nutrient uptake patterns have been developed in northern Argentina (Orioli *et al.*, 1967).

Large cassava responses to balanced fertilization on deep soils are common in other parts of the world. The absence of such information in Latin America is one of the most significant gaps in soils research.

Potatoes

Responses. Valverde *et al.* (1966) and McCollum and Valverde (1968) summarized research conducted from 1950 to 1964 throughout the Peruvian Sierra. A multiple regression equation was produced from 58 experiments. They found that nitrogen was the first limiting nutrient followed closely by phosphorus and with a strong interaction between the two. Extrapolations showed that a rate of 240 kg N/ha was the economic optimum but due to lack of data beyond 160 kg N/ha they recommended a blanket application of 160-160-100, which can triple potato yields. Nitrogen response was inversely proportional to the soil organic matter content. Substantial site and season variability occurred but it was less with nitrogen than with phosphorus or potassium. Improved varieties produced sharper response curves and higher optimum rates. The interaction with spacing was also studied. Increased yields at high rates appeared to be related to the various yield components in the following order: number of tubers per plant, plant population, and tuber size.

A large number of experiments have also been conducted in São Paulo, Brazil in a wide variety of soils. Nitrogen responses were always present with highest yields attained between 60 and 120 kg N/ha (Gomez and Freire 1962, Nobrega *et al.*, 1964, Gargantini *et al.*, 1965). In acid soils no interactions were observed between NPK rates and liming (Book and Freire 1961, Book *et al.*, 1961).

Sources, timing and placement. The traditional "guano de islas" was extensively evaluated against synthetic nitrogen sources in Peru (McCollum and Valverde 1968). Guano was as efficient but cheaper than inorganic sources, but the latter had to be applied to achieve the recommended high rates. No significant differences between urea,

ammonium sulfate, ammonium nitrate and calcium nitrate were observed, which led the authors to recommend whichever source was cheaper. No differences due to timing of application were found.

Brazilian workers have compared several organic sources such as cacao or castor meal with inorganic carriers (Book and Freire 1960, Gomez *et al.*, 1967). Their data shows a consistently superior behavior of organic sources which the authors attribute to poor placement or timing of the inorganic sources, or variability in the nitrogen content of the organic sources. Placement studies have shown that applying all of the nitrogen in the planting furrow is effective only if followed by rains but could lead to salt damage in dry weather (Nobrega *et al.*, 1963ab, Nobrega 1964). Splitting applications in halves or delaying one application was more effective in dry periods.

Sweet potatoes and yams

Worldwide experience with sweet potatoes indicates that moderate amounts of nitrogen in the order of 40 to 60 kg N/ha produce positive responses, but excessive amounts increase the top:root ratio and decrease tuber yields. The limited experience in Tropical America suggests that positive nitrogen responses are not as common. Landrau and Samuels (1959) obtained positive responses up to 82 kg N/ha in two out of four sites in Puerto Rico and negative responses in the rest. They found no relationships between responses and soil properties. A large number of experiments conducted in major soils of São Paulo, Brazil show only occasional economic responses to nitrogen, but most yields obtained were low (Camargo 1951, Camargo and Freire 1962abc, Breda *et al.*, 1966ab). Experiments on sources and placement methods provided no clear trends, except that organic manures performed generally better than NPK applications.

Yams (*Dioscorea* spp., known as ñame, inhame, cará) are extensively grown in the Caribbean and other areas. Experience in West Africa has shown that yield increases in the order of 10 to 20 percent are generally obtained with 6 ton/ha of farmyard manure or ammonium sulfate applied at rates of 20 to 150 kg N/ha. The effects of manures seem related to improvements in soil physical properties. The timing of inorganic nitrogen application is very much related to the nitrate fluctuations in the soils in Ustic environments (DeGeus 1967). In Trinidad, Chapman (1965) found that the timing of nitrogen applications affected yields dramatically. When 120 kg N/ha as ammonium sulfate was applied at planting, yields decreased but when the same rate was applied three months later yields increased by 50 percent. Chapman attributed this effect to leaching losses at planting and the fact that at three months the leaf area index increases sharply and the plants started producing secondary shoots. He also observed that staking is probably

necessary to obtain yield responses to nitrogen. Ferguson and Haynes (1970) also in Trinidad, observed a differential response with species. *Dioscorea alata* responded positively to 200 kg N/ha while *D. esculenta* peaked at 56 kg N/ha and responded negatively to higher rates. Gooding (1971) reported that rates of 20 kgN, 72 kg P_2O_5 and 51 kg K_2O increased yam yields in over 100 experiments in Barbados. The experimental design unfortunately, prevented the evaluation of individual nutrient effects.

Grain Legumes

Beans

Dry beans (*Phaseolus* spp.) are second only to corn in total area planted in Tropical Latin America. They constitute the main plant protein source in the diets and are found growing in most Latin American farms. The nitrogen requirement of beans in tropical areas is in the order of 60 to 150 kg N/ha. It is expected that symbiotic fixation provides a substantial amount of that requirement. Fassbender (1967) reviewed reports from Costa Rica, Brazil and Peru and found little evidence that Rhizobium innoculation was effective. In fact, a negative correlation between bean production and nodulation has been reported in Brazil (VanWambeke 1970). Aluminum or manganese toxicity, calcium and phosphorus deficiency, high nitrate contents and high host specificity are some of the explanations given for this phenomenon.

The response of beans to inorganic nitrogen is extremely variable in the region. Fassbender (1967) reported that optimum recommended rates ranges from 30 to 60 kg N/ha in Mexico, Central America, Peru and parts of Brazil, but rates from 100 to 400 kg N/ha have been recommended in Costa Rica and Minas Gerais, Brazil.

Miyaska and co-workers found infrequent responses to nitrogen in a large number of field trials conducted throughout São Paulo, Brazil. When acid Latosols were limed, yields increased but nitrogen responses, if present in unlimed plots, decreased (Miyasaka *et al.*, 1963). The Brazilians have also studied green manure additions and found in most instances sharp positive responses in the presence and absence of applied nitrogen (Miyasaka *et al.*, 1967bd, Mascarenhas *et al.*, 1967bc, Hiroce *et al.*, 1969). Little difference was found between inorganic nitrogen sources (Miyasaka *et al.*, 1963, Mascarenhas *et al.*, 1966). In one experiment on terra roxa soil, delaying applications of 50 kg N/ha significantly decreased yields, although nodulation increased as applications were delayed (Miyasaka *et al.*, 1963).

In spite of a comparatively large number of publications on this subject, the information obtained is very limited due to the superficial nature of most trials.

Soybeans

Only references from the Campo Cerrado of Brazil were obtained for this crop. Except for studies conducted by DeFreitas *et al.* (1960) in Goias and Mascarenhas *et al.* (1967b) in São Paulo, other studies report no responses to nitrogen fertilization in spite of the wide variability in soil types. Where responses were obtained, excellent nodulation was present although it tended to decrease with applied nitrogen rates. The yield levels obtained suggest that nitrogen fertilization of soybeans of minor importance in the Campo Cerrado. Phosphorus and liming were crucial.

Pastures and Forages

Cattle production, mainly for beef is more important in the Latin American tropics than in tropical Africa or Asia. With over 552 million hectares in pastures and meadows in the area, it is not surprising that nitrogen fertilization has received widespread attention throughout the region. Most soils of tropical Latin America do not mineralize enough nitrogen over a long period of time for satisfactory forage and pasture production, even those with high organic matter, total nitrogen contents and narrow C/N ratios (Blue, 1968). The main approach has been towards massive nitrogen fertilization of grasses with limited attention to the introduction of tropical legumes.

Responses

Oxisols and Ultisols. In the highly weathered and leached Oxisols and Ultisols, pastures are often the only source of nutrition of beef cattle. In Ustic environments, animals suffer severe weight losses during the dry season which delays the slaughtering age to four or six years. A two-year study by Quinn *et al.* (1961) showed that when 200 kg N/ha per year was applied to Guinea grass *(Panicum maximum)* pastures in the Campo Cerrado of Brazil, the production of total digestible nutrients and the live weight increase per hectare doubled; the carrying capacity increased from 1.4 to 3.5 steers/ha. When nitrogen was applied during the dry season the gains were superior to those obtained with applications during the rainy season, and the quality of the pasture tended to be more uniform. Quinn *et al.* (1963) postulated that available soil nitrogen was depleted at the end of the rainy season, that applications at that time were subjected to lower leaching losses and that they had

a residual effect in the following rainy season. A subsequent report (Quinn *et al.*, 1963) showed no responses to dry season applications due to severe drought. These studies underscore the need to relate nitrogen responses to soil moisture status in Ustic environments.

