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Vol. 1

LAND IN TROPICAL AMERICA
LA TIERRA EN AMERICA TROPICAL

A Guide to Climate, Landscapes, and Soils for Agronomists in Amazonia, the Andean Piedmont, Central Brazil and Orinoco

Guía de Climas, Paisajes y Suelos para Agrónomos en la Amazonía, el Piedemonte Andino, Brasil Central y Orinoco

Guía de Climas, Paisagens e Solos para Agrónomos na Amazônia, o Pedemonte Andino, Brasil Central e Orenoco

T. T. Cochrane, L. G. Sánchez,
L. G. de Azevedo, J. A. Porras, and C. L. Garver

CIAT
Centro Internacional de Agricultura Tropical

EMBRAPA-CPAC
Empresa Brasileira de Pesquisa Agropecuária
Centro de Pesquisa Agropecuária dos Cerrados

Centro Internacional de Agricultura Tropical, CIAT
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Prologue

Latin America, particularly South America, is known as the region of the world with the most abundant land resources in relation to its population base. At present the region has the lowest population density per hectare of arable land, as well as the lowest percentage of arable land under cultivation. Comparisons of potentially arable land in Latin America with that under tillage show that only 18 to 35 percent is presently utilized for agriculture. These figures are considerably lower than estimates for other regions of the world; however, there is a fairly wide range in figures as a result of variations in the information base utilized and the criteria used for the different studies.

Within the present land use pattern, extensive areas of land are underutilized or left fallow as most of the agricultural production takes place in the more fertile areas close to urban markets, where large mechanized farms coexist with a sizable small farm sector. In order to design an agricultural growth strategy that would utilize land, labor and capital resources efficiently, the countries in the region need to assess the following complementary development strategies and their trade-offs:

1. Intensify production by large farmers who control the more fertile areas, primarily through mechanization and greater use of inputs.
2. Intensify small-scale production through the use of improved germplasm, combined with appropriate use of inputs, to achieve higher, more stable yields.
3. Expand crop and livestock production onto the less fertile frontier lands through the use of adapted germplasm and appropriate use of inputs.

As a first step toward providing the necessary information to design such a strategy, CIAT and EMBRAPA have collaborated in the systematization of existing information on the central lowlands of tropical South America, which constitute the major frontier area of the continent. Although there is abundant information on the area, much of it is contained in unpublished technical reports from diverse sources and is not necessarily compatible. An attempt has been made to systematize all this information in this report, complementing it where necessary with primary data, within the framework of a "land systems approach," where information on climate, soils, topography and vegetation is reported systematically for purposes of comparison. The data base has been computerized to facilitate information retrieval and analyses of aggregates. The data are presented here in the form of maps and tables, with text in English, Spanish and Portuguese, to permit broad access by individuals from research or rural development programs who might not have computer facilities available to them.

CIAT and EMBRAPA are pleased to make available to the scientific community and rural development planners the results of more than three years' collaborative efforts in the hope that the information contained herein, although far from perfect, will facilitate agricultural research, as well as the design of agricultural growth strategies that take into consideration the agricultural potential of these regions, thereby contributing to improved production and productivity.

As the report is based on data available at the time of the study, we would welcome new information to update the computerized files.

August 1984

Gustavo A. Nores
Deputy Director General
CIAT

Elmar Wagner
Head
CPAC-EMBRAPA

Prólogo

América Latina, en particular América del Sur, se conoce como la región del mundo con mayor abundancia de recursos de tierras en relación con su población. En la actualidad América del Sur posee la más baja densidad de población por hectárea de tierra cultivable, así como el porcentaje más bajo de tierra cultivable bajo explotación. Comparaciones entre estimativos de la superficie arable en América Latina con la superficie actualmente bajo cultivo muestran que solamente un 18 a 35 por ciento se utiliza actualmente en agricultura. Estas cifras se consideran inferiores a los estimativos para otras regiones del mundo; sin embargo, hay un amplio rango en los estimativos como resultado de las variaciones en la base de información utilizada y en los criterios empleados en los diferentes estudios.

Dentro del patrón actual de uso de tierra, hay grandes extensiones de tierras subutilizadas o inexplotadas ya que la mayor parte de la producción agrícola tiene lugar en las zonas más fértiles próximas a los mercados urbanos, donde generalmente coexiste un sector de fincas grandes y mecanizadas con un amplio sector de fincas pequeñas. Con el fin de diseñar estrategias de desarrollo agrícola que utilicen de manera eficiente los recursos de tierra, de mano de obra y de capital, los países de la región deben considerar estrategias alternativas de desarrollo, sus ventajas relativas, y su complementariedad potencial; entre ellas:

1. *Intensificación de la producción en el sector de fincas grandes que generalmente controla las zonas más fértiles, principalmente por medio de la mecanización y mayor empleo de insumos.*
2. *Intensificación de la producción en el sector de fincas pequeñas mediante el uso de germoplasma mejorado, junto con empleo adecuado de insumos, para lograr rendimientos mayores y más estables.*
3. *Expansión de la producción agrícola y ganadera en las tierras menos fértiles de frontera mediante el uso de germoplasma adaptado y uso adecuado de insumos.*

Como un primer paso en la obtención de la información necesaria para diseñar estrategias de desarrollo que incluyan estas regiones de frontera, CIAT y EMBRAPA colaboraron en la sistematización de la información existente acerca de las tierras bajas centrales en América del Sur tropical, las cuales constituyen el mayor territorio de frontera en el continente. Aunque hay abundante información sobre el área, en su mayor parte ésta se encuentra en informes técnicos de diversas fuentes no publicados y que contienen información no necesariamente compatible. En el presente trabajo se hizo un esfuerzo por sistematizar tal información, complementándola donde fuera necesario con datos primarios. Se utilizó un enfoque de "sistema de tierra" en el cual la información sobre clima, suelos, topografía y vegetación se presenta en forma sistematizada a fin de hacer posibles las comparaciones.

La base de datos ha sido computarizada para facilitar la recuperación de la información y el análisis de agregados con objetivos específicos. En esta publicación los datos se presentan en forma de mapas y cuadros, con textos en inglés, español y portugués para hacerla ampliamente accesible a usuarios en programas de investigación y desarrollo rural que no tengan acceso a computador.

CIAT y EMBRAPA se complacen en poner a disposición de la comunidad científica y de los planificadores del desarrollo rural los resultados de tres años de esfuerzos conjuntos. Se espera que la información resultante, aunque diste de ser perfecta, facilite la investigación agrícola y el diseño de estrategias de desarrollo agrícola que tomen en consideración el potencial agrícola de esas regiones, contribuyendo así a una mayor producción y productividad.

Como el trabajo está basado en datos disponibles en el momento en que se realizó el estudio, ambas instituciones acogerán con beneplácito nueva información que permita actualizar sus archivos computarizados.

Agosto de 1984

Gustavo A. Nores
Director General Adjunto
CIAT

Elmar Wagner
Jefe
CPAC-EMBRAPA

Prólogo

A América Latina, em particular a América do Sul, é conhecida como a região do mundo com maior abundância de terras em relação à sua população. No momento, a América do Sul possui a mais baixa densidade populacional por hectare de terra cultivável, bem como a mais baixa porcentagem de terras cultiváveis sob utilização. Comparações entre o potencial de terras aráveis na América Latina com a área atualmente sob cultivo, mostram que somente 10 a 35% são utilizados para a agricultura. Estes dados são consideravelmente mais baixos do que estimativas feitas para outras regioẽs do mundo. Contudo, há uma variação bastante ampla nos números, resultantes das diferenças de informações básicas utilizadas e dos critérios usados pelos diferentes estudos.

Dentro do padraõ atual de utilização da terra, existem grandes extensões sub-utilizadas ou inexploradas, de vez que a maior parte da produção agrícola ocorre nas áreas mais férteis, próximas a mercados urbanos, onde grandes propriedades mecanizadas coexistem com um setor razoável de pequenos produtores. Com a finalidade de estabelecer estratégias de desenvolvimento agrícola que utilizem de maneira eficiente os recursos terra, trabalho e capital, os países da regiaõ devem considerar estratégias complementares de desenvolvimento e seu potencial, em termos de vantagens relativas, a saber:

1. Intensificação da produção pelos grandes produtores que detêm as áreas mais férteis, principalmente através da mecanização e do maior uso de insumos:
2. intensificação da produção em pequena escala, através do uso de germoplasma melhorado, combinado com o uso apropriado de insumos, para a obtenção de rendimentos maiores e mais estáveis.
3. Expansão da produção agrícola e pecuária para terras menos férteis de fronteira, através do uso de germoplasma adaptado e do uso adequado de insumos.

Como um primeiro passo para a obtenção da informação necessária ao estabelecimento de estratégias de desenvolvimento que incluam esta última regiaõ, o CIAT e a EMBRAPA atuaram em colaboração na sistematização de informação disponível sobre terras baixas centrais da América do Sul Tropical, as quais se constituem na maior fronteira do continente. Muito embora exista abundante informação sobre a área, a maior parte está contida em relatórios técnicos não publicados, de diversas fontes e não necessariamente compatíveis. No presente trabalho, foi feito um esforço de sistematizar estas informações, complementando-as, quando necessário, com dados primários. Foi utilizado o enfoque de "sistemas de terra", no qual as informações sobre clima, solos, topografia e vegetação são apresentadas de forma sistematizada para efeitos de comparação.

A base de dados foi computarizada para facilitar a recuperação de informações e a análise de agregados. Os dados são apresentados nas formas de mapas e tabelas, com textos em inglês, espanhol e português, para permitir amplo acesso a usuários em programas de pesquisa e de desenvolvimento rural, que podem não dispor de facilidades de computação.

O CIAT e a EMBRAPA têm o prazer de colocar à disposição da comunidade científica e de planejadores do desenvolvimento rural, os resultados de mais de três anos de esforços conjuntos e esperam que a informação contida neste trabalho, ainda que longe de ser perfeita, venha a facilitar a pesquisa agrícola bem como ao delineamento de estrategias para o desenvolvimento, que levem em consideração o potencial destas regioẽs, contribuindo, desta forma, para o aumento da producão e da produtividade.

Considerando que a trabalho se fundamentou em dados disponíveis à época do estudo, ambas as instituições acolherão, com entusiasmo, novas informações que permitam atualizar seus arquivos computarizados.

Agosto de 1984

Gustavo A. Nores
Diretor Geral Adjunto
CIAT

Elmar Wagner
Chefe
CPAC-EMBRAPA

Contents

Preface

This book is the first of three volumes describing and mapping land in the central lowlands of tropical South America according to its various aspects: climate, vegetation and landscape, topography, and soil factors.

Volume 1 presents a description of the project's objectives, methodology, and procedures, and then provides interpretations and guidelines for local, seed-based agrotechnology transfer using the map and land-systems data.

Volume 2 includes the *Land Systems Map* (in two parts), on a scale of 1:5,000,000, and the *Legend to the Map*, which provides a concise summary of the soil constraints by land system. A booklet of individual zone maps, on a scale of 1:2,000,000, is also included.

Volume 3, a more complete summary of the land systems, includes computer printouts of generalized land information, specific land facet and landform descriptions, and meteorological station data; in addition, soil profile descriptions of many land systems are provided.

The following land systems are not included in the *Map*, *Legend*, or *Computer Summary*: 90-91, 115, 118-200, 231-249, 312, 314, 386-387, 487-600, 655-800. Land systems were designated by numbers used to identify them during the course of the study, and do not necessarily follow a numerical or geographical continuity.

Computer summaries are missing for the following land systems that are coded and listed in the *Map* and *Legend*: Ab 383, Ab 384, Aa 421, Fb 422, Be 486, and Fo 855. Information on these land systems was not sufficiently complete to computerize them.

The study upon which the work is based was completed over a period of four years (1977–1981) with the cooperation of many people and organizations.

The data for the study were collected from records in various countries, including Bolivia, Brazil, Colombia, Ecuador, Peru, and Venezuela, and from various small- and large-scale studies. The wide range of documents and people who assisted in this project are included in the Bibliography to Volume 1.

Special thanks, however, must be given to the staffs at EMBRAPA-CPAC and CIAT for their dedication to the tasks of compiling, computerizing, and mapping the data. Yuviza Barona typed the manuscript; Ligia García, Conrado Gallego and Camilo Oliveros drafted and drew many of the small maps and completed the large Land Systems Map; Alvaro Cuéllar developed and printed the photographs. Esperanza Castañeda and Alexandra Walter did the editing and translations. For all of them, and the many others too numerous to mention who assisted in this project, we are extremely grateful.

Prefacio

Este es el primero de tres volúmenes que contienen la descripción y los mapas de las tierras bajas centrales de América del Sur tropical según sus diversos aspectos: clima, vegetación y paisaje, topografía y factores edáficos.

El Volumen 1 presenta una descripción de los objetivos del proyecto, su metodología y procedimientos, y proporciona orientaciones y pautas para la trasferencia de tecnología agrícola local, basada en el uso de semilla mejorada, utilizando el mapa y la información sobre sistemas de tierra.

El Volumen 2 incluye el Mapa de Sistemas de Tierra *(en dos secciones), a una escala de 1:5,000,000 y la* Leyenda para el Mapa, *que ofrece un resumen conciso de los limitantes del suelo en cada sistema de tierra. También se incluye un folleto de mapas de zonas individuales, a una escala de 1:2,000,000.*

El Volumen 3 es un resumen más completo de los sistemas de tierra e incluye impresos de computador con información generalizada sobre la tierra, descripciones específicas de las facetas de tierra y de la forma de la tierra y datos de la estación meteorológica; asimismo ofrece descripciones de perfiles de suelos de varios sistemas de tierra.

