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9. ABSTRACT

Describes the objectives, methods, and accomplishments of USAID-sponsored Tropical Soils Program at N. Carolina State University (1970-1975). Major objective was to develop a methodology for making economically sound recommendations regarding use of fertilizers in developing countries in tropical regions, based on information gained from soil research in Latin America. Phase I was a two-year literature search. Phase II consisted of field and laboratory studies at Yurimaguas, Peru; Brasilia, Brazil; and Turrialba, Costa Rica. Progress was made in developing a fertility-capability soil classification system which groups soils having similar fertility management limitations. The system was used to group 678 Brazilian soil samples into 23 fertility-capability units; samples from 73 Peruvian sites, into five units. Fertilizer recommendations specified by unit groups dramatically increased economic returns from use of fertilizer. Long-term field experiments are needed to evaluate residual effects of liming and fertilization. Amazon jungle problems of yields require interdisciplinary research, with inputs from animal scientists, plant breeders, pest management specialists, and economists.

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AGRONOMIC-ECONOMIC RESEARCH ON TROPICAL SOILS[1/]

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The purpose of this paper is to describe North Carolina State University's tropical soils research program, its rationale, methods of operation, accomplishments to date and prospects for the future. A description of anticipated needs in terms of the objectives of this workshop is also included. The work reported here represents the efforts of twelve faculty members and seventeen graduate students of the Soil Science Department who are involved in this program.

RATIONALE

The ability of the world to feed its human population has been a major concern during the past two hundred years. The recent successes in increasing wheat and rice production since the late sixties provided the impression that world food production could increase at the same rate as population. The current energy and fertilizer shortage has dispelled this cautious optimism and once more the need to increase world food production at a faster rate than population growth is a top concern of mankind.

Plants grow on soils. Therefore, the field of soil science has played and will continue to play a critical role in increasing world food production. It has been well established that the greatest potential for increasing world food production lies in vast regions of the tropics (Kellogg and Orvedal, 1969). Tropical agriculture, however, developed first on soils with high base status, mostly in

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alluvial plains and valleys. Examples of these are the rice bowls of Southeast Asia, the Central Plateau of Mexico, the Cauca and Mantaro Valleys of the Andes and the Ethiopian highlands. The impact of the "green revolution" is very much limited to these soils, particularly those which are irrigated.

The properties of high base status soils deserve some examination. They have generally developed from alluvium, sediments or volcanic ash rich in calcium, magnesium or potassium. They present no acidity problems and therefore, require no investments in lime. Nitrogen is the only nutrient element which is commonly deficient. Occasionally phosphorus deficiencies, micronutrient disturbances and moderate salinity problems occur but these can be corrected at low cost. In other words, high base status soils are almost synonymous to high native soil fertility, and low cost of supplying additional nutrients to crops.

Agricultural development in the temperate regions followed the same pattern of first settling on high base status soils. When farmers ran out of them, they started using low base status soils. In southeastern United States, shifting cultivation was practiced on such soils, particularly in cotton plantations until the 19th century. With the use of manures, fertilizers and lime, continuous cropping became established in these low base status soils.

The extent of continuous cropping on low base status soils in the tropics is limited to small areas, like southern Brazil. Only about 10% of the tropics (approximately 503 million hectares) is presently under cultivation, mostly high base status soils. The President's Science Advisory Committee (1967) estimated that an additional 1200 million hectares are potentially arable in the tropics. These presently unused or underutilized areas consist mainly of highly weathered low base status soils (Oxisols and Ultisols) presently under rainforest or savanna vegetation.

The expansion of cultivated area in the tropics, therefore is quite different from the way United States agriculture moved into its heartland during the last century. While U.S. farmers found primarily high base status soils in the Midwest and Great Plain States, tropical farmers moving into the vast savannas, jungles and underpopulated highlands must come to grips with low base status soils. In the long-run, the race between world food production and world population will be decided in such tropical regions.

It is widely acknowledged that one of the main limiting factors preventing full-scale agricultural development in the tropics is the inadequate knowledge of how to manage these low base status soils in tropical environments (Drosdoff, 1967). An examination of the positive and negative properties of such soils is in order. From the nutritional viewpoint, there is no question that the cost of supplying nutrients to crops is higher in these soils than in the previously discussed high-base status ones.