In Ultisols and Alfisols of Puerto Rico, Vicente-Chandler and coworkers have studied different levels of management intensities on pastures and forages. In Udic environments, unimproved natural pastures on steepland produce about 5 ton/ha of dry matter per year, an average annual weight increase of 100 kg/ha and a carrying capacity of 0.5 to 0.7 animals/ha with an annual nitrogen uptake of 100 kg N/ha. When pastures of improved species such as Guinea, Elephant grass (*Pennisetum purpureum*), Para grass (*Panicum purpuraceum*, syn. *Brachiaria mutica*) or Pangola (*Digitaria decumbens*) are fertilized with 400 kg N/ha per year, the annual forage consumed by animals reached 14 ton/ha with 16 percent protein content. This production supported a live weight increase of 1100 kg/ha and a carrying capacity of 5.5 steers/ha. Annual nitrogen uptake by such grasses averaged 300 kg N/ha. When the same species were cut as forage every two months, annual production reached 40 ton/ha of dry matter with Elephant grass fertilized at the rate of 800 kg N/ha per year. Guinea, Pangola and Para grass produced maximum annual yields of 25 ton/ha per year with 400 kg N/ha and Molasses grass (*Melinis minutiflora*) reached 14 ton/ha with an optimum rate of 200 kg N/ha. The excellent quality forage increased the carrying capacity to 10 animals/hectare. Adequate levels of other nutrients and lime plus proper cultural practices were necessary for obtaining such yield levels. (Vicente-Chandler *et al.*, 1967).

Highlands. In the Andean highlands and intermountain valleys of Central America and Colombia, nitrogen applications often increase grass forage yields by a factor of ten times. The absence of nitrogen responses has not been reported, even in land just cleared from jungle in Costa Rica (Blue 1967). Soil differences are more closely associated with other nutrient limitations, particularly phosphorus and sulfur. The magnitude of the responses varies primarily with altitude, species and rainfall distribution. A large number of long term experiments conducted in Colombia by Lotero, Chaverra and associates plus several short-term experiments conducted in Costa Rica by Blue and Tergas indicate that higher forage production and optimum nitrogen rates are found in low altitudes than at high elevations. Elephant grass produced 40 to 42 ton/ha of dry matter with 600 kg N/ha per year in the Atlantic lowlands of Costa Rica and Colombia while at elevations of about 1500 m in both countries the optimum yields ranged from 20 to 32 ton/ha at rates between 100 and 200 kg N/ha per year (Blue 1967, Lotero *et al.*, 1968).

Studies with over 20 grass species, conducted in the main intermountain valleys of Colombia show that applications of 50 to 150 kg N/ha after every cut or grazing produce optimal yields. An average annual yield of 50 ton/ha of Pangola dry matter was obtained in Cali with 900 to 1200 kg N/ha per year (Crowder *et al.*, 1964).

In Ustic environments grasses such as Yaragua grass (*Hyparrhenia rufa*) produce less and responded to lower N applications than Pangola or Elephant grasses in Udic environments in Costa Rica (Blue 1967). The decrease in quantity and quality of pastures during the dry season was studied by Tergas and Blue (1971) in the Guanacaste peninsula of Costa Rica. They observed that applying 75 to 150 kg N/ha one month prior to the dry season, increased Yaragua grass production during the first two months of the dry season. Afterwards, yields, protein content and the contents of most elements except calcium sharply declined apparently due to translocation into the root system. They suggested to store pastures harvested at the end of the rainy season as hay. Similar recommendations have been made by Vicente-Chandler *et al.* (1967) for the south coast of Puerto Rico.

Legume-grass mixtures

The present knowledge of pasture legumes in Latin America was summarized by Williams (1967). Although a significant proportion of species such as *Desmodium* and *Centrosema* are found in some unimproved grasslands in Costa Rica and South America, the extensive use of legumes in forages and pastures is very limited. Tropical kudzu (*Pueraria phaseoloides*) has been grown in association with Molasses, Elephant and Para grass in humid regions in Puerto Rico (Vicente-Chandler *et al.*, 1967). An initial application of 42 kg N/ha was necessary for the establishment and nodulation of kudzu, but further applications almost eradicated the legume. Kudzu-grass pastures on steep Ultisols produced up to 12 ton/ha of dry matter consumed by cattle per year which resulted in annual grain weights of 500 kg/ha and a carrying capacity of 2.5 young animals/ha. Intensively fertilized grass pastures however, produce more forage and more protein than kudzu-grass mixtures. Vicente-Chandler *et al.* (1967) estimated that kudzu fixed about 200 kg N/ha per year.

Timing, placement and sources

There is complete agreement in the region that the optimum timing of nitrogen applications is to split the annual rate into equal amounts after each cut (four to six times a year) or the same number for pastures, regardless of soil, climate or species differences (Crowder *et al.*, 1967, Herrera *et al.*, 1967, Vicente-Chandler *et al.*, 1967). Both forage yield and quality are more uniform throughout the region than with more

or less frequent applications. In locations with strong dry seasons, the situation is completely different, but additional data beyond the previously mentioned work of Quinn *et al.* (1963) a d Tergas and Blue is scarce.

Lotero *et al.* (1968) found no differences between placement methods such as broadcast, banded or around bunches of Elephant grass in Colombia.

No significant differences between commercial inorganic nitrogen sources have been found throughout the region (Lotero *et al.*, 1968, Rodríguez *et al.*, 1966, Rodríguez 1970, Vicente-Chandler and Figarella 1962, Werner *et al.*, 1967). In such cases, urea is recommended because of its lower cost and lower acidifying effect, provided that it is applied under conditions unfavorable for volatilization. Villamízar and Lotero (1967) reported that sodium nitrate was superior to urea and ammonium sulfate in a long-term Pangola trial in Medellín, Colombia. No adequate explanation was advanced. No references were found on the evaluation of slow-release nitrogen sources for pastures and forages.

Efficiency. Because of need for protein determinations, data on apparent nitrogen recovery by grasses are abundant in the region. Recovery rates range from 20 to 100 percent and vary with location, species and rates. Vicente-Chandler *et al.* (1967) obtained an average of 48 to 56 percent in cut grasses at the recommended nitrogen rates of 200 to 800 kg N/ha per year in Puerto Rico. In addtion, they estimated that an additional 12 percent of the added nitrogen remains in the soil as organic nitrogen when an annual rate of 800 kg N/ha was applied for five years. They observed no major differences in fertilizer recovery among species but a decrease in efficiency with increasing rate of applications. In Costa Rica, Blue (1967) observed significant recovery differences between species in three major ecological areas. Pangola recovered over 80 percent while Elephant grass received 20 to 30 percent in the udic lowlands. Yaragua grass was superior to Bahia grass (*Paspalum notatum*) in the Ustic lowlands and Kikuyo (*Pennisetum clandestinum*) was superior to elephant grass at high elevations. Recovery values in Colombia at optimum nitrogen rates vary from 50 to 75 percent (Crowder *et al.*, 1967, Lotero *et al.*, 1968, Villamízar and Lotero 1967). Urea is usually recovered in lesser amounts than ammonium sulfate and sodium nitrate, but these differences do not seem large enough to affect the economic aspects.

Effects of intensive nitrogen applications on soil properties. The recommended rates for intensive forage production previously mentioned can add over 2500 to 4000 kg N/ha to the soil in three to five years. Applications of 2500 kg N/ha during four or five years in a limed Tropohumult from Puerto Rico and in an Andept of Colombia with

initial pH near 6.0 decreased topsoil pH by 1.0 to 1.5 units when ammonium sulfate was used. With sodium nitrate, the pH increased by about 0.8 units. With urea or ammonium nitrate the pH decreased slightly (Vicente-Chandler *et al.*, 1967, Villamízar and Lotero 1967, Herrera *et al.*, 1967). Higher rates of urea, 5.4 to 10.8 ton N/ha, decreased the pH from 5.8 to 5.0 and 4.5 in Medellín, Colombia (Ramírez and Lotero 1969). The predictable effect of such changes on the base status of the topsoil has been documented by Ramírez and Lotero (1969) and Vicente-Chandler *et al.* (1967). Depletion of bases to 60 cm in the subsoil was caused by heavy N applications in two Puerto Rican soils (Abruña *et al.*, 1958). When lime was applied with heavy rates of N, the base status of acid subsoils was dramatically increased because of the downward movement of calcium and magnesium applied at the surface as lime (Pearson *et al.*, 1962).

The effect of intensive nitrogen fertilization on soil compaction by grazing in Puerto Rican soils was studied by Vicente-Chandler and Silva (1960). They found that heavy nitrogen fertilization decreased soil compaction in the topsoil with Pangola, Para and Elephant grasses. They concluded that physical properties do not deteriorate in heavily fertilized pastures on Puerto Rican Ultisols.

Conclusions

Substantial nitrogen fertilization research has been conducted in Tropical Latin America, but the amount and quality of information obtained is unbalanced both geographically and in terms of relative crop importance. Beyond simple response curves, extensive information is available for crops such as corn, rice, potatoes and forages only in one or two countries per crop. The lack of data on cassava fertilization is one of the most glaring gaps. The need for substantial nitrogen applications on beans implies that symbiotic nitrogen fixation by Rhizobia has not been effective in the region. More emphasis on the use of legumes as a nitrogen source for pastures is badly needed.

In many instances, nitrogen responses were linear. Higher rates should be included in future experiments to obtain estimates of optimum rates particularily if improved varieties or cultural practices are used. The variation of nitrogen needs with seasons, moisture stress, soil acidity, lodging susceptibility and other factors needs more attention. Nitrogen uptake patterns by several crops are available only in a few locations. There is a need for better estimates of the amounts released by the soil and the efficiency of fertilizer use. There is also a need for experimenting more closely with the main cropping systems used such as upland rather than irrigated rice. This information can be

obtained rather quickly with fewer but more carefully controlled experiments.