Los sistemas de tierra que aparecen a continuación no están incluídos en el Mapa, *en la* Leyenda *ni en el* Resumen de Computador: *90-91, 115, 118-200, 231-249, 312, 314, 386-387, 487-600, 655-800. Los sistemas de tierra fueron designados por números utilizados para su identificación durante el transcurso del estudio y por ello no se observa necesariamente una continuidad numérica o geográfica.*

No existen resúmenes de computador para los siguientes sistemas de tierra codificados e incluidos en el Mapa *y en la* Leyenda: *Ab 383, Ab 384, Aa 421, Fb 422, Be 486, y Fo 855. La información para estos sistemas de tierra no fue lo suficientemente completa para computarizarla.*

El estudio en el cual se basó el trabajo se completó con la colaboración de muchas personas y organizaciones, durante un período de cuatro años (1977–1981)

Los datos para el estudio fueron recolectados de los archivos de varios países, incluyendo Bolivia, Brasil, Colombia, Ecuador, Perú y Venezuela, y de varios estudios a pequeña y gran escala. En la Bibliografía del Volumen 1 se citan las personas y documentos que fueron de ayuda para este proyecto.

Agradecemos especialmente al personal de EMBRAPA-CPAC y del CIAT por su dedicación a la tarea de compilar, sistematizar y cartografiar la información; a Yuviza Barona quien mecanografió el manuscrito; a Ligia García, Conrado Gallego y Camilo Oliveros, quienes delinearon y dibujaron varios de los mapas individuales y completaron el Mapa de Sistemas de Tierra; a Alvaro Cuéllar quien se encargó de las fotografías, a Esperanza Castañeda y Alexandra Walter quienes hicieron la edición y traducción. A todos ellos y a las demás personas muy numerosas para mencionar aquí, que colaboraron en este proyecto, expresamos nuestros sinceros agradecimientos.

Prefácio

Este é o primeiro de três volumes que contém a descrição e os mapas das terras baixas centrais da América do Sul tropical segundo seus diversos aspectos: clima, vegetação e paisagem, topografia e fatores edáficos.

O Volume 1 apresenta uma descrição dos objetivos, metodologia e procedimentos, e depois oferece indicações e modelos para a transferência da tecnologia agrícola local baseada no uso de sementes melhoradas empregando o mapa e os dados em sistemas de terra.

O Volume 2 inclui o Mapa de Sistemas de Terra (em duas seções), a uma escala de 1:5,000,000, e a *Legenda* para o *Mapa*, que fornece um resumo conciso das limitações do solo em cada sistema de terra. Também foi incluido um folheto de mapas de zonas individuais, a uma escala de 1:2,000,000.

O Volume 3, é um resumo mais completo dos sistemas de terra, e inclui impressos de computador contendo informação generalizada sobre a terra, descrições específicas das facetas de terra, da forma da terra, dados da estação meteorológica, alem disto, oferece descrições dos perfis de solos de vários sistemas de terra.

Os sistemas de terra apresentados em seguida não se incluem no *Mapa*, na *Legenda*, e também no *Resumo de Computador*: 90-91, 115, 118-200, 231-249, 312, 314, 386-387, 487-600, 655-800. Os sistemas de terra foram designados por números utilizados para a sua identificação, durante o decurso do estudo, é esta a razão de não se observar, necessariamente, uma continuidade numérica ou geográfica.

Não há resumos de computador para os seguintes sistemas de terra codificados e registrados no *Mapa* e na *Legenda*: Ab 383, Ab 384, Aa 421, Fb 422, Bc 486, e Fo 855. A informação para estes sistemas de terra não foi suficientemente completa para a computação.

O estudo em que foi baseado o trabalho, concluiu-se com a colaboração de muitas pessoas e organizações, no espaço de quatro anos (1977–1981).

Os dados para o estudo foram coletados dos arquivos de vários paises, incluindo Bolivia, Brasil, Colômbia, Equador, Peru e Venezuela, e de vários estudos em pequena e grande escala. Os documentos e pessoas que colaboraram com o projeto estão mencionados na Bibliografia do Volume 1.

Agradecemos especialmente ao pessoal da EMBRAPA-CPAC e do CIAT por sua dedicação à tarefa de compilar, computarizar e cartografar a informação; a Yuviza Barona, que datilografou o manuscrito; a Ligia García, Conrado Gallego e Camilo Oliveros pela delineação e desenho dos mapas individuais e a finalização do Mapa de Sistemas de Terra; a Alvaro Cuéllar que se encarregou das fotografías, a Esperanza Castañeda e Alexandra Walter pela edição e tradução. A todos eles e a outras pessoas, numerosas demais para serem mencionadas aquí e que colaboraram neste projeto, manifestamos nossos sinceros agradecimentos.

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- **Dr. Almiro Blumenschein**
  Head, EMBRAPA-CNPAF (Centro Nacional de Pesquisa de Arroz e Feijão), Goiania, Brazil;
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- **Ing. Antonio Sainz**
  Head of Soils Department, Ministry of Agriculture, La Paz, Bolivia;
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  Professor of Soil Science, North Carolina State University, Raleigh, U.S.A.;
  Profesor de Edafología, Universidad del Estado de Carolina del Norte, Raleigh, E.U.;
  Professor de Edafologia, Universidade do Estado de Carolina do Norte, Raleigh, E.U.;

- **Dr. Leslie D. Swindale**
  Director-General, ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Hyderabad, India;
  Director General ICRISAT (Instituto Internacional para la Investigación en Cultivos para los Trópicos Semi-áridos), Hyderabad, India;
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- **Dr. Goro Uehara**
  Professor of Soil Science, University of Hawaii, Honolulu; U.S.A.;
  Profesor de Edafología, Universidad de Hawai, Honolulú; E.U.;
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- **Dr. Nasser Ahmad**
  Professor of Soils, University of the West Indies, St. Augustine, Trinidad & Tobago;
  Profesor de Edafología, Universidad de las Indias Occidentales, St. Augustine, Trinidad & Tobago;
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  Head, EMBRAPA-CPAC (Centro de Pesquisa Agropecuária dos Cerrados), Planaltina, D.F. Brazil;
  Jefe, EMBRAPA-CPAC (Centro de Pesquisa Agropecuária dos Cerrados), Planaltina, D.F. Brasil;
  Chefe, EMBRAPA-CPAC (Centro de Pesquisa Agropecuária dos Cerrados), Planaltina, D.F. Brasil;

- **Ing. José da Silva Madeira Neto**
  Coordinator, Resource Evaluation Program, EMBRAPA-CPAC;
  Coordinador, Programa de Evaluación de Recursos, EMBRAPA-CPAC;
  Coordenador, Programa de Avaliação dos Recursos, EMBRAPA-CPAC;

- **Dr. Luiz H. Rodrigues**
  Coordinator, Computer Laboratory, EMBRAPA-CPAC;
  Coordinador, Laboratorio de Computación, EMBRAPA-CPAC;
  Coordenador, Laboratório de Computação EMBRAPA-CPAC;

- **Ing. Nivaldo Faria de Castro**
  Research, Computer Laboratory, EMBRAPA-CPAC;
  Investigador, Laboratorio de Computación, EMBRAPA-CPAC;
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Introduction. THE LAND-SYSTEMS STUDY

In recent years there has been a slowdown in the pace of the Green Revolution. Metz and Brady (1980) stated:

> The Green Revolution has failed to fulfill expectations in most areas of the world. Yields and production levels are only a fraction of those predicted when the new high-yielding varieties were first released in the 1960's. There is a growing recognition that environmental factors are largely responsible for this failure of new crop varieties to live up to expectations.

In other words, many high-yielding cultivars of crops that performed well in one tropical climate-soil environment have often given disappointing results in another.

Part of the reason for this is that, in the not too distant past, plant breeders were looking for "super cultivars" of crops that would solve food production problems in the tropics, as if the word "tropics" was a sufficient definition of environment. Unfortunately this is not so. Consequently, there is now an increasing awareness of the need to develop new crop cultivars compatible with the many climate-soil environments of the tropics, and an urgent need to define these environments more precisely.

Objectives

CIAT began land-resource survey work in mid-1977 to meet the growing concern with deviation from the expected performances of so-called "improved" varieties of tropical crops when they were grown in locations different from where they were developed. From the outset, this work was designed to help with the development of food-production technologies based on superior seeds and vegetative propagating material. Its objective was to provide a geographical and agroecological base to guide selection and breeding priorities for a given crop and to assist in choosing representative field sites for testing potentially higher yielding or disease-resistant crop cultivars. A further objective was to identify analogous areas where germplasm-based agrotechnology specific to, or advantageous in, a location with given climate, landscape, and soil conditions might successfully be transferred.

The work started in a modest way as a survey of the "acid-infertile" savanna regions of tropical America (CIAT, 1978b, 1979; Cochrane, 1979b) to gain a better understanding of their climate and soils and to select representative localities for testing promising grass and legume accessions. In 1979 the survey was broadened to include the forested regions and to serve as a base for a better understanding of environments for CIAT's other commodity crops, including cassava, beans, and rice, and for tropical crops generally (CIAT, 1980; Cochrane, 1980b). By 1981 the study covered a large part of tropical South America and was extended to the Gulf Coast of Mexico, a total area of over 1000 million ha. The survey was collaborative work, carried out in conjunction with the Ministries of Agriculture of Colombia, Bolivia, Ecuador, Perú, and especially the Centro de Pesquisa Agropecuária dos Cerrados (CPAC), Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), Brazil.

Geographic Scope

The geographic extent of the present study was limited to one of the least known areas of the tropical world— the lowlands of South America east of the Andes, as outlined in Figure 1. This region covers 820 million ha and extends from the Panamanian isthmus to southern Brazil. It includes the Amazon and Orinoco basins and the Precambrian shield region of central Brazil. Approximately 200 million ha are covered by savannas, and the remainder by forests.

A Land Systems Map of this area, reduced from the original 1:1,000,000 scale, is printed and enclosed in Volume 2

Area in Land Systems Study

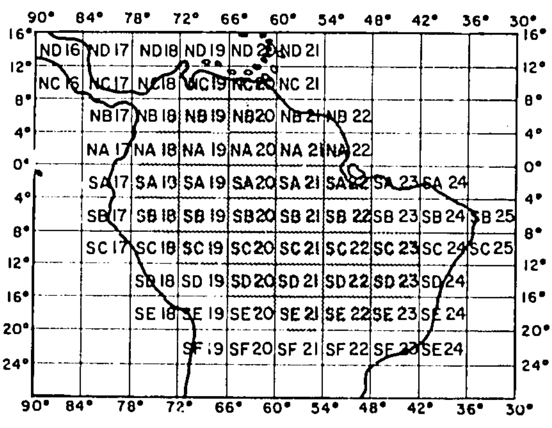


Fig. 1 Geographical extent of CIAT's land resource survey, later detailed on the Land Systems Map (Vol. 2). The letter-number codes refer to sheets of the International Chart of the World at the Millionth Scale.

of this study, *The Land Systems Map and Its Legend.* The map is described and explained in Chapter 2.

Methodology

The methodology for the study was modeled on the land-systems approach developed by Christian and Stewart (1953) in assessing land resources of the Katherine-Darwin region of northern Australia. It reduces land-resource information to a common base by defining a land system as "an area or group of areas throughout which there is a recurring pattern of climate, landscape and soils." This definition, while conceptually similar to the Australian approach, differs in that it introduces climate as a direct parameter for land-system definition. Thus, inherent in the delineation of land systems is the treatment of environmental parameters in the following categorical order to form a true land classification:

1. Climate
   a. Radiant energy received
   b. Temperature
   c. Potential evapotranspiration
   d. Water balance
   e. Other climatic factors
2. Landscape
   f. Land-form
   g. Hydrology
   h. Vegetation
3. Soil
   i. Soil physical characteristics
   j. Soil chemical characteristics

Land systems are delineated directly onto satellite and side-looking radar imagery after climatic analyses have been performed.

Although the work has mainly been an exercise in collating existing information available in the literature, a strategic amount of field work was carried out to help fill in knowledge gaps. A small airplane was flown by the senior author to reach hinterland areas. Following the collection, revision, and mapping of climate, landscape, and soil information, the data were coded and recorded on magnetic tape as a computerized data base to both facilitate speedy analysis and retrieval of information and map making. The mechanisms of computerization are undergoing constant improvements as new innovations become available.

Climate

The climatic work was initially subcontracted to Utah State University (Hancock et al., 1979). Long-term meteorological data for over 1000 stations throughout tropical America were assembled and recorded on computer tape. However, there are some large areas, particularly in the Amazon, without stations and where distances are too great to permit highly reliable extrapolations. Fortunately, it was possible to establish a relationship between physiognomic vegetation classes and climatic parameters, which enabled this problem to be overcome (Cochrane and Jones, 1981). Recently, the preliminary climatic data base was considerably expanded by CIAT's meteorologist so that it now contains summaries from over 4000 stations.

Hargreaves' (1972, 1977a) equation based on solar radiation and temperature was used to calculate potential evapotranspiration (POT ET) to assess the water balance and provide an approximation of the amount of energy available for plant growth. In addition, his monthly water balance methodology was adopted to determine the water balance and growing seasons. To define a wet month, Hargreaves' Moisture Availability Index (MAI) concept was used; in this concept, POT ET is equated with the 75% probability level of precipitation occurrence (DEP PREC) to determine the amount of rainfall that will be equalled in 3 out of 4 years. Therefore, MAI = DEP PREC ÷ POT ET. A wet month has an MAI greater than 0.33.