Profitable ways of solving these problems have been developed and used in similar soils of the temperate regions. Morphologically, chemically and mineralogically, a large proportion of these low base status tropical soils are very similar to the soils of southeastern United States, South Africa and in some cases Hawaii. Our understanding of the basic principles governing the behavior of such soils (for example,the chemistry of exchangeable aluminum) is directly applicable to their tropical counterparts. The transformation of such principles into practices, however, requires research to adapt it to specific climatic, agronomic, economic and social conditions of the various regions in the tropics.

On the positive side, most Oxisols and Ultisols of the tropics possess excellent physical properties. Their great depth eliminate physical barriers to root development. Their high contents of iron and aluminum oxides bind sand, silt and clay particles to provide excellent structural stability. It is common in certain Oxisol areas with 80% clay content, to see tractors plowing the fields one day after a heavy rain. The excellent structure also renders many of these soils more resistant to erosion. On the negative side, however, many Oxisols do not retain as much available water to plants as other soils with similar clay contents.

Much of the tropical literature has traditionally emphasized the dangers of laterite or plinthite formation in these soils after cleared of their native vegetation (McNeil, 1964). Although this phenomenon undoubtedly takes place, it is quite limited in areal extent. Present estimates indicate that it may be restricted to less than 5 percent of the tropics usually in well-defined positions in the landscape. The vast majority of these low base status soils (previously called Latosols) present no such problems.

The development of soil management systems in these tropical regions should be based on the following precepts: 1) an understanding of the properties, areal distribution of the soils and the behavior of minerals, nutrients and water in them. 2) An understanding of the specific physical, economic and social environments of a tropical region. 3) An understanding of what farmers are presently doing, and a realization that they are probably operating at the optimum level with the resources that they have at their disposal.

Research would then determine how the present practices can be improved (either gradually or drastically). Due to present and projected shortages of petroleum inputs, the most realistic improvements are likely to result from practices requiring minimum inputs of expensive fertilizers and lime added to crop and varieties well adapted to these conditions. Instead of maximum yield per crop, the objective should be maximum annual yield per unit of soil fertility input.

PROGRAM HISTORY

The Technical Assistance Bureau of AID organized a concerted attack on solving the previously mentioned soil management constraints by awarding two research contracts to Cornell and North Carolina State Universities. Contract AID/csd 2806 was awarded to North Carolina State University on July 1, 1970 for a five year period. It is in the process of extension-revision. The project objectives were "to develop methodology for an economically-sound system of making fertilizer recommendations based on information gained from soil analysis, fertilizer response, soil chemistry and soil fertility data primarily from Latin America for developing countries in tropical regions."

The work plan consisted of two phases. Phase I involved a review and analysis of present knowledge, identification of priority research problems and development of a research strategy to solve these problems. Phase II consisted of generating the needed information from field and laboratory studies and devising means for extrapolating the results to other areas with similar environmental conditions.

The objectives of Phase I were achieved in the first two years. A comprehensive review of the literature and other sources of information was compiled by the project staff and published in English and Spanish as "A Review of Soils Research in Tropical Latin America."

Travel to several countries to determine potential areas for field research and cooperation of national and international research institutions took place within this period. As a result of the literature review, travel, and suggestions from LDC scientists, a research strategy developed. The most crucial research needs not likely to be solved by other ongoing projects were to increase food production via improved soil management in:

1) Tropical rainforests presently under shifting cultivation.
2) Acid Oxisol savannas virtually unused.
3) Highly populated intercropped areas affected by volcanic activity.

A search for representative sites to conduct the necessary field work was made and cooperative agreements were signed with local research institutions in each of the three major ecological regions.

Field research programs were initiated in August 1972 in: 1) Yurimaguas, Peru at the Campo Experimental de Yurimaguas of the Ministry of Agriculture in cooperation with that institution, as a representative site for the Amazon Jungle, 2) Brasilia, Brazil at the Centro de Pesquisas Agropecuarias de Brasilia in cooperation with EMBRAPA (formerly DNPEA) and the Cornell University contract, as a representative site of the acid Oxisol savannas and, 3) Throughout Central America with headquarters in CATIE, Turrialba, Costa Rica in cooperation with that institution and the Ministries of Agriculture of Costa Rica, El Salvador and Guatemala for work on subsistence volcanic ash areas, characterized by intercropping.