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CHAPTER 6

Soil Acidity and Liming

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Early attempts at liming soils in the humid tropics often did not give favorable responses. Very often soils were limed to pH 7 which resulted in decreased yields brought about by micronutrient deficiencies and decreased phosphorus availability. In the past 20 years, however, soil scientists have shown that aluminum is the principal cation in acid soils of pH 5.5 and below. As a result of these new concepts, the approach to liming of highly weathered acid soils has been considerably modified. Lime rates are now being based on amounts required to neutralize the exchangeable aluminum rather than bringing the soil to pH 6.5 or 7. The purpose of this review is to look at the nature of soil acidity and response to lime in the humid tropics in the light of modern concepts of soil acidity.

Soil Acidity and Exchangeable Cations

Soils of the Llanos Orientales

The savanna soils of the eastern plains of Colombia are acid and highly weathered and are primarily Ultisols and Oxisols. The pH of the surface soils ranged from 4.2 to 5.1 with the majority being below pH 4.7 (Esperanza, 1963). Exchangeable Al accounted on the average for 68 percent of the exchangeable cations. The average exchangeable aluminum and calcium plus magnesium were 3.1 and 1.5 meq/100g, respectively.

Brazil

Representative soils from various areas of Brazil were analyzed as to their pH and cation saturation (Anastacio, 1968). At pH 5.5 and greater, the soils contained essentially no exchangeable aluminum but with soils with a pH of less than 5 the average exchangeable aluminum saturation was 58 percent. The average exchangeable aluminum saturation of soils within the range of pH 5 to 5.5 was 16 percent.

The average exchangeable aluminum saturation of Red-Yellow Latosols with a pH less than 5 was 72 percent, of Red Latosols was

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79 percent and Red-Yellow Podzolics was 63 percent (Pratt and Alvahydo, 1966). The exchangeable calcium plus magnesium content of the Red Latosols was 0.2 meq/100g or less. The Red Latosols are the principal soils found in the Campo Cerrado of Brazil. These soils are highly weathered, devoid of basic cations and have a high exchangeable aluminum saturation throughout the solum. The exceptions to this are the Terra Roxa soils formed from basalt which have a high base saturation.

Amazon Basin

The surface horizons of the well drained forest soils in the Amazon Basin of Brazil had an average exchangeable aluminum saturation of 44 percent and the well drained savanna soils had a saturation of 57 percent (Sombroek, 1966). The poorly drained soils, however, generally had a very low aluminum saturation.

The exchangeable aluminum saturation of the A horizon of well drained soils in the upper Amazon Basin of Peru ranged from 30 to 80 percent when the pH was less than 4.5 (Sanchez and Buol, 1971). The B horizons on the other hand had an aluminum saturation of 71 to 92 percent. The A_1 horizons of the poorly drained soils contained almost no exchangeable aluminum even though the soils were acid. The B horizons, however, had an exchangeable aluminum saturation ranging from 33 to 46 percent.

Volcanic ash soils

In a review on volcanic ash soils, Fassbender and Molina (1969) point out that most soils formed from volcanic ash have pH values greater than 5. However, under conditions of intense weathering, soils formed from volcanic ash may have a high exchangeable aluminum saturation (Fox *et al.*, 1962). Much of the charge of volcanic ash soils is pH dependent and the buffer capacity of these soils may be very high particularly as pH 7 is approached.

Effect of Liming on Phosphorus Availability

Beneficial effects

The exchangeable aluminum content of Ultisols and Oxisols is one of the factors affecting the fixation of phosphorus (Sa *et al.*, 1968, Esperanza, 1963). Liming decreased the phosphorus fixation of acid volcanic ash soils limed to pH 5.8 which contained appreciable amounts of extractable aluminum (Fassbender and Molina, 1969).

Neutralization of exchangeable aluminum greatly enhanced uptake of fertilizer phosphorus from Latosols (Fox *et al.*, 1964). Liming of an

acid Andosol from Costa Rica increased the uptake of fertilizer phosphorus by tomatoes (Fassbender, 1969). Application of lime to an acid Latosol, pH 4.6, which reduced the exchangeable aluminum saturation from 58 to 8 percent and raised the pH to 5.4, increased the yield response of dry beans to phosphorus fertilization almost three-fold (Mascarenhas *et al.*, 1969).

Liming of acid Campo Cerrado soils which have a high total phosphorus content increased the available soil phosphorus level and also reduced the need for fertilizer phosphorus (Mikkelsen *et al.*, 1963). Availability of native soil phosphorus in certain acid Campo Cerrado soils was increased by liming (McClung *et al.*, 1961). Increased mineralization of organic phosphorus along with neutralization of exchangeable aluminum are possible explanations of this effect. Raising the pH of Zamorano soils in Honduras from 5.5 to 6.5 increased the mineralization of organic phosphorus (Awan, 1964).

Detrimental effects

Adjusting the pH of acid Aluminous Latosols to 7 drastically decreased the uptake of fertilizer phosphorus (Fox *et al.*, 1964). Formation of calcium phosphates apparently was the main reason for the decreased phosphorus uptake. Similarly it was found that the phosphorus fixation capacity of Andosols was increased when the soil pH was raised above 5.8 (Fassbender and Molina, 1969). Yield reduction of sweet potatoes on soils limed to pH 6.7 was associated with an appreciable reduction in available phosphorus (Camargo *et al.*, 1962).

Crop Response to Liming

Corn

Large responses to liming were obtained on the Campo Cerrado soils in Brazil which generally have a pH of less than 5 and have a high exchangeable aluminum saturation. (Freitas *et al.*, 1960, Mikkelsen *et al.*, 1963). Poor growth of corn was found on Pinhão soils with pH 4.2 and 4.8 (Igue and Schmidt, 1962). Normal growth was obtained at pH 5.2. In experiments in the Paraiba Valley of São Paulo, responses to lime were not obtained until the phosphorus application was 120 kg P_2O_5/ha (Gomes *et al.*, 1963).

Essentially no response to liming was obtained on four soils in Brazil in which the pH ranged from 5.5 to 6.5 (Viegas *et al.*, 1960). An increase of only 3 bushels per acre was obtained from liming a Terra-roxa misturada soil which had an initial pH of 5.6 (Miranda *et al.*, 1964).

Potatoes and sweet potatoes

Potato yields in São Paulo increased approximately 2 tons/ha by liming when the initial pH was less than 5.5 (Boock and Freire, 1961). At pH 5.7, no response to lime was obtained. In another study, liming of a poorly drained soil, pH 4.7 increased potato yields 3 tons/ha (Boock *et al.*, 1961).

Sweet potato yields in São Paulo were decreased when the pH was raised to 6.7 (Camargo *et al.*, 1962). With adequate fertilization, sweet potatoes did not respond to liming on a soil with pH 5.6 (Freire *et al.*, 1962). Liming the soil to pH 7 decreased sweet potato yields.

Beans

An increase of 952 kg dry beans/ha was obtained with liming a Latosol with an initial exchangeable aluminum saturation of 58 percent and a pH of 4.6 (Mascarenhas *et al.*, 1969). Applications of 4 tons lime/ha raised the pH to 5.4 and reduced the exchangeable aluminum saturation to 8 percent. In another study, a response to lime was obtained at pH 4.65 but not at pH 5.05 (Miyasaka *et al.*, 1966).

Beans did not respond to the applications of lime on seven Terra-roxa misturada soils in São Paulo which ranged in pH from 5.6 to 6.6 (Miyasaka, *et al.*, 1966). Liming caused a slight decrease in yields at all locations.

Soybeans

Numerous reports are present in the literature indicating large increases in soybean yields when acid soils are limed. Yields were increased 77 percent when a Dark Red Latosol with an initial pH of 5.0 was limed to pH 5.7 (Mikkelsen *et al.*, 1963). Responses to lime also were obtained on a Red Latosol with an initial pH of 5.5 (Mascarenhas *et al.*, 1969). A yield response of 59 percent (12 bu/a) was obtained on a soil at Campinas, São Paulo by increasing the pH from 5.2 to 5.9 (Miyasaka *et al.*, 1966). In studies on a soil derived from Botucatu sandstone with a pH of 5.2 maximum response to lime was obtained only after application of 120 kg P_2O_5(Miyasaka *et al.*, 1964). Liming increased yields of soybeans on two soils in São Paulo with pH's of 4.8 and 5.5 (Mascarenhas *et al.*, 1967).

The beneficial effects of lime in increasing soybean yields on soils with an initial pH of 5.5 may be due to increased availability of molybdenum as the pH is raised. Soil molybdenum in Latosols is probably fixed by hydrated iron oxides and becomes more available.

Sugar Cane

Yield of sugar cane in Puerto Rico was only 25 metric tons/ha, where the exchangeable aluminum saturation was greater than 70 percent and was over 100 tons/ha when the exchangeable aluminum saturation was less than 30 percent (Abruña and Vicente-Chandler, 1967). Cane yields were less than 1 ton/acre on a very acid Ultisol in Puerto Rico (Abruña *et al.*, 1968).

An increase in sugar cane production was obtained with moderate amounts of lime applied to an acid volcanic ash soil (Fassbender and Molina, 1969). At higher rates of lime, the yields were decreased.

Summary

The highly weathered Oxisols and Ultisols generally have a pH less than 5 and an exchangeable aluminum saturation greater than 50 percent. The poorly drained soils of the Amazon Basin have a low exchangeable aluminum saturation in the A horizon. Most volcanic ash soils have a pH greater than 5.