Soil Moisture

Hargreaves (1975) quotes several sources illustrating good correlations between moisture availability index and crop production, when soil moisture is adequate for a week or more, and recommends the level "less than 0.34" to define a dry month. In this context, it should be emphasized that the use of a standard climatic parameter for defining a dry month (or conversely a wet month) must always be interpreted in light of the ability of a soil to retain and supply moisture. The level needs to be adjusted according to the moisture-holding capacity of that soil. On the other hand, the use of the MAI provides a measure of the climatic potential to supply and extract soil moisture at a given locality during a given period of time; in the case of these studies, at monthly intervals. Using the MAI for climatic estimation (detailed in Chapter 3) is innovative in that it takes an agriculturally acceptable rainfall probability estimation into account.

Landscape

After climatic analysis, the landscape was subdivided into land systems, which were delineated on 1:1,000,000 satellite imagery and, for some areas, on side-looking radar imagery. Although satellite imagery is superior to radar imagery for delineating land systems, it was not possible to obtain cloud-free imagery for many high-rainfall areas; in those circumstances, side-looking radar imagery provided a sufficiently accurate topographical base.

Land systems were mapped to illustrate analogous areas of land, insofar as practical farming is concerned. These land systems are physiographic units, based on repetitive patterns of topography, vegetation, and soils, within a given climatic circumstance.

Native vegetation classes were identified following the physiognomic criteria of Eyre (1968) for tropical forests and Eiten (1972) for tropical savannas.

The mapping of land systems provided a common base for bringing existing land resource information together. After delineation, maps were collated and drawn at the scale of 1:1,000,000 and numbered according to the International Chart of the World at the Millionth Scale index (Kerstenetzky, 1972), see Figure 1. They were then computerized in 5- × 4-minute units (approximately 6800 ha at the equator) to serve as the basis for thematic map production. The field work was carried out to provide on-the-ground control, to help standardize descriptive criteria, and to study the variation of landscape features within the land systems. These variations, although not mapped because of scale limitations, were described as "land facets," and the proportion of each land facet within the land systems was estimated from a study of the imagery. In this way, selected landscape features and soil descriptions and properties were computed on the basis of the land-facet subdivision.

Figure 2, which shows a part of land system No. 46, illustrates how land systems were subdivided into land facets. It should be noted that, because the smallest mapping unit was the land system, thematic mapping (or one feature map) for a given characteristic in this volume, unless otherwise stated, represents the rating of the major land facet.

Soil Classification

The subdivision of land systems into land facets was particularly useful to bridge the gap between land systems and soil units. Clearly, land facets will contain soils with a variation in properties; but some level of generalization must be made in making an inventory of land resources. In fact, all but the most detailed of soil maps picture soil units that always contain a proportion of soils different from those of the majority of soils depicted by that unit.

The most extensive soils in each land facet were first classified as far as the Great Group category of the Soil Taxonomy system (Soil Survey Staff, 1975); the soils were then described in terms of their main physical and chemical properties. This was because Soil Taxonomy does not provide for the grouping of soils "having similar physical and chemical properties that reflect their response to management and manipulation for use" until the soil Family category is reached. The amount of soil survey work needed to classify soils to the Family level throughout the region according to that system was far too great.

In addition to classifying soils according to Soil Taxonomy, the soils were classified according to the FAO-Unesco legend (FAO-Unesco, 1974).

Physical and Chemical Soil Properties

Apart from describing the soil properties inherent in soil classification (Eswaran, 1977), many physical and chemical properties of the topsoils (defined as the 0- to 20-cm depth) and subsoils (21- to 50-cm depth) of the individual land facets were recorded, tabulated, and coded, when the information was available.

Soil physical properties coded include slope, texture, presence of coarse material, depth, initial infiltration rate, hydraulic conductivity, drainage, moisture-holding capacity, temperature regime, moisture regime, and presence of expanding clays.

Soil chemical properties coded include pH; percentage of Al saturation; exchangeable Al, Ca, Mg, K, Na; total exchangeable bases (TEB); effective cation-exchange capacity (ECEC); organic matter (OM); available soil P [available P data using the Olsen (Olsen et al., 1954), Truog (Jackson, 1958), and Brazilian (Vettori, 1969) methods, approximated to assume values derived by the Bray II method (Bray and Kurtz, 1945)]; P fixation; available soil Mn, S, Zn, Fe, Cu, B, and Mo; free carbonates; salinity; percentage of Na saturation; presence of cat clays; X-ray amorphism; and elements of importance to animal nutrition. The soil chemical properties

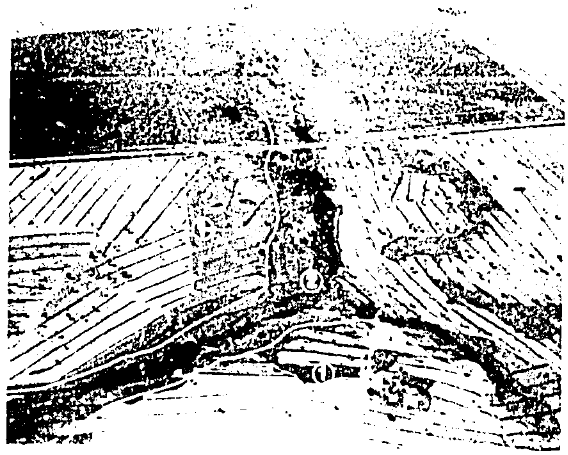


Fig. 2 Land system No. 46, subdivided into land facets 1 and 2.

were summarized separately and also computer coded according to the Fertility Capability Soil Classification System (FCC), devised by Buol et al. (1975), but in a slightly modified form.

It should be emphasized that the quantity and quality of the data varied considerably from region to region, that minor and trace element information was seldom available, and that there were often large distances between sampling sites, all of which compounded the problems of generalizing data. A small-scale "reliability" map has been printed alongside the Land Systems Map to illustrate the variability in the quality of the base data.

The Data Management System—Computerization

Science starts with systematization. Because of the quantity and complexity of data available for the study, and in view of likely interaction within these data and with other agronomic information, it was decided from the outset to code all information on computer-compatible formats. These, together with the detailed methodology, have already been described by Cochrane et al. (1979b). As the data base grew, it was computer input to facilitate diverse analyses and decision making.

Initially, the methodology for this aspect of the work followed that developed by the Statistical Analysis System (SAS) (Barr et al., 1976), which contains procedures for statistical analyses and data reporting. Thus storage, analysis, and retrieval of information was greatly facilitated and the information immediately made available to interested institutions on computer tape. Computerization also facilitates revision and updating of data.

Data Input

The information summary, or "data base," of the land systems of tropical America is summarized in Parts 1 and 2 of Volume 3 in this study, *Computer Summary and Soil Profile*

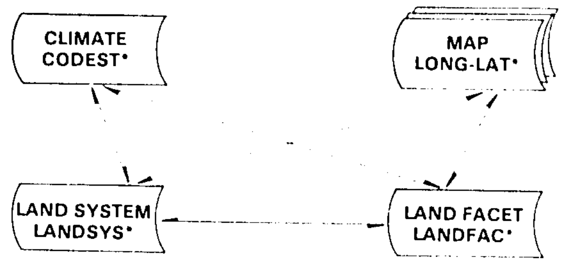


Fig. 3 Schematic of computer files on the data base concept used for the Land Systems Map. Asterisks indicate actual name used for the four cross-referenced files. Information may be combined from two or more files as shown by the interconnecting lines.

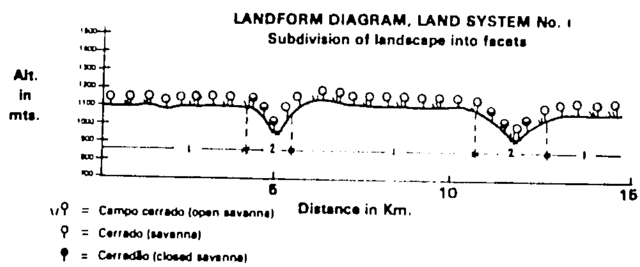
Descriptions of the Land Systems. Technically speaking, the storage, retrieval, and analysis of data and map reproduction by computers is no longer a novelty; this can be achieved in many ways. In fact, the new programs and innovations that are constantly coming on the market ensure the speedy obsolescence of previous systems. What should not become obsolete are the base data per se.

The geographical subdivision of the region into land systems provided a minimal unit for map making; further subdivision of the land systems into land facets provided the building blocks for describing and comparing topography, vegetation, and soils. Consequently, much of the information was summarized as data sets that refer to units or units within units, which facilitated programmer access to data and the revision of specific parts of the data base as additional information was received.

The land-system information is currently organized in four computer files including SAS files (Barr et al., 1976), schematically represented in Figure 3. Three of these files, climate, land system, and land facet, will be explained in this section, with reference to Part 1 of Volume 3, which is made up of printouts of the data recorded for individual land systems, and Part 2, which contains a selection of the meteorological data sets. The fourth file, map, will be explained in terms of its function in making maps from the climate, landscape, and soil data. As an example, Figure 4 replicates a printout of the base data of land system No. 1.

Climate file. The climate file, also incorporated as part of CIAT's SAMMDATA (South American Monthly Meteorological Data) file, is made up of data for individual meteorological stations. These are indexed by geographical coordinates, altitudes, and reference numbers to facilitate assignment to land systems and facets within systems. The parameters recorded were described on a monthly basis and are detailed in Chapter 3. The file allows easy programmer

```
LAND SYSTEM -    1
************

CLIMATE    2070  LUZIANIA
AREA                 2078400 HAS.
ALTITUDE                1100 MTS.
PHYSIOGRAPHIC UNIT NO.  1
GENERALIZED CLASSIFICATION
  UPLANDS,ABOVE 900M
  WELL DRAINED LANDS
  FLAT LANDS,SLOPES<8%
  SAVANNAS

DISTANCE BETWEEN PERENNIAL STREAMS 5-10KM
DEPTH OF WELLS,MAIN LAND FACET 5-10M

LANDSCAPE FACETS
                          FACETS
                       1     2     3
GENERAL DESCRIPTION    A     V
PERCENTAGE OF L.S.    85    15     0
TOPOGRAPHIC CLASS.   (%)
FLAT POOR DRAIN.
  < 8%                90
  8-30 %              10    50
  > 30 %                    50

ALTITUDE IN MTS     1050   900

ORIGINAL VEGETATION CLASS. (%)
  SEAS.IN.P.
  CL + CS
  CC                  50
  C                   50    20
  CO                        80
  THF
  SLSF
  SOSF
  CAAT
  OTHER

INDUCED VEGETATION (%)

  PASTURE             40    10
  CROPS                5
```




```
                              FACETS
                           1     2     3
SOIL CLASSIFICATION
  ORDERS                   O     O
  SUBORDERS                OUS   OUS
  GREAT GROUPS             OUSAC OUSAC
SOIL PHYSICAL PROPERTIES
  SLOPE                    A     A
  DEPTH                    P     P
  INIT. INFIL. RATE        A     A
  HYDRAUL. CONDUCT.        A     A
  DRAINAGE                 B     B
  MOIST. HOLD. CAP.        B     B
  TEMP. REGIME             I     I
  MOIST. REGIME           SO    SO
  EXPANDING CLAYS          O     O
  TEXTURE                  C C   L L
  COARSE MATERIAL          B B   B B

SOIL CHEMICAL PROPERTIES
  PH                       H H   H H
  AL SATURATION %          A H   A H
  EXCHANGEABLE AL          A M   A M
  EXCHANGEABLE CA          B B   B B
  EXCHANGEABLE MG          M S   M B
  EXCHANGEABLE K           K Y   K K
  EXCHANGEABLE NA          B B   B B
  TOTAL EXCH. BASES        B B   B B
  CATION EXCH. CAPAC.      E E   E E
```

```
                                FACETS
                               1     2     3
SOIL CHEM. PROP. (CONT).
  ORGANIC MATTER %             M B   M B
  PHOSPHORUS                   B B   M B
  PHOSPHORUS FIXATION          I     I
  MANGANESE                    U     U
  SULPHUR                      U     U
  ZINC                         B     B
  IRON                         U     U
  COPPER                       U     U
  BORON                        U     U
  MOLYBDENUM                   U     U
  FREE CARBONATES              A     A
  SALINITY                     B     B
  NATRIC                       B     B
  CAT CLAY                     N     N
  X-RAY AMORPHOUS              N     N

ELEMENTS OF IMPORTANCE MAINLY TO
ANIMAL NUTRITION

  CO                           U     U
  I                            D     D
  SE                           U     U
  CR                           U     U
  NI                           U     U
  OTHERS                       U     U
FERTILITY CAPABILITY CLASSIFICATION
TYPE AND SUBSTRATA TYPES    CC    LL
MODIFIERS FACET  1    DHAKEI
          FACET  2    DHAKEI
          FACET  3
```

Fig. 4 Base data of land system No. 1 from the four computer files in Figure 3. Part 1 of Vol. 3 (*Computer Summary and Soil Profile Descriptions of the Land Systems*) includes such base data for land systems 1 to 855.

access to the data, which can be updated to incorporate better estimates of the climatic parameters as additional information becomes available. A minimal number of data set printouts appear in Part 2 of the *Computer Summary* to describe the climates of the land systems of the study region. (An example is also included in Table 3-1 in Chapter 3.)

On the printouts of the individual land-system descriptions of the study (see Figure 4), the subheading CLIMATE indexes the number and name of a meteorological data set that approximates the climatic factors of the major part of the land system.

Land-system file. The land-system file records generalized landscape characteristics of the land systems and the subdivision of the land systems into land facets.

The data in the land-system file, which is largely reproduced in Figure 4, includes the following: AREA, ALTITUDE, PHYSIOGRAPHIC UNIT NO., GENERAL CLASSIFICATION, DISTANCE BETWEEN PERENNIAL STREAMS, and DEPTH OF WELLS. These descriptors are explained in the glossary to Part 1 of the *Computer Summary*. The two dimensional landform diagram in Figure 4 was sketched by hand.