These three regions encompass a large proportion of the tropics. Tropical rainforests cover approximately 30 percent of the tropical land mass. The largest areas are in the Amazon and Congo Basins and in the hill country of Southeast Asia. A large proportion of the tropical rainforest have similar soil properties and rainfall regime to that found in the Yurimaguas Station. Tropical savannas with acid soils such as those of Brasilia cover approximately 31 percent of the tropical land mass. The largest areas are in the Cerrado and Llanos of South America as well as in central and eastern Africa surrounding the Congo Basin. The areal extent of subsistence intercropping tillage in volcanic areas is difficult to estimate. It is probably less than 5 percent of the tropical area, but the numbers of people involved is substantially larger. In addition to the Central American highlands, similar conditions exist in parts of Indonesia, the Philippines and in the Rift Valley of Africa. Many of these soils derived from volcanic ash (called Andepts) have similar physical properties to those previously described and frequently present similar fertility limitations, particularly those derived from acid ash.

The principal research sites are illustrated in Figure 1. Supplementary activities were conducted in countries or with soils from the countries shaded. The initial geographical emphasis in tropical Latin America reflect the Department's long-term involvement in the region. The selection of research sites and research questions to be answered was made in a way in which the results would be applicable to other tropical regions with similar environmental conditions.

Field research is supplemented by research conducted on Campus through (1) soil characterization, soil and plant analysis of experimental plots, (2) greenhouse and laboratory research to answer questions posed by the field data, (3) economic analysis of crop response to fertilizers and methodology for optimizing recommendations and (4) develop and test a Fertility Capability Soil Classification System as a means for grouping soils with similar fertility problems together for extrapolation purposes.

The program's objectives are to develop a "package" of economically sound soil and fertilizer management practices for the three areas of action.

METHODS OF OPERATION

The operations of a Land Grant University in conducting such a program are considerably different from those of an international research institute or a U.S. Government organization. A procedure was developed in the light of prior experience which permits the accomplishment of the research objectives in accord with the University's policies and philosophy. The first requisite is a long-term commitment from the administration at the University, School of Agriculture, and Departmental level for international research aimed at alleviating the world food crisis. This we are fortunate to have. In order to weave this program through the fabric of the Department, efforts were made to involve a significant number of tenured faculty and graduate students. At present there are 17 professors and 17 graduate students involved in this program. A project leader coordinates their activities. The project is closely coordinated with other international activities of the Soil Science Department such as the 211(d) Institutional Development Grant and the International Soil Fertility Evaluation and Improvement Program.

Most of the work is conducted by well-trained graduate students professionally committed to a career in tropical soils. They have language competency and are highly motivated to work hard and establish a professional reputation. Their student status permits them to devote full time to their research. In cases where there is considerable daily contact with administrators or when the utilization phase begins, a PhD. level position is required to coordinate local activities. Our experience with assistant professors having prior international assignments suggest that such coordinators must be of a similar age as their counterparts. Through cooperative agreements with the host institutions, NCSU staff work closely together with host-country personnel and within the national research institutions.

Field researchers need considerable backstopping from campus-based personnel. Frequent faculty travel to the research locations for advisory consulting purposes is essential. The graduate student advisors keep close personal contacts with their students. Supplementary greenhouse and laboratory research is conducted on campus to answer questions raised by the field research or to determine whether the results can be extrapolated to other areas. Additional field work is conducted in other countries primarily by graduate students from such countries for similar purposes.

PROGRAM ACCOMPLISHMENTS

A summary of the accomplishments to date follows. For further details, the reader is referred to our Annual Reports for 1971, 1972, and 1973, and the published papers and theses listed in the references.