Neutralization of exchangeable aluminum by liming increased phosphorus uptake and the yield response to phosphorus fertilizers. Liming of certain newly cleared soils decreased response to phosphorus fertilizers apparently because of increased availability of soil phosphorus.

Phosphorus availability was decreased when the soil pH was raised above 6.7 and crop yields were decreased. Raising the pH of acid Andosols above 5.8 increased phosphorus fixation.

Crop response to liming can in most instances relate to neutralization of exchangeable aluminum and supplying of calcium and magnesium. In most instances, if the pH is 5.5 or above very little response to liming will be obtained. Yields of legumes may be increasd by liming to pH 6 because of increased availability of molybdenum.

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CHAPTER 7
Phosphorus

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The highly weathered soils, Oxisols and Ultisols of the tropics along with Andosols, are generally very deficient in phosphorus. Many of the soils fix large quantities of added phosphorus. Therefore, without the application of phosphorus sustained crop production at high yields is not possible. The purpose of this paper it to summarize some of the research findings on phosphorus fixation and response to phosphorus fertilization with soils in the tropics.

Phosphorus Fixation

Relative fixation capacity

The largest amounts of phosphorus are fixed by amorphous hydrated oxides of iron and aluminum followed by gibbsite, goethite, kaolin and montmorillonite. The more crystalline the material, the smaller the fixation capacity. Work with soils of Costa Rica indicated that the order of phosphorus fixation, largest to least, was Latosols, Andosols and Alluvial soils (Fassbender, 1966).

Latosols from the Amazon Basin of Brazil had a lower phosphorus absorption capacity than soils in other tropical areas (Fassbender, 1969). This could be due to a lower clay content and, therefore, a lower content of amorphous hydrated oxides.

Soils in the coffee growing area of Colombia had a very high phosphorus fixation capacity (Lopez, 1960). Many of these soils are formed from volcanic ash and would contain appreciable amounts of allophane, an amorphous aluminum silicate.

Factors related to phosphorus fixation

Phosphorus fixation by volcanic ash soils of Chile was related to the iron oxide content. Studies with soils in São Paulo, Brazil indicated that within a soil group, phosphorus fixation was related to the iron oxide content of the soil (Pratt *et al.*, 1969). Red-yellow Podzolic soils fixed more phosphorus per unit of iron than did the Red Latosols. The iron compounds in the Red Latosols were thought to be more crystalline.

Phosphorus fixation by volcanic ash soils of Chile was related to the

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amount of aluminum extracted with *N* NH_4OAc at pH 4.8 (Alamos *et al.*, 1967). It has been found that the younger the volcanic ash soils, the greater the phosphorus fixation. Apparently with time the amorphous materials have formed more crystalline products. Liming of an Andosol from Costa Rica had no effect on the amount of phosphorus retained (Fassbender, 1969). Only when exchangeable aluminum is present would liming reduce phosphorus fixation.

Forms of phosphorus in soils

Volcanic ash soils. Most of the phosphorus in Andosols from Costa Rica was in the inorganic form and was bound to aluminum and iron compounds (Fassbender, 1968). Recent volcanic ash soils in Central America had approximately 44 percent of the total P present as the inorganic form (Fassbender, 1969). Volcanic ash soils in Honduras which were formed in situ had most of their P in the occluded form (Morillo *et al.*, 1968). Similarly in Colombia, the inert P (occluded) accounted for 50 percent of the soil P and only 15 percent in the aluminum-P (Blasco, 1969). Studies in Chile showed that with time the amount of organic P decreased and the amount of Fe-P increased (Casado-Perez, 1966). Since volcanic ash soils have most of their phosphorus in the more unsoluble forms, the availability of phosphorus will generally be low.

Latosols. Iron phosphate was the main form of P in a Latosol from Costa Rica and accounted for 42 percent of the inorganic P (Fassbender, 1966). Almost all of the P added to the soils was bound to compounds of Fe and Al. The inert form of P was the largest fraction in Latosols of Colombia and the next largest was the organic form (Blasco and Bohorquez, 1968). Latosols from the Amazon Basin of Brazil had the largest fraction of their phosphorus in the occluded and reductant form (Vieira and Bornemiza, 1968). The organic P ranged from 20 to 50 percent of the total P. When phosphorus was added to the soils from the Amazon Basin of Brazil, approximately 63 percent was converted to Al-P and Fe-P (Fassbender, 1969). The phosphorus availability of Latosols will generally be quite low because most of the phosphorus is in the form of very insoluble Fe and Al compounds. Highly weathered soils from Brazil, Trinidad and El Salvador had most of their phosphorus in the occluded or Fe forms (Dahnke *et al.*, 1964, Jorge and Valadares, 1969 and Weir, 1966).

Alluvial. The form of phosphorus in alluvial soils will depend upon the materials from which the soils are formed. In a study in Costa Rica, Fe-P accounted for 40 percent of the inorganic phosphorus (Fassbender, 1966). Recent alluvial soils in the lower part of the Choluteca River basin in Honduras were high in Ca-P (Morillo and Fassbender, 1968).

Factors affecting the form of P

Soil pH. The natural pH of a soil which is a reflection of the calcium saturation will determine the form of P that will be present. Studies with soils in Central America showed that pH 5.5 was the dividing line as to whether the main form was Ca-P or Al-P + Fe-P (Fassbender *et al.*, 1968).

Weathering. As soils become more highly weathered there is generally a decrease in the calcium content and increasing amounts of reactive Al and Fe. Therefore, with increased weathering there is a shift from Ca-P to Fe-P and the result is a decrease in phosphorus availability (Westin and De Brito, 1969).

Moisture conditions. The moisture content of a soil determines the oxidation-reduction potential of the soil. Studies in Trinidad showed that during the dry season there was an increase in reductant P (Fe-P) while with wet conditions (anaerobic), there was an increase in Al-P (Ahmad, 1967). Work with Venezuela soils indicated that soils with a distinct dry season tended to have a higher proportion of Fe-P while with impeded drainage Al-P predominated (Westin and De Brito, 1969).

Soil Test Correlations

Central America

A greenhouse study with 110 soils from Central America indicated that 66 percent were extremely deficient in phosphorus and only 15 percent contained adequate phosphorus (Fassbender *et al.*, 1968). Correlation of soil tests with phosphorus uptake gave the following correlations coefficients: Egner-Riehm (Calcium lactate) 0.947, Olsen ($NaHCO_3$) 0.870, Bray I (HCl + NH_4F) 0.856, Melich (HCl + H_2SO_4) 0.856 and Saunders (NaOH) 0.340.

For a group of soils from Honduras, the Olsen method ($NaHCO_3$) gave the best measure of P retention (Morillo and Fassbender, 1968).

Colombia

Studies were conducted in the mountain and inter-mountain valleys of Colombia to correlate soil test values with response of wheat to phosphorus fertilization (Navas *et al.*, 1966). The Bray II method (HCl + NH_4F) gave the best correlations. The following levels were established for the purpose of making recommendations: low (0-20 ppm), medium (20-40 ppm) and high (greater than 40 ppm).

The laboratory analyzing samples from the coffee growing area of Colombia has used 0.08 *N* H_2SO_4 as an extractant (Lopez, 1958). Many of the soils in this area have been formed from volcanic ash.

Brazil

Based on 217 experiments with cotton on Terra Roxa and Massapé-Salmourão soils, soil test levels were established using a 0.05 *N* H_2SO_4 solution as an extractant (Verdade *et al.*, 1967). Soil test levels for sandy soils were: low (0-7 ppm), medium (7-14 ppm) and high (greater than 14 ppm); while for clay soils the levels were: low (0-17 ppm) and high (greater than 17 ppm).

Peru

Field experiments were conducted with potatoes throughout the Sierra of Peru (Valverde *et al.*, 1966). The critical soil P level was 7 ppm with the Olsen method. Below the critical level, fairly large increases in potato production were obtained with applications of phosphate fertilizer.

Response to Phosphate Fertilization

Corn

The Campo Cerrado soils of Brazil are generally deficient in phosphorus and corn yields are very low without phosphorus fertilization (Mikklesen *et al.*, 1963). In the São Paulo region, the application of 80 kg P_2O_5/ha to previously unfertilized soils increased corn yields approximately 100 percent while with previously fertilized soils, responses were less than 20 percent (Viegas *et al.*, 1961).

Other studies in São Paulo with the soil groups, Massapé, Terra Roxa, Arenito Bauru, Glacial and Terciário indicated that maximum yields were obtained with 150 kg P_2O_5/ha (Viegas *et al.*, 1963). Optimum yields in Minas Gerais, Brazil were obtained with 108 kg P_2O_5/ha (Braga and Yahmer, 1968). A study with a Terra Roxa Misturada soil showed that 200 kg P_2O_5/ha from Algerian rock phosphate was equal to 60 kg P_2O_5/ha from superphosphate (Viegas *et al.*, 1960).

Experiments were conducted at 26 locations in the tropical regions of Veracruz, Mexico with alluvial soils, volcanic ash soils, and soils formed from marine deposits (Laird *et al.*, 1963). Phosphorus fertilization increased yields in 26 percent of the locations. Yield increases from the application of 40 kg P_2O_5/ha ranged from 1.15 to 2.17 tons/ha. In another study at 47 locations with volcanic ash soils in El Bajío, Mexico, applications of 40 kg P_2O_5/ha increased yields 0.61 tons/ha (Laird and Rodriguez, 1965).