Land-facet file. The land-facet file records the coding of the description of the landscape (land) facets of the land systems under the following headings: GENERAL DESCRIPTION, PERCENTAGE OF L.S. (land system), TOPOGRAPHIC CLASS, ALTITUDE, ORIGINAL VEGETATION CLASS %, INDUCED VEGETATION %, SOIL CLASSIFICATION, SOIL PHYSICAL PROPERTIES, SOIL CHEMICAL PROPERKTIES, ELEMENTS OF IMPORTANCE MAINLY TO ANIMAL NUTRITION, and FERTILITY CAPABILITY CLASSIFICATION. These headings continue the descriptive data of the land system printouts of the study (Part 1 in Volume 3 or refer to Figure 4). These descriptors are also detailed in the glossary to Part 1 of the *Computer Summary*.

Map file. The Land Systems Map units were indexed by geographical coordinates in a map file. Grids subdividing the 1:1,000,000 land-systems maps into 5-minute latitude by 4-minute longitude areas were placed over the 1 to 1,000,000 land-systems maps. Each 5- × 4-minute area was identified by the coordinates of its northwest extremity. The Land Systems Map used the Lambert Conical Projections of the World Map at the Millionth Scale (Wernstedt, 1972) as a geographical base; each of these projections covers an area of 6° longitude by 4° latitude. At the equator, an area of 5 minutes of latitude by 4 minutes of longitude covers about 6800 ha. Each one of these areas was identified as belonging to a given land system on the basis of the land system occupying the greatest part of that area.

Once the 5- × 4-minute areas had been coded, they were computerized and recorded as separate files covering the same areas as the World Map at the Millionth Scale and identified using the same terms. Figure 5 illustrates a computer printout of one of the sectors of the Land Systems Map, Map SC-22.

Clearly, the system of indexing the maps facilitates thematic and single-factor mapping as computer printouts. Figure 6 is a computer-produced single-factor or thematic map of the percentage of Al saturation of topsoils over the same area as Figure 5; it was made by assigning the percentage of aluminum saturation in the topsoils of the predominant land facets to the land systems. This became the basic procedure in making such maps. The system also facilitates the drawing of maps according to various map projections and scales and is convenient for revising different segments as further information comes to hand.

Data Output

The computerized data base descriptors for the study are described in the glossary to coding in Part 1 of the *Computer Summary and Soil Profile Descriptions*. This section also details the criteria used to synthesize and code the data input and explains how agronomists without access to computers might also use the study. Basic output includes printouts of the land-resource information for individual land systems, as recorded in Part 1; meteorological data of the type recorded in Part 2 and described in Chapter 3; and map construction, including thematic and single-factor maps. However, the true value of computerization lies in the speed and flexibility of analyses to help define climate-soil limitations and advantages for the growth of crops and to define analogous geographical areas for the more effective transfer of cultivars growing well in any given environment.

Use of the Study by Agronomists

As already noted, Part 1 of the *Computer Summary* is made up of printouts with virtually complete summaries of the landscape and soils of all the land systems identified on the Land Systems Map. These summaries provide a ready reference to the landscapes and soils of the region. Part 2 presents a selection of prin.outs of monthly meteorological data sets to describe the climates of the land systems identified on the Land Systems Map. This is only a small fraction of the number of data sets available in the climate file.

The criteria used to describe the data summarized in the *Computer Summary* are explained more fully in the text. Additionally, use is made of the thematic and single-factor map-making capabilities of the map file to help illustrate overall constraints and advantages to developing germplasm-based agrotechnology throughout the study region. Further information relevant to the computerization of the study has been recorded by Cochrane et al. (1979). The entire study is available from CIAT or EMBRAPA-CPAC on computer tape, by special request, along with specific details of its organization and programs used in the retrieval and analysis of information and map making.

Because many agronomists contributing to the development of seed-based agrotechnology live in rural areas and do not have access to computer facilities, care has been taken to include comprehensive data-base summaries and other pertinent information as appendices. Part 1 in Volume 3 contains summaries of the landscape and soil information for all the land systems mapped and their facets; Part 2 is a selection of meteorological data sets that may be used to approximate climatic conditions in any given land system. Part 3 records a range of typical soil profiles to provide a better guide of soil

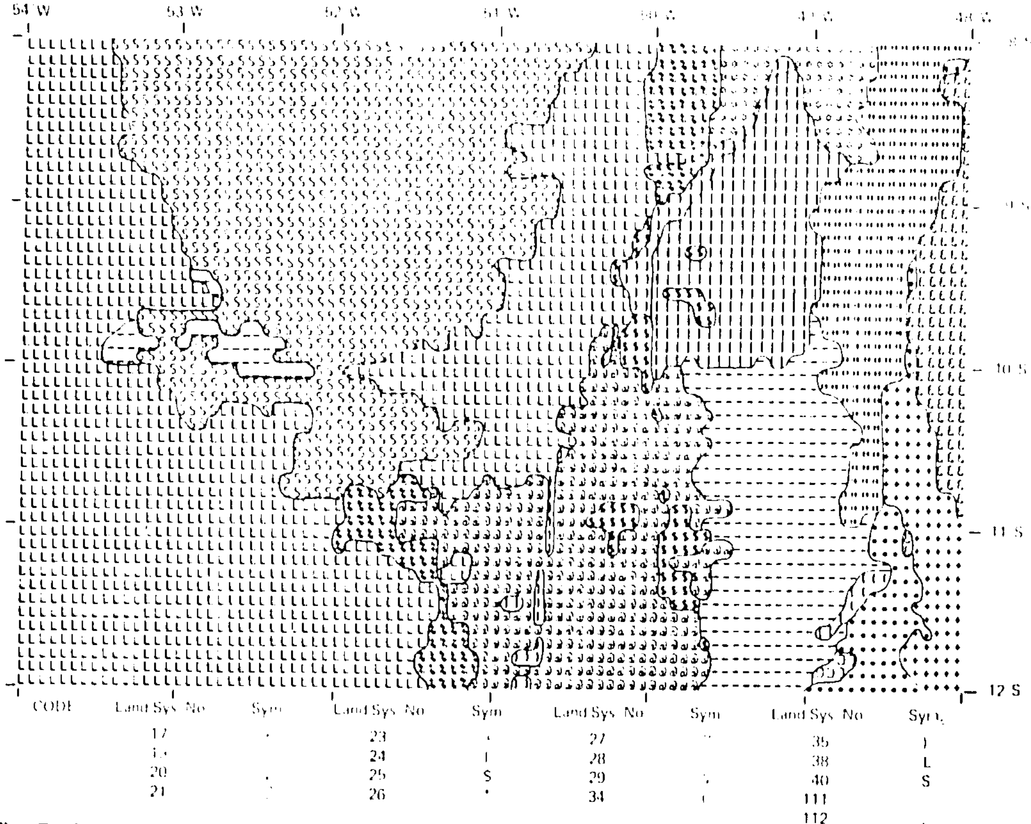


Fig. 5 A computer pı intout of the land system covering International Chart Map No. SC-22 (Tocantins, Goias, Brazil) from the map file.

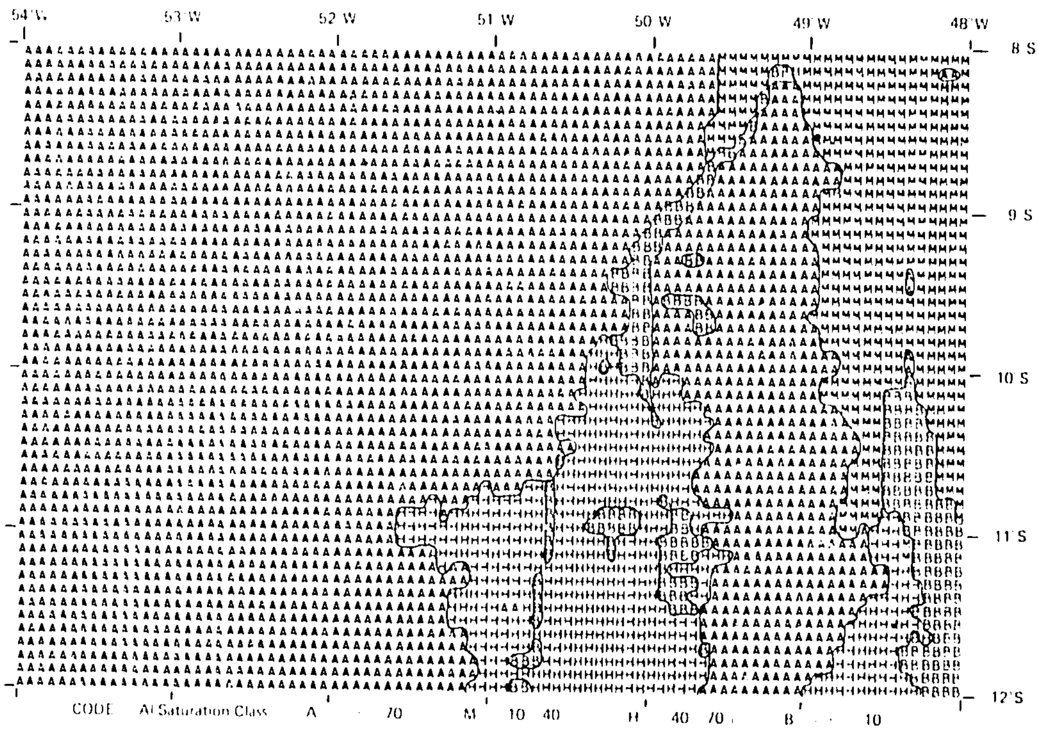


Fig. 6 Single-factor computer map, showing percentage of aluminium saturation over area covering International Chart Map No. SC-22 (Tocantins, Goias, Brazil).

characteristics. Guidelines for agronomists who wish to use the data base are detailed in Chapter 9; this chapter also provides some additional suggestions for accelerating the adaptation of seed-based agrotechnology to local farming conditions.

Agrotechnological Development

While the survey and resulting Land Systems Map were oriented to the problem of developing germplasm-based agrotechnology, they do have a significant interaction with agrotechnological development in general. Figure 7 provides a picture of the overall scope and implications of this system to agricultural development.

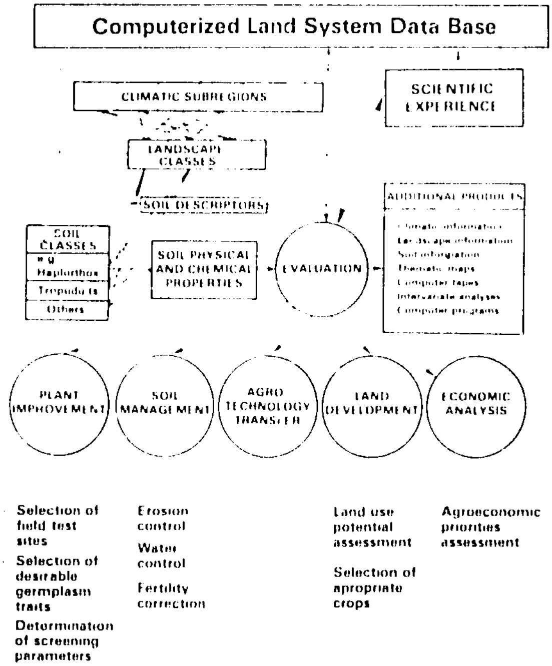


Fig. 7 Flow chart of relationship of land-system mapping with agrotechnological development. Solid lines indicate computer pathways for using the land resource study; dashed lines indicate contributions of the study to spheres of agrotechnological development.

Chapter 1. LAND-SYSTEMS MAPPING FOR SEED-BASED AGROTECHNOLOGY TRANSFER

Land systems define areas of similar landscape where the same type of farming might succeed. Consequently, their careful description is fundamental to land planning and transfer of agrotechnology.

The following text presents a methodology of classifying land systems and an understanding of how they might be interpreted by agronomists in Tropical America. The case study included in this chapter emphasizes how land-systems mapping contributed to research within CIAT's Tropical Pastures Program.

A Historical Note

After the discovery of the new world, it was not long before explorers with illusions of the quest for "El Dorado" penetrated the inner recesses of the South American subcontinent. Missionaries followed; they helped stabilize settlements of indigenous peoples, stimulated agricultural production, and were mainly responsible for introducing cattle on the native savannas. Mining for gold and precious stones, and especially the rubber boom of the Amazon toward the end of the 19th century, attracted fortune seekers and resulted in further settlement. However, it wasn't until the effects of the build-up of population pressure in the Andean highlands and in the coastal strip of Brazil became felt in the 1940s that serious efforts were made to encourage colonization and agricultural development.

Colonization and bringing new land into production have proceeded apace during the past two decades, with varying success. Many new agriculture-based communities have flourished. On the other hand, a general failure to understand the nature of tropical climates and soils and a lack of germplasm adapted to the various ecosystems have often led to unnecessary hardship. The success in transforming the world's ultimate reserve of undeveloped land resources into productive agricultural lands will depend to a considerable extent on renewed efforts to understand the nature of the land resources.

Previous Knowledge of the Region

The FAO-Unesco Soil Map of the World (1971, 1974) indicates that there are extensive areas of very poor and possibly fragile soils, mainly Ferralsols (Oxisols) and Acrisols (Ultisols), supporting the lowland savannas and Amazonian forests of tropical South America. This suggests the need for understanding the nature of these land resources.