Soil Management in Shifting Cultivation Areas

The reasons why farmers practice almost exclusively shifting cultivation in the Amazon Jungle are usually related to a rapid soil fertility depletion after clearing and increasing difficulties in weed control. The first step was to characterize the representative soils of the region, which appear in generalized soil maps as Oxisols or Latosols (Aubert and Tavernier, 1972; FAO-UNESCO, 1971). These studies showed that Ultisols rather than Oxisols are the predominant well-drained soils of the Amazon Basin located outside the geological influence of the Guyana and Brazilian shields. No evidence of laterite formation in this region has been observed. This dispelled one of the most common fears found in the literature that these soils will turn essentially into brick after clearing the jungle (McNeil, 1967). These soils have management characteristics quite different from the Oxisols. Phosphorus fixation capacity is much lower than in Oxisols due to coarser topsoil texture and different mineralogy. They are, however, extremely acid with pH values of about 4, and deficient in nitrogen, phosphorus, potassium, sulfur, and several micronutrients. Morphologically, they are strikingly similar to the Ultisols of the Coastal Plain of North Carolina and adjacent states (Sanchez and Buol, 1974).

Experiments on land clearing methods in Ultisols in Yurimaguas showed that the traditional slash and burn practice was superior to mechanized clearing with a bulldozer. Yields of upland rice, cassava, pastures, corn, and soybeans were consistently higher with slash and burn at several fertility levels. The fertilizer value of the ash, the severe compaction measured in the bulldozed plots and the movement of the topsoil by the bulldozer blade are the factors thought to be responsible for these differences.

In order to quantify the changes that occur as a result of clearing and cultivation, as well as the fertilizer and lime requirements needed to counteract the marked fertility decline, a long-term continuous cropping experiment was planted. Several cropping sequences and fertility treatments were installed on the same soil in areas cleared at one year intervals. In this way, the soil changes can be monitored as a function of time after clearing.

Preliminary results so far indicate that continuous cropping is feasible in these Ultisols with moderate applicates of lime, nitrogen, phosphorus, potassium and in some instances sulfur, boron, and molybdenum. High yields were obtained with upland rice, cassava, soybeans and Panicum maximum pastures. Corn and beans seem to be more sensitive to pests, aluminum toxicity and micronutrient deficiencies. Results to date indicate that the economics of continuous crop production in these shifting cultivation areas will depend largely on the transportation costs of fertilizers and lime.

Soil Fertility in Acid Savannas

Studies in the Campo Cerrado of Brazil indicate that the management of these Oxisols is primarily a matter of fertility and subsoil moisture interactions. Liming to raise the pH to 5.5 in the top 30 cm of the soil increased corn yields and decreased moisture stress during critical short term droughts that occur during the rainy season. Only a moderate rate of 2 tons/ha when incorporated in the top 30 cm was necessary to produce high corn yields in the first two crops. The estimated investment in lime, about U.S. $20/ha is less than previously thought necessary to eliminate aluminum toxicity to corn in these very acid soils.

Although applications of nitrogen, potassium and zinc are also necessary, the amounts required are also within the economic range. The management of phosphorus, however, is the primary fertility problem due to the extremely high phosphorus fixation capacity of these Oxisols. The "Dark Red Latosol" on which the experiments were conducted required the equivalent of about 2800 kg P_2O_5/ha when broadcast applications were used to provide the desired amount of phosphorus in the soil solution. Such an investment is not possible by farmers unless ample credit is available and they are allowed to depreciate it over the years as a capital investment.

Broadcast applications were superior to banded applications during the first rainy season crop because they promoted more root development which in turn attenuated the effects of short-term droughts. In the subsequent irrigated dry season crop, banded applications were superior. These results suggest that a corrective level of broadcast phosphorus supplemented by banded applications with each crop may be the best management scheme. The best way to manage phosphorus will depend in the long-term residual effect of these alternatives.

The high cost of such phosphorus applications using ordinary superphosphate raises serious economic questions. This problem is being tackled from three different angles: 1) Utilization of cheaper sources of phosphorus such as rock phosphates, 2) Reducing the soil's phosphorus fixation capacity through ammendments like lime and silicates, and 3) Selecting varieties and species more tolerant to low levels of available soil phosphorus.

Outreach studies on the properties and distribution of Campo Cerrado soils indicate a remarkable uniformity in terms of low fertility, and point out the areas where different results might be expected due to soil or climatic properties (Lopes, 1975).

Soil Management in the Central American Highlands

A fertilization program for intensive forage sorghum production during the rainy season in northern El Salvador became a simple solution for counteracting the severe weight losses of dairy cattle during the dry season. Heavily fertilized forage sorghum is preserved in inexpensive trench silos and used as the principal source of food during the dry season.