Rice

Responses to phosphorus by upland rice have been frequent on the Campo Cerrado soils of Brazil (Oliveira *et al.*, 1964, 1965, 1966). Maximum yields in São Paulo were obtained with 60 kg P_2O_5/ha (Oliveira *et al.*, 1965). On a Terra Roxa Misturada soil at Campinas, 60 kg P_2O_5/ha increased rice yields 48 percent (Miranda and Freire, 1967). No response was obtained to phosphorus fertilization of rice in northeast Brazil on alluvial soils of the Coastal area (Vasconcelos and Almeida, 1966).

No response to phosphorus fertilization was observed in 38 experiments with rice in Peru (Carmen, 1968). Similarly, no response to phosphorus was found in 11 experiments conducted in Colombia (ICA, 1970).

Wheat

Soils of the Sabana of Bogotá, situated in the Andean highlands, have a rather low level of available phosphorus (Vega *et al.*, 1959). Optimum wheat yields were obtained with a rate of 160 kg P_2O_5/ha. Studies in southern São Paulo showed that a seven-fold increase in wheat yields was obtained with application of 240 kg P_2O_5/ha (Jorge *et al.*, 1965). When dark Red Latosols were low in phosphorus, rates of 120 to 180 kg P_2O_5/ha were required for maximum yields (García *et al.*, 1965). Soils of the Central Andean Plateau are generally deficient in phosphorus and large responses in wheat yields are obtained with phosphorus fertilization (Peña-Herrera, 1961).

Root crops

The average increase in potato yields with phosphorus fertilization was 42 percent in field studies conducted in four regions of São Paulo (Freire and Boock, 1960). Large increases were obtained with 120 kg P_2O_5/ha and smaller increases beyond this up to 180 kg P_2O_5/ha. In the Paraiba Valley lowlands of São Paulo, average yield increases due to phosphorus were 28 percent as compared with 37 percent for nitrogen (Gargantini *et al.*, 1965). Bauxite P was found to be a very poor source of phosphorus as compared with superphosphate when applied at the rate of 120 kg P_2O_5/ha (Book and Freire, 1960).

Five experiments on phosphorus fertilization were conducted in the Antioqua region of Colombia where many of the soils are formed from volcanic ash (Rodriguez *et al.*, 1960). Average yields were 4.1 tons/ha without application of phosphorus and 15.3 tons/ha with application of 450 kg P_2O_5/ha.

In the Sierra of Peru, 95 percent of the experiments showed a response of potatoes to phosphate fertilization. Optimum yields of potatoes were obtained with application of 160 kg P_2O_5/ha (Valverde *et al.*, 1966).

Very little published information is available for root crops such as cassava and sweet potatoes.

Beans and soybeans

Beans generally responded to phosphorus fertilization in São Paulo when grown on soils which had not been fertilized previously (Miyasaka, 1966). In many instances responses were much greater when the soils were limed presumably due to the neutralization of exchangeable aluminum (Mascarenhas *et al.*, 1967). Yield responses on Arenito Bauru soils in São Paulo were linear up to 120 kg P_2O_5/ha (Miyasaka *et al.*, 1965). In Costa Rica, beans responded to phosphate fertilization in studies conducted with three soils (Martini and Pinchinat, 1967.

Soybeans gave large responses to phosphate fertilization in studies with Latosols at various locations in Brazil (Freitas *et al.*, 1960; Mascarenhas *et al.*, 1968). A linear increase in yields up to 120 kg P_2O_5/ha was obtained in an experiment at Itararé in Brazil (Miyasaka *et al.*, 1966). At Campinas, soybean yields were increased 43 percent with phosphate fertilization (Miyasaka *et al.*, 1960).

Forages and pastures

The Campo Cerrado soils of São Paulo and Goias are very deficient in phosphorus. Yield of grasses and legumes without phosphorus application were less than 10 percent of that obtained with phosphorus fertilization (McClung *et al.*, 1957). In Central Brazil, grasses are not fertilized and under these conditions, Pangola grass does not supply adequate phosphorus for grazing animals (Gomide *et al.*, 1969). During the dry season, grasses grown in the hinterlands of São Paulo were phosphorus deficient (Andreasi *et al.*, 1966).

A very large percentage of the soils in Panama used for grazing are deficient in phosphorus (McCorkle, 1968). Elephant grass grown on an alluvial soil in the Turrialba Valley of Costa Rica maintained a high level of production with 100 kg P_2O_5/ha/year (Guerrero *et al.*, 1970). Studies with a Puletan fine sandy loam in British Honduras showed that maximum yield of forages was obtained at 64 ppm of added P, but the phosphorus content of the forage was probably not adequate except at 220 ppm of added P (Blue, 1969).

The volcanic ash soils of Chile (Trumao soils) are very often deficient in phosphorus. A minimum rate of 100 kg P_2O_5/ha is needed for the

establishment of grass-legume pastures on the volcanic ash soils (Goic, 1968).

In studies on Múcara and Catalina clays in Puerto Rico, Napier grass responded to 150 kg P_2O_5/ha (Figarella, 1964). A number of studies have been conducted in Puerto Rico on the amount of phosphorus removed annually by some of the tropical grasses. Para grass cut every 60 days produced 70 tons/acre/year of green forage which contained 52 lbs P (Vincente-Chandler *et al.*, 1960). Napier grass cut every 60 days produced 130 tons/acre/year of green forage which contained 120 lbs of P (Vicente-Chandler *et al.*, 1960). Guinea grass produced 73 tons/acre/year of green forage which contained 70 lbs P/acre (Vicente-Chandler *et al.*, 1960). These results show that under tropical conditions where it is possible to grow grasses the year around, the removal of phosphorus can be extremely high. Under these conditions, phosphorus applications need to be considerably higher than those applied in temperate regions.

Cotton

Results of 217 experiments on fertilization of cotton in São Paulo indicated that phosphorus was one of the major limiting factors (Verdade *et al.*, 1965). Average responses to phosphorus applications of 290 kg/ha were obtained on sandy soils and 330 kg/ha on clay soils in São Paulo (Fuzatto and Cavaleri, 1966). Large increases in yield of cotton were obtained with phosphorus fertilization of Terra Roxa soils in São Paulo (Schmidt *et al.*, 1962). Applications of 30 kg P_2O_5/ha generally were adequate except on those soils quite deficient in phosphorus. A large residual effect to phosphorus fertilization was obtained on a Massapé-Salmourão soil in São Paulo (Neves *et al.*, 1962).

Liming tended to reduce the response to phosphorus of cotton grown on Campo Cerrado soils in Sao Paulo which were just brought into cultivation (McClung *et al.*, 1961). This effect could be due to neutralization of exchangeable aluminum in these acid soils which resulted in better root growth and increased availability of soil phosphorus. The soils of the Campo Cerrado, however, are generally very deficient in phosphorus.

Sugar cane

Application of 90 kg P_2O_5/ha resulted in an average yield increase of 40 tons cane/ha on soils in São Paulo which had only been fertilized once with phosphorus (Alvarez, Pimentel and Segalla, 1963). On soils which had previously received two to five applications of phosphorus, yield responses averaged less than 12.5 tons cane/ha. Along the seacoast in São Paulo, optimum yields on lowland soils were obtained with

100 kg P_2O_5/ha (Alvarez, Miranda and Oliveira, 1963). On a Terra Roxa Misturada-glacial soil in São Paulo, an application of 40 kg P_2O_5/ha was adequate (Alvarez, Segalla, Arruda, 1963). Rates of phosphorus required for optimum yields of sugar cane in Brazil are considerably lower than those used in Hawaii where 175 kg P/ha are applied at planting on volcanic ash soils (Fox, 1969).

A number of experiments have been conducted in São Paulo, Brazil with sugar cane comparing the efficiency of natural rock phosphates with superphosphates. In a study with five soils in São Paulo ranging in pH from 4.8 to 5.6, superphosphate increased sugar cane yields 35 percent while four natural rock phosphates gave yield increases of 10 to 28 percent (Alvarez *et al.*, 1965). In another study, four natural rock phosphates were 40 to 63 percent as effective as superphosphate when applied at the rate of 100 kg P_2O_5/ha (Freire *et al.*, 1968).

Summary

The highly weathered soils of the tropics, Ultisols and Oxisols are generally quite deficient in phosphorus. These soils also have a large capacity to fix fertilizer phosphorus. The less crystalline the hydrated oxides of iron and aluminum, the more tightly the phosphorus is held. Soils formed from volcanic ash have a very high phosphorus fixation capacity because of amorphous aluminum silicate, allophane.

Large responses to phosphorus fertilization have been obtained on the highly weathered soils in the tropics. Rates of phosphorus on deficient soils generally giving optimum yields were 100 to 150 kg P_2O_5/ha for corn, soybeans, sugar cane, and forages; 120 to 240 kg P_2O_5/ha for wheat; 120 to 180 kg P_2O_5/ha for potatoes; and 60 kg P_2O_5/ha for rice.

Very little work has been done on the amounts of phosphorus required to bring the soil test values up to optimum levels. There is also a need to study the residual effect of phosphorus from given applications of phosphorus.

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CHAPTER 8

Potassium

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The potassium status of soils and plants in Latin America varies considerably. This is to be expected because of extreme differences in parent material, degree of weathering, and the diversity of crops grown. These and other factors need to be isolated in order to discuss the subject realistically. In the following review, an attempt is made to note pertinent research efforts that shed some light on potassium and problems encountered in determining its need.