There are many, often conflicting, opinions as to the nature of these two regions. In the case of the savannas, their very existence is an enigma that has provoked considerable controversy (Goodland, 1970). Nevertheless, Eiten's (1972) review of the savannas of Central Brazil, locally called "Cerrados" (see Photo Plate 22), and many more recent studies published in the proceedings of the fourth and fifth symposiums on the Cerrados (Ferri, 1977; Marchetti and Dantas Machado, 1980) indicate that these lands are now much better understood.

Many authorities consider the Amazon forest soils (see Photo Plate 4) incapable of sustaining agriculture or livestock production after the primary vegetation is removed (Gouru, 1961; Seltzer, 1967; Reis, 1972; Tosi, 1974; Goodland and Irwin, 1975; Budowski, 1976; Schubart, 1977; Irion, 1978; Goodland et al., 1978). Yet there is ample evidence to show that agriculture and livestock production on well-drained lands is not only possible but also profitable (Falesi, 1972, 1976; Alvim, 1978, 1979; Sánchez, 1977, 1979; Serrao et al., 1979; Toledo and Morales, 1979; Cochrane and Sánchez, 1982).

The amount of soil-survey and land-resource inventory information available for tropical South America has increased rapidly during the past 15 years. An attempt has been made to incorporate this work into the CIAT study. Principal sources have been referenced in the bibliograhy, which is by no means exhaustive, however. As noted by McQuigg (1980):

> There is an astonishing amount of information available in most countries on climate, soils, and other factors important to agricultural success. But this information has only modest value to farmers and planners until it is organized, usually with a computer, into a system which offers capabilities for simulating, predicting results and better managing farm production.

CIAT's methodology for land-resource appraisal was designed to facilitate the speedy appraisal and systematization of the large amount of information available in tropical America.

A Case Study: Using the Land Systems Map to Define Agroecosystems for Tropical Pastures

The work on a Land Systems Map for the region, presented in this book, was originally commissioned as a study of the acid-infertile savanna regions with the express purpose of selecting representative localities for testing promising grass and legume accessions (CIAT, 1978b). It is therefore fitting to provide an overview of how the region as a whole was subdivided into agroecozones for CIAT's Tropical Pastures Program and, specifically, to summarize the findings from the Land Systems Map about the major soil constraints within those ecozones (CIAT, 1981).

After following the procedures outlined in later chapters, five agroecozones were selected to define and subdivide the humid lowlands of central tropical South America. These are shown in Map 1 (see Map Plates), which is based on computer printouts of land-system groupings integrating the broad climatic, topographic, and natural vegetation classes (defined in later chapters). It is a first approximation to put gross climate and landscape differences into perspective. Table 1-1 summarizes the five agroecozones in terms of their major vegetation, climatic, and topographic characteristics. (The very poorly drained forested areas indicated on the map were included within the forest subdivisions according to their climatic regime.)

The basis for the subdivision of the lowlands of tropical South America into climatic subregions is summarized in Chapter 3. The close relationship of the wet-season potential evapotranspiration (WSPE) to the natural vegetation growing on well-drained soils (Cochrane and Jones, 1981) indicates that gross natural vegetation characteristics are a function of the amount of energy plants can use, as accorded by annual water-balance patterns. This finding was used as a first broad criterion for subdividing the region into agroecozones for perennial pasture production. The second criterion was soil drainage. In poorly drained lands, for instance, the ability of plants to withstand waterlogging is of primary importance. Consequently, the poorly drained savannas, including the picturesquely described *Pantanal* of Brazil, which are found throughout the climatic subregions b to e (defined in Table 3-4, Chapter 3), were grouped together as an "agroecozone" for pasture production because they are lands affected by a common problem of prolonged periods of annual waterlogging. The first subdivision of the region, however, was only possible through the second—grouping the vegetation classes of the well-drained soils of the land systems. Further, it is obviously necessary to study climatic characteristics in much greater depth.

It was axiomatic that the soil physical and chemical conditions within the agroecozones would have to be defined more carefully for (1) choosing representative sites for testing promising high-yielding pasture plant accessions and (2) developing reasonable criteria for both preliminary screening and advanced field testing of germplasm. By computerizing the land-resource study, an in-depth analysis of soil physical and chemical constraints within the agroecozones was facilitated. This resulted in a summary of the soils found on the mainly well-drained, not too steep slopes (less than 30%) within the predominantly well-drained agroecozones (Table 1-2, Sections a to l).

The many factors relevant to soil physical and chemical conditions summarized on the computer formats for the land facets of the land systems, and described in detail by Cochrane et al. (1979), were examined separately within the

Table 1-1. Agroecozones determined for CIAT's Tropical Pastures Program in the central lowlands of tropical South America.

Agroecozone	Climatic parameters	Flat, poor drainage	< 8% slope	8-30% slope	> 30% slope	Total area (ha × 10⁶)	Percentage of total area
		Area (ha × 10⁶) in each topography class					
Poorly drained savanna	WSPE < 900 mm, 6 mos. wet season, WSMT > 23.5 C	49	0	0	0	49	7
Isohyperthermic savanna	WSPE 900-1060 mm, 6-8 mos. wet season, WSMT > 23.5 C	17	72	12	10	111	6
Isothermic savanna	WSPE 900-1060 mm, 6-8 mos. wet season, WSMT < 23.5°C	1	25	9	7	42	6
Semi-evergreen seasonal forest	WSPE 1061-1300 mm, 8-9 mos. wet season, WSMT > 23.5°C	53	145	94	4	296	41
Tropical rain forest	WSPE > 1300 mm, > 9 mos. wet season, WSMT > 23.5°C	69	88	55	5	217	30
	Total area (ha × 10⁶)	189	330	170	26	715	
	Percentage of total area	26%	46%	24%	4%		

a. WSPE = total wet-season potential evapotranspiration.
b. WSMT = wet-season mean monthly temperature.

Table 1-2. Summary of the aereal extent of major soil constraints of importance to pasture germplasm selection for the well-drained soils of the central lowlands of tropical South America, by natural vegetation and topographic class.

Soil: Order	Soil: Percentage within class	Soil: Great Group	Area covered (ha x 10^6)	Area with chemical constraints[a] (ha x 10): Toxicity: Al	Toxicity: Al (sat)	Deficiency: K	Deficiency: Ca	Deficiency: Mg	Deficiency: P	P fixation	Area with physical constraints[b] (ha x 10^6): MH	S
				ISOHYPERTHERMIC SAVANNA								
a) Topographic class 0-8%												
Oxisol	66.5	Haplustox	19.24	7.53	7.72	14.07	11.93	8.04	13.40	9.89	9.48	4.80
		Acrustox	17.57	14.64	6.44	17.57	17.57	5.31	17.38		9.83	16.50
		Haplorthox	6.02	1.94	1.68	5.65	3.45	4.99	4.28	3.46	5.67	
		Eutrustox	5.03	0.76	1.01	0.76		0.46	0.30	0.30	1.01	
		Subtotal	47.86	24.87	16.85	38.05	32.95	18.8	35.36	23.48	32.66	4.80
		% with constraint		51.9%	35.2%	79.5%	68.8%	39.2%	73.8%	49.0%	68.2%	10.0%
Entisol	23.1	Quartzipsamments	12.71	0.28	4.60	12.71	12.71	11.23	12.63		12.71	12.71
		Tropofluvents	1.88									
		Ustipsamments	1.49			1.49	1.49	1.49			1.49	1.49
		Ustifluvents	0.51									
		Subtotal	16.59	0.28	4.60	14.20	14.20	12.72	12.63		14.2	14.2
		% with constraint		1.6%	27.7%	88.8%	85.5%	76.6%	76.1%		85.5%	85.5%
Alfisol	6.7	Rhodustalfs	2.44									
		Haplustalfs	2.43			0.17	0.17	0.17	0.17			
		Subtotal	4.87			0.17	0.17	0.17	0.17			
		% with constraint				3.5%	3.5%	3.5%	3.5%			
Ultisol	2.0	Plinthudults	1.48	1.48		1.48	1.48	1.48	1.48			1.46
		% with constraint		100.0%		100.0%	100.0%	100.0%	100.0%			98.6%
Inceptisol	1.0	Dystropepts	0.66			0.66					0.66	0.66
		Eutropepts	0.14									
		Subtotal	0.80			0.66					0.66	0.66
		% with constraint				82.5%					82.5%	82.5%
Mollisol	1.0	Haplustolls	0.32									
		TOTAL	71.92	26.63	21.45	54.56	48.80	33.17	49.64	23.48	47.52	21.12
		% of topographic class		37.0%	29.8%	75.8%	67.8%	46.1%	69.0%	32.6%	66.0%	29.3%
		Rank order of importance[c]		2	2	1	1	2	1	2	1	2
b) Topographic class 8-30%												
Oxisol	78.0	Haplustox	7.51	2.26	0.48	5.18	4.95	2.48	4.95	2.34	4.58	0.19
		Eutrustox	1.64		0.11	0.11						
		Acrustox	0.05			0.05	0.05		0.05			
		Subtotal	9.20	2.26	0.59	5.34	5.00	2.48	5.0	2.34	4.58	0.19
		% with constraint		24.6%	6.4%	58.0%	54.3%	27.0%	54.3%	25.4%	49.8%	2.1%
Entisol	11.0	Troporthents	0.77	0.77	0.77	0.77	0.77	0.77	0.77		0.77	
		Quartzipsamments	0.56			0.56	0.56	0.30	0.26		0.56	0.56
		Subtotal	1.33	0.77	0.77	1.33	1.33	1.07	1.03		1.33	0.56
		% with constraint		57.9%	57.9%	100.0%	100.0%	80.4%	77.4%		100.0%	42.1%

Continued

Table 1-2. Continued.

Soil: Order	Soil: Percentage within class	Soil: Great Group	Area covered (ha x 10[6])	Area with chemical constraints[a] (ha x 10[6]): Toxicity: Al	Toxicity: Al (sat)	Deficiency: K	Deficiency: Ca	Deficiency: Mg	Deficiency: P	P fixation	Area with physical constraints[b] (ha x 10[6]): MH	S
Alfisol	7.1	Paleustalfs	0.84									
		% with constraint							0.84			
									100.0%			
Ultisol	3.2	Haplustults	0.38									
		% with constraint							0.38			
									100.0%			
Inceptisol	1.0	Dystropepts	0.11									
		% with constraint				0.11			0.05			
						100.0%			45.4%			
		TOTAL	11.86	3.03	1.36	6.78	6.33	3.55	7.3	2.34	5.91	0.75
		% of topographic class		25.5%	11.5%	57.1%	53.4%	29.9%	61.5%	19.7%	49.8%	6.3%
		Rank order of importance[c]		2	3	1	1	2	1	3	1	1
c) Combined topographic classes 0-8 and 8-30%			83.78	29.66	22.81*	61.34	55.13	36.72	56.94	25.82	53.43	21.87
% of combined area with constraint				35.4%	27.2%	73.2%	65.8%	43.8%	67.9%	30.8%	63.7%	26.1%
Rank order of importance[c]				2	2	1	1	2	1	2	1	2
				ISOTHERMIC SAVANNA								
d) Topographic class 0-8%												
Oxisol	95.6	Acrustox	9.75	9.75	3.03	9.75	9.75	2.86	9.75	8.37	6.52	
		Eutrustox	7.62	3.07	0.38	3.07	1.38		2.69	4.07	3.29	
		Haplustox	6.74	3.73	1.64	6.74	6.74	4.02	6.74	1.91	6.74	
		Subtotal	24.11	16.55	5.05	19.56	17.87	6.88	19.18	14.35	16.55	
		% with constraint		68.6%	20.9%	81.1%	74.1%	28.5%	79.5%	59.5%	68.6%	
Ultisol	3.5	Rhodustults	0.87									
Alfisol	0.9	Rhodustalfs	0.23									
		% with constraint				0.23						
						100.0%						
Entisol	0.1	Ustifluvents	0.02									
		TOTAL	25.21	16.55	5.05	19.79	17.87	6.88	19.18	14.35	16.55	
		% of topographic class		65.6%	20.0%	78.5%	70.8%	27.2%	76.0%	56.9%	65.6%	
		Rank order of importance[c]		1	3	1	1	2	1	1	1	
e) Topographic class 8-30%												
Oxisol	96.9	Haplustox	5.57	1.98	1.05	5.57	3.39	1.61	4.57		5.57	
		Acrustox	3.01	3.01			3.01		3.01	2.01	2.01	
		Eutrustox	0.35	0.13	0.13	3.01					0.13	
		Subtotal	8.93	5.12	1.18	8.58	6.40	1.61	7.58	2.01	7.71	
		% with constraint		57.3%	13.2%	96.1%	71.7%	18.0%	84.9%	22.5%	86.3%	
Alfisol	3.1	Rhodustalfs	0.29									
		% with constraint										
		TOTAL	9.22	5.12	1.18	8.58	6.40	1.61	7.58	2.01	7.71	
		% of topographic class		55.5%	12.8%	93.0%	69.4%	17.4%	82.2%	21.8%	83.6%	
		Rank order of importance[c]		1	3	1	1	3	1	3	1	
f) Combined topographic classes 0-8% and 8-30%			34.43	21.67	6.23	28.37	24.27	8.49	26.76	16.36	24.26	
% of area with constraint				62.9%	18.1%	82.4%	70.5%	24.6%	77.7%	47.5%	70.4%	
Rank order of importance[c]				1	3	1	1	3	1	2	1	