Major effort was placed on the fertility-related aspects of multiple cropping systems for small farms on soils affected by volcanic ash. Several experiments are underway in identifying how to manage fertilizer applications when more than one crop is grown at the same time.

Greenhouse experiments indicate that a large proportion of Costa Rican soils are deficient in sulfur. Initial studies are also underway aimed at eliminating copper toxicity to rice in lands formerly operated as banana plantations.

Region-Wide Extrapolative Studies

Substantial progress was made in the development of a fertility-capability soil classification system which groups soil having similar fertility management limitations. The first formal version of this system was prepared for presentation at the Tropical Soils Seminar held in Colombia in February, 1974 (Buol et al. 1975). Initial assessment of the system in a world-wide, country-wide, and a county sample showed that large numbers of soil mapping units can be grouped in a small number of fertility-capability units. For example, most of the 678 soil profiles described in the soil survey reports of Brazil could be grouped into 23 fertility-capability units. All the 145 mapping units of the soil survey of Wake County, North Carolina, were grouped into 15 units.

Preliminary evaluation of this system was made using a series of potato fertilization experiments previously conducted in the Sierra of Peru. All 73 sites could be grouped into five fertility-capability units and each group produced a different response to phosphorus applications. When fertilizer recommendations were made for each group instead of using a general recommendation, the economic returns to fertilization increased dramatically. It was also found that this classification system supplements soil tests. Further evidence of its usefulness in other areas and possible modifications are being investigated.

The economists refined their concept of profit-prediction criterion and applied it to various models used in the analysis of corn and rice fertilizer responses in Costa Rica and corn in Minas Gerais, Brazil. The graphic linear response and plateau model proposed by Waugh, Cate and Nelson (1973) gave the best recommendations without the use of a computer or complex calculations.

Additional research projects were conducted throughout the region to supplement the data from priority area and/or to investigate at depth some critical issues. Soil characterization studies in relation to landscape position were initiated in an Oxisol-Ultisol area in western São Paulo, Brazil, in an Andept area in central Costa Rica, in the Llanos Orientales of Colombia and in the Maracaibo Basin of Venezuela.

Laboratory and greenhouse studies have shown that the lime-phosphorus interactions in certain Oxisols of Panama reflect the field observations in Brasilia (Mendez, 1973) Low soil phosphorus availability is believed to be the principal factor responsible for the low rates of organic matter mineralization in Andepts from Colombia (Munevar, 1974). Diffusion was identified as a major factor accounting for the increased availability of phophorus in flooded rice soils in India and Peru (Turner, 1974). The potassium release properties of certain Ultisols from Guyana confirm the existence of a strong release of non-exchangeable sources of potassium. More complicated soil testing methods than the dilute double acid extractant were not necessary for estimating available potassium in these soils and in their North Carolina counterparts.

Special emphasis has been made in disseminating these results as quickly as feasible to about 450 tropical soil scientists, institutions, and libraries throughout the world. The first edition of the "Review of Soils Research in Tropical Latin America" was quickly exhausted. A second English printing and a Spanish version were made in order to satisfy the demand.

PRESENT STATUS AND OUTLOOK

Most of the ongoing research activities described require several years for satisfactory completion. No sound recommendations on how to manage tropical soils can be based on three years of field work. Our plan for the next few years is essentially to continue research until the stated objectives are satisfied.

The basic issues on how to develop continuous cropping in jungle areas under shifting cultivation, how to economically apply phosphorus, lime and micronutrients to savanna Oxisols, and how to apply fertilizers in intercropped systems require the evaluation of long-term residual effects in current experiments and the initiation of additional ones. A short description on the outlook for the three areas of concentration follows.

Although research on shifting cultivation has been conducted for many years in Africa, particularly by Belgian, French, and British scientists in colonial days, no specific recommendations on how to transform these systems into continuous cropping when population pressures increase have been developed. When this question was asked of African scientists at a meeting on Tropical Soils Research in Ibadan, Nigeria in 1972, none present could say that they had a set of packages which they could recommend to solve this problem. Since 1971, IITA's Farming Systems Program has been attacking this problem in a systematic fashion in seasonal forested areas with high base status Alfisols. To our knowledge, the only other ongoing systematic soils research program on shifting cultivation is this Yurimaguas project. It is also the only one working on acid soils and the only one in the Amazon basin.