Soil Potassium

Total K ordinarily does not correlate with plant uptake and thus is primarily just of academic interest. It varies tremendously with degree of weathering. In southern Brazil, Oliveira *et al.* (1971) found total K varied from 1,780 to 14,200 ppm in soils from the orders Alfisol, Inceptisol, Mollisol, Ultisol, and Oxisol. In Panama, Martini (1966) found 1,000 to 2,000 ppm in red lateritic and savanna soils, 3,000 to 4,300 ppm in alluvial soils, and 8,000 to 9,000 ppm in volcanic soils.

Soils derived from volcanic material may vary in total K depending on the nature of the erupted material and the degree of weathering. Caicedo (1971) found an average of 6,000 ppm in volcanic soils of Colombia, but also noted that K was easily leached from these soils. Graham and Fox (1971) also found that the labile pool of K in soils was related to the degree of weathering. In Hawaii where rainfall varied from 7 to 180 inches/year, this pool ranged from 4.71 to 0.09 meq/100g.

Inclusion of at least a portion of this labile pool may be beneficial in interpreting soil tests for K. In recent work with potatoes in Peru, McCollum and Valverde (1968) obtained yield responses to K in about half of their experiments, yet found no relation between sodium acetate (pH 4.8)-extractable K and the degree of response. Often a strong acid is used to estimate this pool. In a pot study in Brazil, HNO_3-extractable K correlated better with total K uptake by 13 cuttings of ryegrass than did exchangeable K (Oliveira *et al.*, 1971). The same type of study conducted in Colombia (Marin *et al.*, 1967)

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gave similar results. These are not in agreement, however, with the conclusions drawn by Crisóstomo and Castro (1970).

The potassium supplying power may also be determined by leaching studies. Using a couple of these techniques, Martini (1966) found the K supplying power of soils from Panama related better to exchangeable K than the HNO_3-extractable or total K. Thus, the relative importance of labile K seems dependent on the type of study conducted. Unfortunately, there have been insufficient field studies run to clarify the situation.

There may be a climatic effect on the status of K in the soil. Hardy and Bazan (1966) found that the nutrient status of soils differs at different times of the year. In volcanic soils, this may be related to their porous nature. Bornemisza (1960) found an unusually high amount of water in air dried soil derived from recent volcanic material. He observed potassium fixation on drying. Mulching has also been noted to increase K availability (Bull, 1963). Moisture relation is one of the factors affected by this practice.

Palencia and Martini (1970) analyzed for exchangeable K when studying 39 ash-derived soils from Central America. The soils averaged 1.8 meq K/100 g with a standard deviation of 1.2. Thus, ⅔ of the soils were in the range of 0.6 to 3.0 meq K/100 g, and ⅙ would be expected to be less than 0.6 meq/100 g. In contrast to this, a computation of the data of Crisóstomo and Castro (1970) from 20 Brazilian soils gave a range of 0.1 to 0.4 meq K/100 g.

Palencia and Martini also noted some relationships of climatic effects and soil K level. Exchangeable K increased with an increase in the mean annual temperature and decreased with an increase in elevation. Temperature and elevation, of course, are highly rated. They also noted that the level of exchangeable K decreased with increasing rainfall and increased as the number of dry months increased. In this instance, the length of the dry season and rainfall are closely associated. However, this is not always true. Some areas may be compared in which both the annual rainfall and length of dry season are greater at one site as compared to another. Thus, it would seem more logical when evaluating climatic effects to consider average temperature and rainfall per month during the rainy season.

Plant Response and Content

Several aspects of plant potassium were considered pertinent for this review. The K content of tissue, any critical level noted, and the general responsiveness to K fertilizers were of primary interest. Due to the wide variety of crops grown, many were combined into each of

the eight headings listed in the following paragraphs.

Cereals

The response of corn to K has been studied in Mexico in Jalisco (Laird and Lizarraga, 1959) and in Veracruz (Laird *et al.*, 1963). Responses were found in only 5% of the tests but the soils were generally high in exchangeable K. More frequent responses have been noted in Brazil. From reports of several workers, it may be deduced that responses occurred about one-third of the time. Gallo *et al.* (1965) also listed a critical level for K in corn tissue. Using the basal third of the fourth leaf without the midrib, the critical level was 2.1 percent. In a later work (Gallo *et al.*, 1968), these workers found a strong association between K content and soil type. The critical level even appeared related to soil type, being 1.7 percent in terra roxa and 2.8 percent in gravelly podzolized soils.

Little information is available on K fertilization of wheat. No responses were shown on soils of the inter-Andean uplands of Ecuador but they had a high content of K. In Brazil, Blanco *et al.* (1967) found wheat responded to fertilizer K if the soil test level was less than 0.1 meq/100 g. Responses have been noted at higher soil K levels by Jorge *et al.* (1965) but only at higher rates of P fertilization.

Several studies have been conducted with rice in Brazil and Peru. In most of them, there was either no response or a very minor one to K fertilization.

Root crops

The response of potatoes to potassium has been studied in Peru, Colombia and Brazil. Although yield increases have been shown about half of the time, there seems to be little association with the level of available K in the soil. Boock and Freire (1960) noted responses on soils varying from 0.2 to 1.4 meq/100 g. In comparison, data from sandy soils in Wisconsin have shown responses only when the soil K was less than 0.25 meq/100 g. Potato yield increases on soils testing high in K have also been found in Colombia (Rodriguez *et al.*, 1960). McCollum and Valverde (1968) found responses to K in Peru but could not relate these to soil K levels. The frequency of responses to K indicates that further work on calibration of a K soil test is needed. It is possible that another extractant may be helpful or it may be that the amount of K in relation to other ions should be considered.

Although cassava is an important food crop in much of Latin America, there are few reports of experiments with potassium. It has been found that placement is critical and KCl applied in the furrows will decrease the stand (Ribeiro da Silva and Freire, 1968a). These same

authors (1968b) have found very good response to K at soil test levels of 0.10 to 0.12 meq/100 g but not at 0.22 meq/100 g. All these experiments were on quite sandy soils.

Grain legumes

Dry beans are an important part of the diet in much of Latin America. For this reason, quite a number of fertilizer studies have been conducted with this crop. Responses to K, however, have not been noted often. Of the many studies conducted by Miyasaka in Brazil, only about 10% have responded to K. According to general fertilizer suggestions similar results have been achieved in other areas. Fassbender (1967) reviewed the fertilization of beans and reported that over half of the suggestions from other areas in Latin America did not recommend the inclusion of potassium.

Responses with soybeans have been similar to those with dry beans. Castor beans, however, may react differently. Canecchio, Rocha and Freire (1963) noted responses in three of five experiments they conducted with this crop in Brazil.

Forages and pastures

The response of alfalfa to K has been studied in Mexico (Alvarado and Nuñez, 1967), Brazil (McClung *et al.*, 1957), and Colombia (Marín *et al.*, 1960). In no case was there any yield response to K. It was noted in the Colombian study that the soil was relatively high in K.

Most of the reports on grasses deal with their elemental composition, although no critical tissue levels are given. Response data are sketchy. Caro-Costas and Vicente-Chandler (1963) found applied K increased molasses grass yields in Puerto Rico. Ahmad *et al.* (1969) found no effect of K rates up to 120 lb/acre on pangola grass, but yields were at a maximum when the K rate was 20 lb/acre.

Fiber crops

Many fertility studies have been conducted with cotton in Brazil. Verdade *et al.* (1976) found responses to K in only 10 to 209 experiments. Available soil K (0.05 *N* HNO_3-extractable) was between 0.05 and 0.33 meq/100 g but no critical soil level was determined because of the small number of responses. Fuzatto and Ferraz (1967) found enough responses to evaluate exchangeable K. They found that this measurement alone, however, only accounted for 23 percent of the variation in expected response. But when the Ca/K ratio was also included, 65 percent of the variation was explained. It seems that this type of interpretation has merit and deserves further investigation in other areas and perhaps with other crops.

Paiva Castro *et al.* (1968) studied flax in a fertilizer trial. Potassium rates did not affect growth or fiber yield.

Sugar cane

Sugar cane frequently responds to K fertilization. Several such reports are available from Brazil. Soil test levels are typically rather low from that area. For instance, Wutke *et al.* (1960) conducted a trial on a soil with 0.05 meq K/100 g and Alvarez and Arruda (1960) ran one on a soil with 0.14 meq K/100 g. Both tests gave large responses to K fertilization.

Leaf analyses also show low K levels in cane in Brazil. Gallo *et al.* (1960) found an average of 1.4 percent leaf K but many fields were below the critical level of 1.00-1.25 percent K. Potassium was considered to be the most limiting element in that area.

Responses have also been noted in Colombia (Valez and Jaime, 1969), Puerto Rico (Gonzales-Velez and Samuels, 1962), and Hawaii (Fox, 1969). In the latter case, it was noted that K is applied frequently on volcanic ash soils because of leaching in the high rainfall area.

Fruits and vegetables

Foliar analysis frequently has been used to assess the K status of citrus. By this means, Puiggros *et al.* (1969) found normal levels of K in Navel oranges grown in Peru. Weir (1955) found leaf analysis of Valencia oranges in Trinidad of limited value. In a later study (Weir, 1969), he found responses both in terms of yield and quantity to a medium rate of K.