SEMI-EVERGREEN SEASONAL FOREST (UNDER NATIVE VEGETATION)

g) Topographic class 0-8%

Oxisol	48.5	Acrorthox	38.80	22.07	28.31	30.06	30.06	4.04	28.52	7.99	22.07
		Haplorthox	26.62	18.42	21.81	17.42	5.61	4.78	16.46	4.36	23.49
		Umbriorthox	4.31	4.31	4.31	4.31	4.31	4.31			4.31
		Eutrorthox	0.35						0.35		0.35
		Subtotal	70.08	44.80	54.43	51.79	39.98	13.13	45.33	12.35	50.22
		% with constraint		63.9%	77.6%	73.9%	57.0%	18.7%	64.7%	17.6%	71.6%
Ultisol	40.5	Tropudults	41.75	26.09	41.68	30.10	30.73	11.67	34.77	9.78	
		Paleudults	15.47	14.11	14.11	6.00	15.47	14.11	4.07	0.22	
		Haplustults	0.89		0.69	0.89	0.07		0.69		0.21
		Plinthudults	0.35	0.35	0.35	0.07		0.07	0.07		
		Subtotal	58.46	40.55	56.83	37.06	46.27	25.85	39.60	10.0	0.21
		% with constraint		69.3%	97.2%	63.4%	79.1%	44.2%	67.7%	17.1%	0.48%
Entisol	6.6	Quartzipsamments	4.79	4.35	4.58	0.55	4.52	4.33	4.53		4.79
		Tropofluvents	3.13			1.30	0.37	0.37	0.25		0.63
		Ustipsamments	1.21	0.71	0.71	0.21	0.18	0.18	0.71		1.11
		Ustifluvents	0.26								
		Tropopsamments	0.16			0.06					0.14
		Subtotal	9.55	5.06	5.29	2.12	5.07	4.88	5.49		6.67
		% with constraint		52.9%	55.4%	22.2%	53.0%	51.1%	57.4%		69.8%
Alfisol	3.5	Hapludalfs	4.55			2.12			0.89		
		Haplustalfs	0.47			0.47			0.47		
		Subtotal	5.02			2.59			1.36		
		% with constraint				51.6%			27.1%		
Inceptisol	0.9	Eutropepts	0.75								
		Ustropepts	0.37								
		Dystropepts	0.24	0.24	0.24	0.24	0.24				
		Subtotal	1.36	0.24	0.24	0.24	0.24				
		% with constraint		17.6%	17.6%	17.6%	17.6%				
Mollisol	0.1	Argiudolls	0.01						0.02		
		% with constraint							100.0%		
		TOTAL	144.48	90.65	116.79	93.80	91.56	43.86	91.78	22.35	57.10
		% of topographic class		62.7%	80.8%	64.9%	63.3%	30.3%	63.5%	15.5%	39.5%
		Rank order of importance[c]		1	1	1	1	2	1	3	2

h) Topographic class 8-30%

Oxisol	56.6	Haplorthox	33.49	36.32	31.92	28.36	23.15	28.05	30.19	6.18	36.65
		Acrorthox	14.39	12.85		12.85	3.17	2.59	12.27		3.17
		Haplustox	0.07		0.07				0.07	0.07	
		Subtotal	52.95	49.17	31.99	41.21	26.32	30.64	42.53	6.25	39.82
		% with constraint		92.0%	60.4%	77.8%	49.7%	57.8%	80.3%	11.8%	75.2%
Ultisol	36.5	Tropudults	27.08	3.05	15.63	12.87	12.53	2.77	12.23	0.91	
		Rhodudults	4.43								
		Paleudults	2.54		2.44						
		Haplustults	0.14			0.04			0.10		0.01
		Subtotal	34.19	3.05	18.07	12.91	12.53	2.77	12.33	0.91	0.01
		% with constraint		8.9%	52.9%	37.8%	36.6%	8.10%	36.1%	2.7%	0.03%
Entisol	4.1	Troporthents	3.82			0.34	0.34	0.34	3.82		3.82
		Quartzipsamments	0.02			0.02		0.02	0.02		0.02
		Subtotal	3.84			0.36	0.34	0.36	3.84		3.84
		% with constraint				9.4%	8.8%	9.4%	100.0%		100.0%

Continued

Table 1-2. Continued.

Soil: Order	Soil: Percentage within class	Soil: Great Group	Area covered (ha x 10^6)	Area with chemical constraints[a] (ha x 10^6): Toxicity: Al	Toxicity: Al (sat)	Deficiency: K	Deficiency: Ca	Deficiency: Mg	Deficiency: P	P fixation	Area with physical constraints[b] (ha x 10^6): MH	S
Inceptisol	1.8	Dystropepts	1.65	1.65	1.65	1.65	1.65	1.65	1.65		1.65	
		% with constraint		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%		100.0%	
Alfisol	1.0	Hapludalfs	0.86						0.28			
		Haplustalfs	0.06								0.02	
		Subtotal	0.92						0.28		0.02	
		% with constraint							30.4%		2.2%	
		TOTAL	93.55	53.87	51.71	56.13	40.84	35.42	60.63	7.16	45.34	
		% of topographic class		57.6%	55.3%	60.0%	43.6%	37.9%	64.8%	7.6%	48.5%	
		Rank order of importance[c]		1	1	1	2	2	1	3	2	
i) Combined topographic classes 0-8 and 8-30%			238.03	144.52	168.50	149.93	132.40	79.28	152.41	29.51	102.44	
% of area with constraint				60.7%	70.8%	62.9%	55.6%	33.3%	64.0%	12.4%	43.0%	
Rank order of importance[c]				1	1	1	1	2	1	3	2	
		TROPICAL RAIN FOREST (UNDER NATIVE VEGETATION)										
j) Topographic class 0-8%												
Ultisol	56.5	Paleudults	26.05	26.05	26.05	26.05	22.56	25.16	8.42			
		Plinthudults	21.47	21.47	21.47	21.47			6.87			
		Tropudults	10.83	10.21	10.21	10.27	1.79	1.80	8.42			
		Subtotal	58.35	57.73	57.73	57.79	24.35	26.96	23.71			
		% with constraint		98.9%	98.9%	99.0%	41.7%	46.2%	40.6%			
Inceptisol	14.3	Dystropepts	6.72	6.72	6.72	0.92			6.11			
		Eutropepts	4.26			4.26						
		Dystrandepts	1.58	0.45	0.45	1.39	0.61	0.45	0.94	1.13		
		Subtotal	12.56	7.17	7.17	6.57	0.61	0.45	7.05	1.13		
		% with constraint		57.1%	57.1%	52.3%	4.9%	3.6%	56.1%	9.0%		
Alfisol	10.7	Hapludalfs	9.41			9.41			9.41			
		% with constraint				100.0%			100.0%			
Oxisol	4.3	Acrothox	2.76	2.76	1.27	2.76	2.76	2.76	1.27	0.45		
		Haplorthox	1.01	1.01	1.01	1.01	1.01	1.01				
		Subtotal	3.77	3.77	2.28	3.77	3.77	3.77	1.27	0.45		
		% with constraint		100.0%	60.5%	100.0%	100.0%	100.0%	33.7%	11.9%		
Entisol		Tropofluvents	3.63			3.13						
		% with constraint				86.2%						
		TOTAL	87.72	68.67	67.18	80.67	28.73	31.18	41.44	1.58		
		% of topographic class		78.3%	76.6%	92.0%	32.7%	35.5%	47.2%	1.8%		
		Rank order of importance[c]		1	1	1	2	2	2	3		
k) Topographic class 8-30%												
Oxisol	74.7	Haplorthox	33.53	31.42	31.42	33.53	13.60	13.20	32.68	11.48		
		Acrorthox	7.47			7.47	7.47	7.47				
		Subtotal	41.00	31.42	31.42	41.00	21.07	20.67	32.68	11.48		
		% with constraint		76.6%	76.6%	100.0%	51.4%	50.4%	79.7%	28.0%		

Ultisol	6.6	Paleudults	2.14	2.14	1.88	2.14		1.88		
		Tropudults	1.51	1.51	1.51	1.51		1.51		
		Subtotal	3.65	3.65	3.39	3.65		3.39		
		% with constraint		100.0%	92.9%	100.0%		92.9%		
Inceptisol	13.3	Dystropepts	7.32	6.40	4.79	7.32		6.40	1.61	1.61
		% with constraint		87.4%	65.4%	100.0%		87.4%	22.0%	22.0%
Alfisol	5.4	Hapludalfs	2.96		0.23	2.96			2.73	
		% with constraint			7.8%	100.0%			92.2%	
		TOTAL	54.93	41.47	39.83	54.93	21.07	30.46	37.02	13.09
		% of topographic class		72.5%	72.5%	100.0%	38.3%	55.4%	67.4%	23.8%
		Rank order of importance		1	1	1	2	2	1	3
II) Combined topographic classes 0-8 and 8-30%			142.65	110.14	107.01	135.60	49.80	61.64	78.46	14.67
% of area with constraint				77.2%	75.0%	95.0%	35.0%	43.2%	55.0%	10.3%
Rank order of importance				1	1	1	2	2	2	3

a. Refers to topsoil, except for Al (sat) = % Al saturation in subsoil.
Al = Al saturation >70%; K = <0.15 meq/100 g soil; Ca = <0.4 meq/100 g soil; Mg = <0.2 meq/100 g soil; P = <3 ppm; P fixation = high P fixation.
For details see: Cochrane et al., 1979.

b. MH = low moisture holding capacity, <75 mm/100 cm soil; S = sandy topsoils.

c. 1 = >50% of area, 2 = 25-50% of area, 3 = < 25% of area.

Great Group soil subdivisions of the topographical classes for each agroecozone. In Table 1-2, Sections c, f, i, and l, the topographical classes 0–8% and 8–30% are grouped together to summarize the major soil constraints. The specification of soils in terms of Great Groups clearly helps with the appraisal of soil conditions, but, as can be seen from Table 1-2, it is not always sufficient to describe specific soil constraints, let alone judge their relative importance in geographical perspective for the determination of desirable germplasm traits.

The following ecosystems were determined for CIAT's Tropical Pastures Program.

Isohyperthermic Savannas

From Table 1-2, Sections a, b, and c, it can be seen that the predominant soil physical constraint throughout this agroecozone is low moisture-holding capacity. This is particularly evident in the Haplustox, Acrustox, and Haplorthox soil Great Groups within the Oxisol order, and in the Quartzipsamments and Ustipsamments of the Entisols; soils with low moisture-holding capacities within these Great Groups account for over 60% of the soils found in the agroecozone as a whole. The tendency for rainfall patterns to be somewhat erratic in some parts of the ecozone suggests a need for plants capable of withstanding moisture stresses, perhaps beyond that indicated by the length and intensity of the dry season.

Soil mineral deficiencies, principally P, K, and Ca, are of primary importance; pasture plants capable of producing satisfactorily in soils with low levels of these elements should be sought. The ability of plants to tolerate high levels of Al and low Mg is of importance over about 30% of the area. Further, the percentage of Al saturation in the subsoil does not tend to be as high as in the topsoil. Phosphorus fixation is likely to be a problem in 30% of the soils. In short, the geographical extent of soils with potential Al toxicity and P-fixation problems is not as large as might be inferred from small-scale, generalized soil maps.

Isothermic Savannas

Table 1-2, Sections d, e, and f, indicate that in isothermic, as in isohyperthermic, savannas, low soil moisture-holding capacity is a serious problem. Over 70% of the soils, virtually all of them Oxisols, have low moisture-holding capacities. This problem is demonstrated by the exaggerated effect the *veranicos* (erratically occurring periods with little rainfall during the "wet season" in Central Brazil) have on crop growth and, to a lesser extent, on pasture production. Pasture plants for this ecozone must be adapted, not only to survive a prolonged dry season of 4 to 6 months but also to resist lesser periods of moisture stress during the wet season. Perhaps the best way to ensure this is to find plants that will grow deep roots under the poor chemical conditions of these soils, coupled with more efficient soil amendments and fertilizers to promote deeper rooting.

In the isothermic savannas, in contrast to the isohyperthermic savannas, both soil deficiency and toxicity problems are of primary concern. Pasture plants should be selected to give satisfactory yields in soils with high levels of the percentage of Al saturation and low levels of P, K, and Ca. Phosphorus fixation also appears to be a potential and widespread problem, so emphasis should be put on choosing germplasm adapted to very low P availability.

The Al saturation percentage levels tend to diminish with depth; this is very important insofar as root penetration is concerned. It also means that the correction of Al toxicities through minimal lime applications, as calculated by the improved liming equation of Cochrane et al. (1980), would provide an alternative, relatively low-cost way of overcoming a serious problem throughout this agroecozone.

Tropical Semi-Evergreen Seasonal Forest

The analytical data of soil samples, taken mainly from soil profiles describing soils under native vegetation, would suggest that potential P, K, and Ca deficiencies could be widespread problems, and that soil Al levels are often high in the tropical semi-evergreen seasonal forest areas (Table 1-2, Sections g, h, i). However, as illustrated by the work of Falesi (1972, 1976) and Serrao et al. (1979), soils under forest vegetation may be changed completely if the vegetation is burned and the resulting ash returned to the soil. In other words, the potential fertility of soils in this ecozone under forest cover is a function not only of the soil's fertility but also of the fertility "stored" in the biomass. Analytical figures can only provide a satisfactory guide to fertility if the vegetation is completely removed by clearing lands by bulldozers. After an adequate burning of vegetation, the fertility of these soils may be restored. If followed up by careful management using deep-rooted pastures, this restored fertility might be maintained for many years.

The phenomenon of "fertility" being stored in biomass would indicate that, provided adequate management techniques are used, pastures not so well adapted to very low soil-fertility conditions for the semi-evergreen seasonal forest agroecozone might be cultivated. On the other hand, there is clearly a lot more to be understood about pasture management in these areas, and the search for pastures better adapted to the ecosystem should continue.