As additional data is gathered, a farm management model for continuous cropping of these jungle soils is slowly developing. The basic concept consists of small (2 has.) annual clearings with the traditional slash and burn practice followed by planting a grain crop with considerable market value without fertilization. Afterwards, about a fifth of the area will be intensively fertilized and planted to food crops in intercropped systems The rest will be planted to grass-legume pasture with minimal fertilization (probably only phosphorus, potassium, sulfur, and micronutrients). Every year, the farmer will repeat the process, in somewhat larger clearings until a 20 to 50 hectare area is conquered and a herd of cattle is gradually built on the permanent pastures. Additional research will bring fruit trees and other permanent crops into the system. In countries such as Peru where cooperatives are likely to be the main farming structure, these figures can be multiplied by the number of farm families which form a cooperative.

The economic solution of soil fertility constraints in the Oxisols areas are more difficult than in the Amazon Jungle. Only long-term experiments which adequately quantify the residual effects of fertilization and liming are likely to provide adequate answers. However, the social and economic constraints are less limiting. The topography and infrastructure already available in the Campo Cerrado of Brazil, plus substantial government incentives for land purchases, fertilizers, liming and equipment, suggest a rather rapid development and increases in food production following the solution of the above mentioned constraints.

The full application of the concept of selecting varieties and species more tolerant to high aluminum saturation levels and low available soil phosphorus is an essential component of the package to be developed. Also, the possibility of selecting grass species and varieties which can fix nitrogen symbiotically is another major consideration.

Very little is presently known on how to manage soils and fertilizer applications in intercropped systems. This is undoubtedly one of our greatest gaps in tropical soil science Attention to this subject was sparked by Bradfield's (1970) work on multiple cropping in IRRI. His results, however, are limited to systems which involve growing flooded rice during the rainy season. Our projected research in Central America will be aimed exclusively to this subject.

Considerable progress has been made in the art of developing a sound methodology for interpreting and extrapolating soil fertility and management research results to other areas. The methods developed by the International Soil Fertility Evaluation and Improvement Program (Cate-Nelson graphs, Linear

Plateau and Response Model) have considerably simplified the process of making fertilizer recommendations based on field data. Such techniques do not require complicated economic and statistical analysis and recommendations can be arrived at without the use of a computer. An economic evaluation of these techniques in comparison with the classic quadratic equations, conducted as part of this research contract, showed no differences in profitability between the two methodologies (NCSU, 1973 Annual Report).

Prior to the initiation of this contract, no systematic procedures were available to extrapolate field fertility data from one region to the other. Natural soil classification systems, including the new U.S. Soil Taxonomy, do not provide for such groupings because they focus on subsoil parameters and essentially ignore the plowed layer where most of the fertility interactions take place. The Fertility Capability Classification System was designed to group soils with common fertility-management problems. It pays the desired attention to topsoil properties without ignoring important subsoil parameters. Its initial evaluation shows substantial promise but also the need for fine tuning of the original scheme.

On-site extrapolation studies are included in the proposal for the extension of this contract. A series of applied research type trials will be conducted in cooperation with several national and international institutions in other jungle and savanna areas after proper soil characterization. Requests for such cooperation have been received from several countries. Their proposed implementation will form the third phase of this project.

NEEDS FOR THE FUTURE

The successful completion of the objectives of this program require resources and time beyond the scope of AID's present commitments. In all cases, substantial inputs are being made by the cooperating national institutions in Peru, Brazil, and Central America. Exchange of germplasm and ideas with the international institutes, particularly CIAT, IITA, CATIE, and IRRI have been fruitful. As soil scientists, however, we are limited in scope to the solution of these major questions we are raising. An integrated, interdisciplinary attack is needed to fully capitalize the advantages of new soil management practices.

Advances in this direction are in progress in the Cerrado of Brazil where EMBRAPA, the national research organization is in the process of developing an interdisciplinary Cerrado Research Center. Through another AID contract, a similar attack on the intercropping problem is now in the process of being organized by CATIE in Turrialba for the Central American region.

What is critically needed is an interdisciplinary attack by the international research community on the Amazon Jungle problems in areas presently under shifting cultivation. The creation of an multidisciplinary research center with inputs from animal scientists, plant breeders, pest management specialists and economists is one of the main gaps in an area which is in the threshold of opening up at a fast rate because of population pressures, and new roads and oil discoveries. We urge this group to seek the necessary mechanism to fill this gap.