Papaya response to K has been studied in Brazil (Carvalho *et al.*, 1963) where no response was obtained and in Hawaii (Awada and Long, 1971) where a positive response was found. In the latter case, the critical concentration was 3.6 percent K in the recently matured petiole.

Bananas have responded to K fertilization fairly consistently in Honduras (Bhangoo *et al.*, 1962) and Brazil (Cunha and Fraga, 1963). In Jamaica, a strong response was noted on Lacatan Bananas by Osborne and Hewitt (1963) but Butler (1960) found no response with the Gros Michel. There does not seem to be a clear reason for this discrepancy.

Other crops

Conflicting reports have been given regarding and beneficial effect of K fertilization on cacao, peanut, and coconut production. Responses have been noted with coffee in Puerto Rico (Rodriguez *et al.*, 1964, Abruña *et al.*, 1965) and Brazil (Amorim *et al.*, 1967), but few reports are available relating yield increases to soil K levels. Plant analysis has

been used frequently to determine the K status of coffee. Gallo *et al.* (1967) and Lott *et al.* (1961) found K to be limiting in many coffee fields in Brazil by this technique.

Summary

Less research has been conducted on potassium than on acidity, phosphorus and nitrogen. Nevertheless, many deficiencies have been shown, and the amount may increase as other limiting factors are removed.

Responses to K are very much related to the sensitivity of the crop being grown. Sugar cane and potatoes have shown yield responses to K half the time or more. Corn has responded about a third of the time, whereas rice and beans seldom do.

A great deal of research still is needed in developing a soil test for K. The lack of correlation of yield response and available K in the Peruvian potato data is a prime example of this. Some of this lack of correlation may be associated with sample drying. The overall effect may be similar to fixation by illite in temperate regions, but the mechanism in tropical soils is unknown. The porous nature of material derived from volcanic ash may be involved. Longer extraction periods might be beneficial in such cases.

Another factor that may improve the eventual interpretation of K soil tests is consideration of the cation exchange capacity of the soil. The work with cotton in Brazil by Fuzatto and Ferraz (1967) certainly indicated this. Since the soils are very diverse in the tropical region of Latin America, such a consideration could be very halpful.

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CHAPTER 9
Sulfur

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Soils from the Central Plateau of Brazil were found to be very deficient in sulfur (McClung and Freitas, 1959). When sulfur was not applied plant growth was only 4 to 30 percent of that obtained with a complete fertilizer treatment. Additional work indicated that the most acute deficiencies were found on soils from upland savannas (McClung *et al.*, 1959). It has been postulated that the very low sulfur content of soils from the Brazilian Campos is due to repeated burning of these areas (McClung and de Freitas, 1959). Burning of dry grass resulted in losses of 75 percent of the sulfur by volatilization.

Sulfur deficiences have also been reported in Central America. Soils from El Salvador which had been previously cultivated were found to be sulfur deficient (Muller, 1965). Medium responses to sulfur were obtained on the principal Latosols of Costa Rica (Martini, 1969).

Organic sulfur contents of virgin soils of the central plateau of Brazil ranged from 72 to 494 lbs S/acre while adjacent sites, cropped for 20 to 30 years contained 48 to 120 lbs S/acre (McClung *et al.*, 1959). Thus under cropping considerable mineralization of organic sulfur had taken place. Mineralization of organic sulfur in soils formed from volcanic ash, however, is limited. The stability of organic matter in volcanic ash is very high because of reactions with allophane and sulfur deficiencies may occur even on soils with a high organic matter content (Fox, 1969).

Large amounts of sulfate were absorbed by a Latosol from Costa Rica which contained large amounts of hydrated oxides of iron and aluminum (Bornemisza and Llanos, 1967). Desorption of sulfate from the Latosol was small compared to soils from temperate regions. Water solubility of absorbed sulfate was very low in volcanic ash soils of Hawaii (Hasan *et al.*, 1970). Pot studies with these soils indicated that a solution concentration of 5 ppm SO_4-S was required for optimum growth of Kikuyu grass.

Responses to sulfur fertilization were obtained on cropped Brazilian soils which contained less than 10 ppm SO_4-S extracted with NH_4OAc (McClung *et al.*, 1959). Adsorbed sulfur in the B horizons of Brazilian soils was readily available to plants. Where soils have been heavily fertilized in the past with sulfate containing fertilizers the adsorbed sulfate in the subsoil may be an important source of sulfur.

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Large responses to sulfur were obtained with cotton on Campo Cerrado soils in São Paulo, Brazil (McClung *et al.*, 1961). Yield increases ranged from 30 to 100 percent. Maximum yield responses were obtained with 30 kg S/ha applied as calcium sulfate. Corn yields were increased approximately 25 percent on Campo Cerrado soils by the application of calcium sulfate (Mikkelsen *et al.*, 1963). A three-fold increase in dry matter production of Batatais grass was obtained with the application of calcium sulfate (McClung and Quinn, 1959). Application of 20 to 40 kg S/ha as calcium sulfate gave maximum yield increases.

Response of soybeans to sulfur fertilization was 350 kg/ha of grain on a soil derived from Botucatu sandstone (Miyasaka *et al.*, 1964). Responses of beans to sulfur fertilization was obtained on only one out of seven sites which had previously received frequent applications of fertilizers (Miyasaka *et al.*, 1966). There apparently was sufficient build up of sulfate in these soils from previous fertilization.

Summary

The highly weathered savanna soils in South America are likely to be sulfur deficient particularly where they have undergone repeated burning. Mineralization of organic sulfur may initially supply some sulfur particularly where the soils are high in organic matter.

Although some volcanic ash soils contain large amounts of organic matter very little organic sulfur is released because of the stable condition of the organic matter.

Considerable amounts of sulfate are adsorbed by Latosols and volcanic ash soils. Where large amounts of sulfate have been adsorbed by the soil, plants are able to obtain adequate sulfur.

Response to sulfur fertilization were obtained on Latosols which contained less than 10 ppm SO_4-S extracted with NH_4OAc. Application of 20 to 40 kg S/ha has given maximum response where sulfur was limiting yields.

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CHAPTER 10

Micronutrients

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The micronutrient status of soils and plants is not well documented throughout Latin America. Observations have been made of deficiency symptoms on many crops but the diversity of soil conditions and the lack of an adequate reporting system has kept the picture incomplete. Also, in dealing with micronutrient problems, investigators have often applied a mixture of these trace elements to correct a deficiency. When these materials did give a response, it has been impossible to tell which of the nutrients was effective.

Observations and studies have been made, however, that allow certain conclusions to be drawn. In central Brazil, problems have been noted with Zn, Mo, and B, as indicated in general articles by Hardy (1962) and Arens (1963). These have been brought to light not only because of the parent material in the old shield area but also because of more research effort and a better reporting system than has been available in other areas of Latin America. For these reasons, much of the information available for this review was from Brazil and it will be biased in that manner.

Because of the importance of soils derived from volcanic ash, an effort was made to review all possible reports of micronutrient deficiencies on these. These soils are known to occur in areas down the Andean chain from Mexico to Chile. Citations from outside this area were included if thought to be pertinent.

The literature has more information available concerning tissue analyses than soil analyses. Both of these aspects as well as well-defined response data will be given by element in the following review.

Zinc

Igue and Bornemisza (1967) recently reviewed the problem of zinc in soils and plants of tropical regions and temperate zones. The bulk of their material, naturally, came from the temperate zones, but this article does provide some good background information for anyone interested in zinc.

A few workers have reported levels of zinc in tropical soils by various extraction techniques. A recent study by Meuer *et al.*, (1971) gave

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the following 0.1 *N* HCl extractable Zn levels for four soils from Brazil

Zn (ppm	Soil
1.3	Aqualf
2.2	Haplohumox
1.6	Haplorthox
1.4	Haplorthox

In a greenhouse study with these soils they found liming to pH 5.5 did not affect Zn uptake. However, liming to pH 6.5 caused Zn deficiency symptoms in soils with less than 1.5 ppm Zn and liming to pH 7.4 gave such symptoms in all soils. Rates of P applied in their study did not affect Zn uptake.

Information gathered in greenhouse studies must be tested in the field with yield measurements to fully interpret a soil test for zinc. Soil and fertilizer P levels may become important under field conditions. Likewise, texture may need to be considered.

Other work in Latin America has indicated soil Zn levels of 1.5 ppm in Argentina (Mazza *et al.*, 1966) and 1.6 - 18.4 ppm on volcanic ash soils of Chile (Schalscha *et al.*, 1968). These were extracted with 0.1 *N* HCl and the levels were considered normal.

Kanehiro (1967) used the same extractant on Hawaiian soils and found they averaged 4.5 ppm Zn. He considered the critical level to be between 1 and 2 ppm. Low levels were found primarily where some of the A horizon had been removed. Another study in Hawaii by Lyman and Dean (1942) set the critical level of Zn at 1.0 ppm when soils were extracted with NH_4Ac and dithizone.

Marinho and Igue (1972) studied zinc absorption from corn grown on three volcanic ash soils from Costa Rica. Using 0.01 *M* Na_2EDTA at a ratio of 1:2 extracting for 30 minutes, they found 1.8, 1.3, and 0.7 ppm Zn. When the samples were left in 0.1 *N* HCl overnight at a ratio of 1:25, the levels were 8.1, 4.3, and 2.2 ppm, and these rather high levels may reflect the time and ratio involved. They considered these soils to be deficient yet found little growth response to applied zinc in a greenhouse study. With adequate P, the Zn concentration of the tissue from the checks was 12, 10, and 7 ppm. At these levels, it is surprising there was no growth response. When using EDTA, other workers have found the critical level of soil Zn to be in the range of 0.8 - 1.4 ppm.