Tropical Rain Forest

Owing to the inherent difficulty of burning forests in very wet areas, the analytical figures indicating chemical constraints for the tropical rain forest agroecozone (Table 1-2, Sections j, k, l) probably serve as a more useful guide for selection criteria for pasture plants than is the case for the semi-evergreen seasonal forests. The percentage of Al saturation levels are often high, and K levels are almost universally low. The P, Ca, and Mg figures appear, on the average, to be slightly higher than those of the other agroecozones, but they clearly reflect the higher proportion of inherently more fertile soils, especially the Inceptisols, Alfisols, and Entisols. These three soils alone account for about 25% of the well-drained soils of the region; their presence indicates that the development of pasture germplasm specifically adapted to acid, infertile soils for this ecozone is not so high a priority as in the other ecosystems.

Discussion

These summaries of the major soil constraints in the agroecozones of CIAT's Tropical Pastures Program take what is known into account. Unfortunately, the recorded soil survey and fertility work rarely includes S, Mn, or minor element assays, because of past analytical and interpretative problems. It is thus possible that germplasm tolerant to low S levels or toxic Mn levels may be required for some regions.

The picture that has emerged from this land-system evaluation of the major soil constraints, and, by inference, the priorities for desired genetic traits in tropical pastures for the acid soils of tropical America's hinterlands, is considerably different from what was previously inferred from generalized small-scale maps.

A first major finding is that P fixation is not a potential problem over much of the area, but is mainly confined to the isothermic agroecozone. This calls for a different emphasis on work designed to tackle P problems. Phosphate rock seems an attractive, low cost solution for correcting P deficiencies for pasture production over much of the region. We still need to learn about the behavior of rock phosphate in the context of overall crop growth, however. There is also a need for more study on the ability of P and other minerals to move down the soil profile and stimulate deeper rooting and, consequently, tap more extensive water and mineral supplies. There is evidence, for instance, that single superphosphate does this task more effectively than triple superphosphate (E. Wagner, CPAC, pers. comm.). Nevertheless, at this point, it is certain that pasture plants should be selected for tolerance to soils with low P levels. This is particularly important in the case of plants for the isothermic savannas.

The second major finding is that potential Al toxicity is not as widespread as previously thought; however, it is an important consideration in the isothermic savanna agroecozone. Fortunately, in this ecozone, the percentage of Al saturation in many soils diminishes with depth, and, thus, the strategic use of minimal lime applications will provide a low-cost solution to many toxicity problems. Pasture plants tolerant to high Al saturation in soils are still highly desirable for the isothermic savanna agroecozone, although this tolerance need not be as great as previously thought. Pasture germplasm need not all be screened for tolerance to very high soil-solution Al levels, as has been the practice in the past.

The third major finding is that soil Ca and K levels are low on a very high proportion of the soils. Low Mg levels are also common. This would suggest that a desirable "trait" in pasture plant germplasm would be tolerance to low available K, Ca, and Mg. (Clearly, deficiency problems of Ca and Mg can be overcome by modest applications of dolomitic limestone; however, the cost of such is a function of distance from suitable and commercially exploited deposits.)

A fourth finding is that the substantial fertility reserves in arboreal biomass infers that care must be taken in interpreting the relative importance of soil chemical constraints for the semi-evergreen seasonal forest agroecozone. It is evident that by burning the forest cover many of these soils will undergo major changes in their nutrient properties. Further, the restored fertility can be maintained for many years under adequate pasture management. This would involve only a minimal input of chemical fertilizers. As a consequence, the search for germplasm adapted to extremely poor soil-fertility conditions need not necessarily be a priority for the semi-evergreen seasonal forest regions. In the tropical rain forest ecosystem, also, the high proportion of inherently fertile soils suggests that the search for pasture germplasm adapted to low soil fertility need not be a top priority.

A fifth finding concerns soil chemical restraints over the entire area. Although germplasm testing sites can now be more carefully located to take advantage of the known soil constraints, these trials should be monitored for the complete gamut of potential nutrient problems. A careful monitoring of nutrient problems using foliar analytical techniques could lead to a wealth of knowledge about potential soil problems over the area. If only one trace element problem is identified in an area, its solution could lead to significant socioeconomic benefits.

Finally, it was found that varying moisture-holding capacities in many of the savanna soils emphasizes the need to maintain perspective in testing pasture plant accessions adapted to the acid soil hinterlands. Climate, especially in the sense of the annual energy available for plant growth as accorded by the soil moisture regimes, is of great importance in determining the adaptability of germplasm to any agroecozone, always providing that soil physical conditions are taken into account and that the germplasm is adapted to acid-infertile soils. It is therefore necessary that germplasm be tested in representative soil sites within the major agroecozones, and over a period of several years, to accurately assess the influences of climate and soil moisture conditions.

Chapter 2. DESCRIPTION OF THE LAND SYSTEMS MAP AND LANDSCAPE FACETS

Land systems were the smallest geographically defined units of this survey. An individual land system represents an area or group of areas throughout which there is a recurring pattern of climate, landscape and soils. It is a unit of land, identifiable both on the ground and from satellite imagery, within which the same type of farming is likely to succeed. Clearly, the delineation of these land units is fundamental to developing practical agricultural technologies. Further, such delineation provides a mechanism for computerizing and comparing land in a geographical context and a means of summarizing land information within a common base.

This chapter describes the steps taken to produce the Land Systems Map in Volume 2 and explains the codes used on it.

Satellite and Side-Looking Radar Imagery

Satellite and side-looking radar imagery at a scale of 1 to 1 million and, in some cases, larger scale aerial photography, were used to help define land-system boundaries.

Satellite imagery dates to the launching of the LANDSAT-1 satellite in 1972 under the ERTS (Earth Resources Technology Survey) program of NASA (National Aeronautics and Space Administration), a civil entity of the United States Government (U.S. Geological Survey, 1977). This was succeeded by the launching of LANDSAT-2 in 1975; additional satellites with more sophisticated sensing equipment are now in orbit, and even more are planned. Each image covers 185 sq km of territory. The resolution is better than 100 m. Techniques for interpreting satellite imagery, and remote-sensing techniques generally, are well documented (Draeger and McClelland, 1977; Lintz and Simonett, 1977), and advances in this field continue steadily (Barney et al., 1977; Johannsen, 1977).

With the exception of wetter areas, most of the delineation of land systems was carried out by satellite imagery using black and white photographic prints. Spectral band 5, the lower red frequency, was most commonly used; this gave a useful image of vegetation and topography. For some regions, spectral band 7, the near infrared end of the spectrum, was selected as it gave better haze penetration and land-water discrimination. Color-composite imagery, which is false color obtained by the integration of the four spectral bands, would have been preferred, but was ruled out because of cost. Figure 2-1 illustrates land-system mapping on a satellite image of the

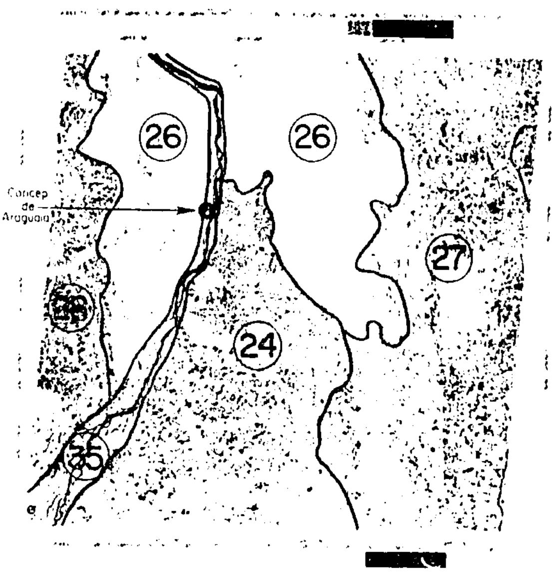


Fig. 2-1 Land-system mapping on a satellite image of the environs of Conceição do Araguaia, southeast boundary of Amazonia Central Brazil.

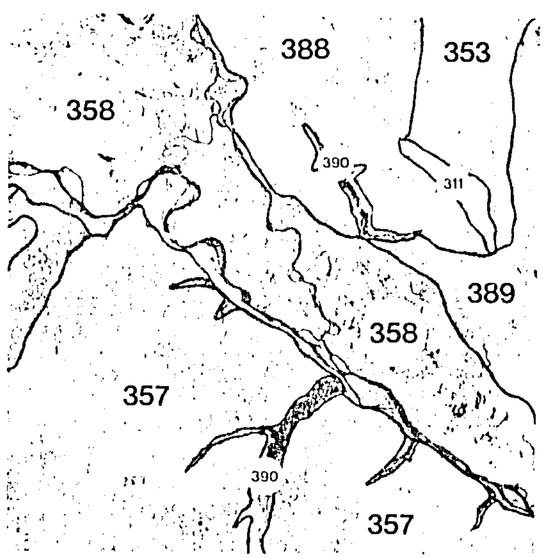


Fig. 2-2 Land-system mapping on radar imagery along the Amazon river about 350 km west of Manaus.

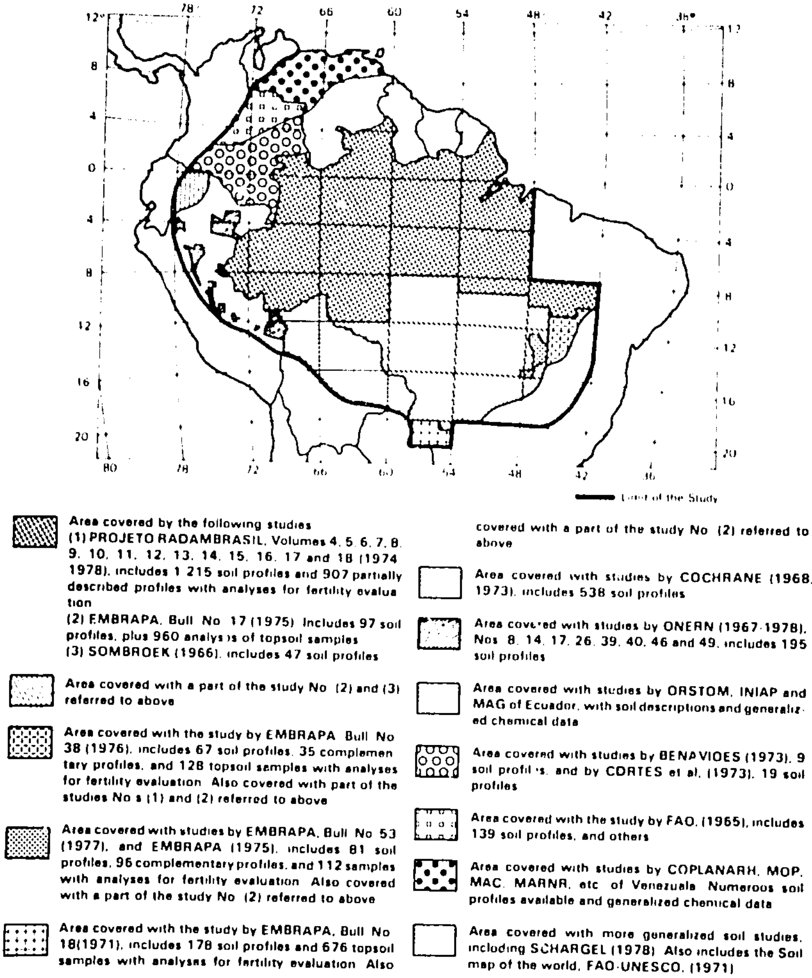


Fig. 2-3 Principal soil studies used as sources of information in the land-resource study.

environs of Conceição do Araguaia, on the southeastern fringe of Amazonia.

Satellite imagery has one major drawback. Due to the relatively short period of time the LANDSAT satellites had been transmitting when the study started, and because orbits were designed to pass over the same area at relatively infrequent intervals (originally 20 times a year, but now more frequently with LANDSAT-2 in operation), it was not surprising to find that, for the wetter areas, it was difficult to get cloud-free imagery.

The largest area affected by the cloud problem was Amazonia. Fortunately, side-looking radar imagery, which is not affected by the presence of clouds, was available for most of Brazil's Amazonia (available from Projeto Radambrasil, Ministério das Minas e Energía), and this was used as a geographical base for the delineation of land systems throughout that region. Side-looking radar imagery produces an excellent topographical picture of the landscape, but it is not nearly as effective as satellite imagery in helping to identify vegetative cover and soil drainage characteristics. Figure 2-2 shows land system mapping on radar imagery along the Amazon river 350 km west of Manaus.

For some areas, including the wet eastern piedmont of Bolivia, aerial photography was used for interpreting the landscape picture.

Land-System Delineation

After climatic analyses and literature research were completed, land-system boundaries were drawn provisionally on the satellite and side-looking radar imagery. The principal soil-survey references used are summarized in Figure 2-3. A guide to the reliability of the major soil-mapping coverage is given on the appended Land Systems Map.

Although the work was mainly an exercise in condensing existing information to a common identifiable base, wherever

Table 2-1. Nine physiographic regions delineated on the Land Systems Map.

Physiographic region code	Region	Physiographic region code	Region
A	Amazon Basin	M	Mojos Pampas
B	Brazilian Shield	O	Orinoco Basin
E	Elbow of the Andes	P	Pantanal
F	Andean Foothills	R	Parana Basin
G	Guayana Shield		

Table 2-2. Seven climatic subregions delineated on the Land Systems Map.

Climatic subregion code	Climate		
	WSPE[a] (mm)	Wet months[b] (no.)	WSMT[c] (°C)
a	>1300	>9	>23.5
b	1061-1300	8-9	>23.5
c	900-1060	6-8	>23.5
d	900-1060	6-8	<23.5
e	<900	<6	>23.5
f	Subtropical		
o	Others		

a. WSPE: total wet-season potential evapotranspiration, the sum of the potential evapotranspiration of the wet months.
b. Wet months are months with a moisture availability index (MAI) >0.33.
c. WSMT: wet-season mean monthly temperatures.

possible and when little or no information was available in the literature, a limited amount of field work was done to check the photo-interpretation and to standardize descriptive criteria. A small Piper PA-18, STOL (short-take-off-landing) airplane was flown by the first author to cover hinterland areas; every effort was made to examine the principal landscape facets within a given land system. During the course of the field work, land system boundaries were fixed.