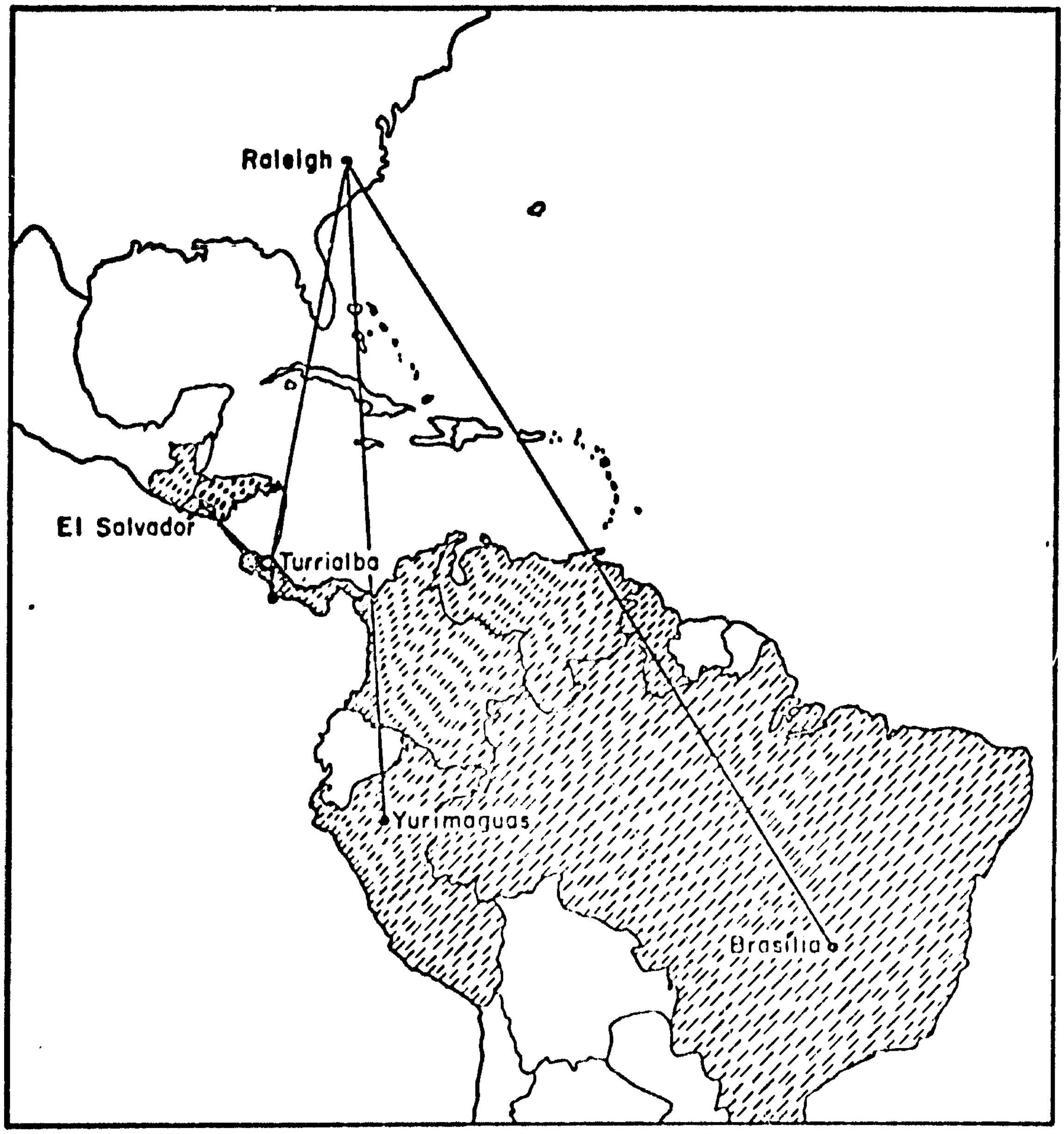

Figure 1. Map of tropical Latin America showing principal field research sites. Region-wide studies have been conducted in or with soils of the countries shaded.

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