Much of the data on zinc from Brazil deals with plant content. The following table gives examples of the information reported.

Crop	Leaf Zn (ppm)	Yield response	References
Upland rice	15	yes	DeSouza and Hiroce, 1970
Corn	17-20	yes	Igue *et al.*, 1961
Corn	16	yes	Freitas *et al.*, 1960
Corn	21	no	Gallo *et al.*, 1965
Cotton	35	no	Freitas *et al.*, 1960
Cotton	26	no	McClung *et al.*, 1961
Soybeans	23	yes	Freitas *et al.*, 1960
Soybeans	57	no	Freitas *et al.*, 1960
Sugar cane	15-18	no	Gallo *et al.*, 1968
Coffee (survey)	8 ppm critical	Some groves deficient	Lott *et al.*, 1961

These observations indicate responses with corn and soybeans when the leaf Zn is less than 20 and 23 ppm, respectively. Viegas *et al.* (1961) also found corn yield responses to Zn in Brazil. Response data from other areas is scarce. Laird and Rodriguez (1965) in Mexico noted Zn responses in two studies but not in 20 others. Although Zn deficiency symptoms have been seen in Latin America, many have not been well documented. For instance, several Zn deficiencies have been found in rice grown on high pH soils in the Cauca Valley of Colombia. Also, in the Campo Cerrado of Brazil, severe Zn deficiencies have been noted in corn and upland rice.

Boron

Boron deficiencies are frequently observed but seldom studied in detail. Often it appears that the uptake of this nutrient is more dependent on climatic factors than on soil conditions. Perhaps as a result of this, Tollenaar (1969), studying B in volcanic soils in Ecuador, stated that soil analysis is not able to give more than a general orientation. Water soluble boron levels have also been determined in Mexico (Flores and Mayazoitia, 1959). They ranged from 0.3 to 3.0 ppm B and were not regarded as deficient. Still the authors felt that yields in some regions would probably increase with the application of borax.

Recently Bingham *et al.* (1971) found volcanic ash soils adsorbed more B than soils derived from other materials. The inference might be made that these are then more likely to be deficient in B. However, the case can also be made that these would retain more B against leaching. Calibration work in the field is needed to see if volcanic ash soils do differ from others in their ability to supply boron.

Boron deficiency has been noted in coffee and other crops on the volcanic ash soils of Ecuador (Tollenaar, 1966). A survey of coffee fields

by foliar analysis in Brazil, though, indicated adequate B levels. Whether these differences are soil or climatic associated is unknown. Work with coffee in Puerto Rico (Bonnet, 1969) did show a definite seasonal effect on B levels which emphasizes the climatic aspect.

In Brazil, McClung *et al.* (1961) obtained yield responses to boron with cotton grown on Campo Cerrado soils. Undoubtedly, conditions where responses could have been obtained exist on other soils and with other crops, but these have not been studied or have not been reported in Latin America.

In the arid areas along the coast of Peru, boron toxicity has been noted. Fox (1968) studied the tolerance of several crops to high concentrations of water soluble boron. Puiggios *et al.* (1969) also noted above optimum levels of B in citrus in that area.

Molybdenum

Molybdenum deficiencies are usually restricted to weathered acid soils. Thus, in the discussion by Hardy (1962) and Arens (1963), it might have been expected that they would list the lack of this element as one of the problems in the Campo Cerrado area of Brazil. Such soils are also high in Mn and Truong *et al.* (1971) found Mo applications especially beneficial for the N metabolism of legumes under these conditions. Ruschel *et al.* (1969) found coating the seeds of soybeans with rock phosphate containing Mo to be an effective treatment.

Non-legumes have also responded to Mo in Brazil. McClung *et al.* (1961) noted responses with cotton and Lott *et al.* (1961) found the foliage of coffee exceptionally low in this nutrient.

Volcanic ash soils may also be low in Mo. Fujimoto and Sherman (1951) found plants contained 0 - 2.5 ppm Mo, which is lower than levels reported from many areas. They also extracted the soils with NH_4Ac and determined the soil levels to be 0 - 0.13 ppm. Volcanic ash soils in Colombia were found to have 0 - 2.4 ppm Mo by Blasco (1969). Such low levels may affect crop production. Bhangoo and Karon (1962) found that of the micronutrients only Mo increased the yields of bananas.

Copper

Although there have been a few reports of Cu deficiency in animals, there does not seem to be any lack of this element for plant growth throughout the bulk of Latin America. One case of a yield increase was reported when rice seed was treated with $CuSO_4$ (Primavesi and Primavesi, 1970). Although the authors considered the effect to be primarily

nutritional, they also noted protection with $CuSO_4$ against the fungus *Pyricularia oryzae*.

Soil analyses in Argentina (Mazza *et al.*, 1966) and Chile (Schalscha, 1968) have indicated adequate Cu levels. Likewise, plant analyses in Brazil (Gallo *et al.*, 1968, Lott *et al.*, 1961) and Peru (Puiggros, 1969) have indicated adequate Cu levels.

Some problems may exist from excessive levels of copper. Aduyi (1971) studied the effects of high rates of Cu on coffee. Root growth was depressed and thus the absorption and translocation of other nutrients could be hindered. Copper has accumulated in soils in Chile where the irrigation water had been used previously in mining operations (Sudzuki-Hills, 1966). Observations have also been made in Central America that Cu toxicity problems have occurred after extended fungicide applications on bananas. Rice grown later on these soils often develop Fe deficiency symptoms.

Iron

There is little evidence of any naural iron deficiency in Latin America. Surveys in Brazil with coffee (Lott *et al.*, 1961) and sugar cane (Gallo *et al.*, 1968) have indicated deficiencies of iron are less probable than for the other nutrients. Tomatoes grown in Argentina (Mazza *et al.*, 1966) were found to have quite high levels of Fe, even though they were grown on neutral or slightly alkaline soils. Since most of the soils are not alkaline in Latin America, Fe deficiency would not be expected to be widespread.

Schalscha *et al.* (1968) analyzed volcanic ash soils of Chile and found the levels of Fe to be adequate. In another study (Schalscha, 1965), it was stressed that measurements of available Fe on volcanic ash soils should be done on samples maintained at field capacity. Air drying affects the level of soluble Fe.

Manganese

There are ordinarily two stages in the development of a Mn deficient soil. First, it must form under reducing conditions, thus allowing leaching of reduced forms of Mn. Second, the soil must be limed, often in excess of crop requirements, to induce the deficiency. Since many of the soils of Latin America are well drained and lime is expensive, it is not likely that Mn deficiencies will exist. One such case has been noted, however, in Puerto Rico in which a peat soil was limed to above pH 6.0. In fact, free calcium carbonate was still being detected in this soil.

Liming any soil will decrease the uptake of Mn. Lopez (1969) noted this with coffee grown on volcanic ash soils in Colombia. In many areas

of Latin America, liming is needed to decrease Mn toxicitv. Coffee grown in Puerto Rico on an acid Alongo clay contained high concentrations of Mn in the leaves. Some workers (Abruña and Vicente-Chandler, 1963) have even questioned the use of NH_4SO_4 as a fertilizer for coffee because of its acidifying effect.

Manganese toxicity is a problem, especially for legume production, on the acid soils of Brazil. Some workers have tried adjusting the type of fertilizer and the variety (Souto and Dobereiner, 1969a) to overcome this problem. These workers have also looked at the Mn tolerance of various tropical forage legumes (Souto and Dobereiner, 1969b). However, if soils are limed adequately to eliminate Al toxicity as a problem then Mn toxicity should be eliminated at the same time.

Summary

An analysis of the information presented in this review on micronutrients indicates that deficiencies of Zn, Mo and B are likely to be encountered in Latin America. Of these, Zn problems occur most frequently with low levels in soils and plants being reported throughout much of the area. A background of information on critical levels in soils and plants is slowly evolving. A soil test that is applicable over the wide range of soil conditions encountered is desperately needed. More than likely the interpretation of this test will need to be based on not only the level of available Zn, but also soil pH, soil and fertilizer P, and perhaps texture. When such a test exists, the true status of Zn in this region can be fully surveyed.

Molybdenum and boron problems occur more sporadically and thus are of secondary importance. Many of the Mo deficiencies, especially as they exist in the Campo Cerrado area of Brazil, might be overcome by applying a higher rate of lime. However, the relatively high cost of lime and the possibility of inducing other problems such as greater Zn deficiency make this impractical. As this marginal level of lime and sufficient P and K are utilized in the old shield area, it may be expected that many legumes should respond to Mo. In other locations where often the pH and organic matter level are more favorable, deficiencies are noted less frequently. Use of present soil test methods, although not calibrated in Latin America, would aid in determining potential problem areas.

Boron deficiencies have occurred in crops grown on highly weathered soils when they were subjected to drought conditions. Soil tests are seldom used for B, but such data when combined with frequency of expected drought could prove helpful.

Problems related to Fe, Mn or Cu are not major in the region but could be important locally. In some cases, Mn toxicity has been noted

but never when an adequate lime level was established. Also, a few cases of Cu toxicity created by mismanagement have been shown.

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