Map Making

The land systems were compiled by drafting boundaries directly from the imagery. They were completed on a segment-by-segment basis, according to the index used by the 1:1,000,000 International Chart of the World at the Millionth Scale (see Figure 1, after Kerstenetzky, 1972).

Computerization and Thematic Maps

The system originally adopted for the computer storage and reproduction of the maps was to subdivide the 1 to 1,000,000 maps into 4-minute longitude by 5-minute latitude segments (approximately 3300 ha at the equator), and then to assign a land-system code on the basis of that land system occupying the greatest proportionate area in any one segment. Once these codes were recorded, it was a straightforward exercise to reproduce maps at desired scales and projections and produce thematic or single-factor maps. Thematic maps were computer-produced by assigning a rating of any of the coded and recorded land-system features to the land-system codes. In the case of land systems with more than one land facet, unless otherwise stated', this feature represents a characteristic of the major land facet of the land system. The computerization of the land systems maps is discussed in greater detail in Chapter 3.

The Printed Land Systems Map

The printed Land Systems Map of the Central Lowlands of Tropical South America (Volume 2) is a composition based on, and reduced from, the original 1 to 1,000,000 sheets. It was produced to provide a geographical overview of the region, always within the precisional imitation of map reproduction at a scale of approximately 1:5,000,000. This map provides a guide to the location of individual land systems; it identifies the predominant land systems in any region of special interest; and it draws a picture of the major advantages and constraints for land use, particularly germplasm suitability or adaptability, for that region. The land systems have been assigned numbers for ease of reference. Apart from depicting land systems, the printed map synthesizes information on climate, topography, vegetation, and soils.

Codes used on the map are described as follows.

Physiography. The capital-letter code preceding the land system number identifies the land system as belonging to one of nine, readily appreciated, broad physiographic regions

Table 2-3. Four topographical classes delineated on the Land Systems Map.

Topography classification	Description	Shading code
Flat, poorly drained	Flat, poorly drained or seasonally flooded	small dots
< 8%	Almost flat, mainly well-drained with slopes less than 8%	unshaded
8-30%	Undulating to rolling; slopes 8-30%	large dots
> 30%	Hilly to steep; slopes greater than 30%	triangles

(Table 2-1). These regions are described in more detail in Chapter 4: they are only approximate separations to provide a very generalized picture of the major physiographic regions within the study area.

Climate. On the Land Systems Map, a small-letter code distinguishes climatic subregions (Table 2-2). The climatic subregions and the terminology used are defined in Chapter 3. The subdivision according to WSPE (wet-season potential evapotranspiration) provides a novel climatic separation; it is an approximate accounting of the amount of energy mature vegetation growing on well-drained soils can use annually, assuming that little or no growth takes place during the dry season. The number of wet months adds to the definition of the climatic subregions, and the temperature criterion separates lowland from higher land and/or higher latitude regions.

Topography. Four broad topographical classes identify the topography of the principal land facets of the land systems by the use of shading codes (Table 2-3).

Vegetation. The natural physiognomic vegetation classes occurring on the principal land systems' "facets" are identified through color codes. These include the following classifications, which are defined in Chapter 4:

1. Well-drained, isohyperthermic savannas
2. Well-drained, isothermic savannas
3. Poorly drained savannas
4. Tropical rain forests
5. Tropical semi-evergreen seasonal forests
6. Tropical (semi-)deciduous seasonal forests
7. Caatinga
8. Gallery forests, associations with palms and other vegetation complexes of poorly drained lands
9. Submontane, subtropical forests.

Soils–the soil classification legend. *A Legend to the Land Systems Map*, for classifying the soils of the land facets of each land system, is also enclosed in Volume 2 of this book. The coding key used is illustrated in Figure 2-4. This is explained in more detail in Volume 2.

Soils were classified to the Great Group category of Soil Taxonomy (Soil Survey Staff, 1975), according to the FAO-UNESCO Soil Map of the World Legend (1974), and by their textures and fertility constraints as rated in the Fertility Capability Classification (FCC) system of Buol et al. (1975).

Great Group soil classes, according to Soil Taxonomy (Soil Survey Staff, 1975) are identified by a series of five-letter codes for the principal land facets of the land systems. The

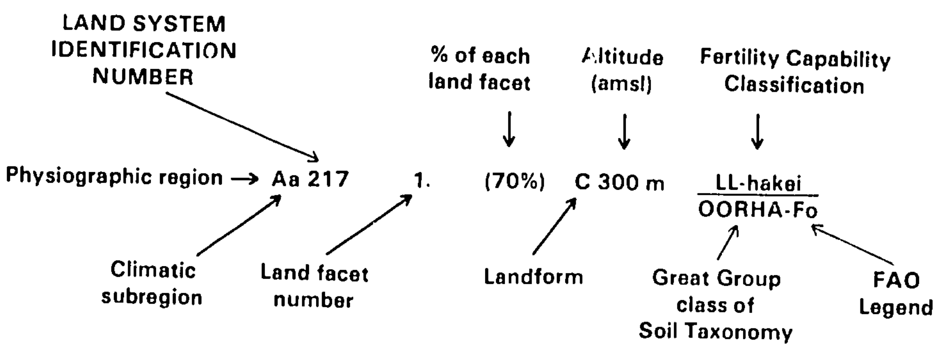


Fig. 2-4 Soil classification legend for the Land Systems Map, including descriptions of the land facets of the land systems.

Table 2-4. Coding used to identify soil Orders, Suborders, and Great Groups according to Soil Taxonomy (Soil Survey Staff, 1975), on the Land Systems Map.

Order		Suborder		Great Group	
Name	Code	Name	Code	Name	Code
Alfisols	A	Aqualfs	AQ	Natraqualfs	NA
				Tropaqualfs	TR
		Udalfs	UD	Hapludalfs	HA
				Rhodudalfs	RH
				Tropudalfs	TR
		Ustalfs	US	Paleustalfs	PA
				Haplustalfs	HA
				Natrustalfs	NA
				Rhodustalfs	RH
				Tropustalfs	TR
		Xeralfs	XE	Haploxeralfs	HA
Aridisols	D	Orthids	OR	Cambrothids	CM
Entisols	E	Aquents	AQ	Fluvaquents	FL
				Haplaquents	HA
				Hydraquents	HY
				Psammaquents	PS
				Tropaquents	TR
		Fluvents	FL	Tropofluvents	TR
				Ustifluvents	US
				Xerofluverts	XE
		Orthents	OR	Troporthents	TR
				Ustorthents	US
		Psamments	PS	Quartzipsamments	QU
				Tropopsamments	TR
				Ustipsamments	US
Inceptisols	I	Andepts	AN	Dystrandepts	DY
				Hydrandepts	HY
		Aquepts	AQ	Haplaquepts	HA
				Humaquepts	HU
				Plinthaquepts	PL
				Sulfaquepts	SU
				Tropaquepts	TR
		Tropepts	TR	Dystropepts	DY
				Eutropepts	EU
				Ustropepts	US
Mollisols	M	Aquolls	AQ	Haplaquolls	HA
		Udolls	UD	Argiudolls	AR
			US	Haplustolls	HA
Oxisols	O	Aquox	AQ	Plinthaquox	PL
		Orthox	OR	Acrorthox	AC
				Eutrorthox	EU
				Haplorthox	HA
				Umbriorthox	UM
		Ustox	US	Acrustox	AC
				Eutrustox	EU
				Haplustox	HA
Spodosols	S	Aquods	AQ	Tropaquods	TR
Ultisols	U	Aquults	AQ	Albaquults	AL
				Paleaquults	PA
				Plinthaquults	PL
				Tropaquults	TR
				Hapludults	HA
		Udults	UD	Paleudults	PA
				Plinthudults	PL
				Rhodudults	RH
				Tropudults	TR
		Ustults	US	Haplustults	HA
				Paleustults	PA
				Rhodustults	RH
Vertisols	V	Uderts	UD	Chromuderts	CH

Table 2-5. Coding used to identify soils according to the FAO-Unesco Soil Legend (1974) on the Land Systems Map.

Soil Legend name	Code	Soil Legend name	Code
Chromic Vertisols	Vc	Dystric Planosols	Wd
Lithosols	I	Gleyic Solonetz	Sg
Thionic Fluvisols	Jt	Orthic Solonetz	So
Calcaric Fluvisols	Jc	Luvic Phaeozems	Hl
Dystric Fluvisols	Jd	Haplic Phaeozems	Hh
Eutric Fluvisols	Je	Luvic Xerosols	Xl
Gleyic Solonchaks	Zg	Haplic Yermosols	Yh
Plinthic Gleysols	Gp	Dystric Nitosols	Nd
Mollic Gleysols	Gm	Plinthic Acrisols	Ap
Humic Gleysols	Gh	Gleyic Acrisols	Ag
Dystric Gleysols	Gd	Orthic Acrisols	Ao
Eutric Gleysols	Ge	Ferric Acrisols	Af
Humic Andosols	Th	Gleyic Luvisols	Lg
Albic Arenosols	Qa	Ferric Luvisols	Lf
Ferralic Arenosols	Qf	Chromic Luvisols	Lc
Dystric Regosols	Rd	Orthic Luvisols	Lo
Eutric Regosols	Re	Calcic Cambisols	Bk
Gleyic Podzols	Pg	Ferralic Cambisols	Bf
Plinthic Ferralsols	Fp	Dystric Cambisols	Bd
Humic Ferralsols	Fh	Eutric Cambisols	Be
Acric Ferralsols	Fa		
Rhodic Ferralsols	Fr		
Xanthic Ferralsols	Fx		
Orthic Ferralsols	Fo		

Table 2-6. Summary of the Fertility Capability Classification (Buol et al., 1975) codes used on the Land Systems Map.

Soil texture[a]		Soil fertility constraints[b]	
Code	Description	Code	Description
S	sandy	g	gleyey
L	loamy	d	dry
C	clayey	e	low ECEC
O	organic	a	Al toxicity
R	rocky	h	acidity
		i	P fixation
		x	X-ray amorphous
		v	vertic, Vertisol
		k	K deficient
		b	basic reaction
		s	salinity
		n	natric
		c	cat clay

a. Classified by the first two capital letters, which refer to the topsoil and subsoil respectively.

b. Or "condition modifiers", given as small letters following the capital letters.

first letter of the code identifies the Order; adding the second two letters gives the Suborder; and adding the last two letters gives the Great Group. For example, OUSAC refers to the Order, Oxisol (OUSAC); the Suborder, Ustox (OUSAC); and finally the Great Group, Acrustox (OUSAC). Table 2-4 summarizes the coding used to identify the soil Orders, Suborders, and Great Groups found in the region.

The coding used to identify soils from the Soil Legend was the same as that used by FAO-Unesco. Table 2-5 lists the soils identified in the region and their codes.

Table 2-6 summarizes the codes used to identify soils according to the Fertility Capability Classification (FFC). Some of the definitions used in this work to define fertility constraints or, to use FCC terminology, "condition modifiers," differ from those used by Buol et al. (1975). These include the definitions of Al toxicity, acidity, and K deficiency; however, the variation in definitions is relatively minor. The FCC coding and definitions are detailed in Chapters 5 and 6.

Apart from land-resource information, the Land Systems Map contains geographical information to identify the approximate location of major rivers, cities, and towns.

Synthesis

The Land Systems Map was prepared to provide a geographic reference base of the land systems and a pictorial representation of their main features in terms of climate, landscape (including natural vegetation), and soils. It is hoped that the innate complexity of agricultural land resources is thus emphasized, because these factors do vary from area to area. Fortunately, in our technologically advancing age, the detailed description and comparison of the many properties of the land systems and their facets can be handled by coding and computerization. In this study, the printed map can best be read and appreciated in the light of the computerized data base, summarized in the form of computer printouts in Part 1 of Volume 3, *Computer Summary and Soil Profile Descriptions of the Land Systems*, the computerized land resource summaries of the land systems, and Part 2, a selection of the meteorological data sets, also in Volume 3.

Chapter 3.
CLIMATE

by
P. G. Jones[a] and T. T. Cochrane

The region denoted in the Land Systems Map extends from a little north of the Tropic of Capricorn to the approximate position of the "meteorological equator" at 10 N. It thus encompasses two distinct climatic regimes—the equatorial (with little change in seasons) and the tropical (with stronger variations). The term "tropical" in this case refers to the areas found both north and south of the central equatorial regions and is preferred for preciseness over the loose term, the "tropics," which is generally used to refer to both regimes.

This chapter briefly describes the major factors determining the climate of these regions; presents a general analysis in terms of some of the better known climatic classifications; and then proceeds to a more detailed description of the estimation of growing-potential as used in the Land Systems Map.

Major Climatic Determinants

The major climatic determinants of both the equatorial and tropical regimes are the South Atlantic anticyclone and the equatorial trough since the Andes effectively isolate the region from strong effects of the Pacific anticyclone. As do Snow (1976) and Riehl (1979), we prefer the term "equatorial trough" to Intertropical Convergence Zone (ITCZ), because, while the low-pressure trough may be readily distinguished, the actual zone, or zones, of convergence are ephemeral and the position may only be fixed by averaging over time. Thus, the ITCZ may be considered an active part of the equatorial trough.

The Equatorial Trough

The position of the equatorial trough follows the seasonal march of the sun, but lags behind by about 2 months. The range of movement from north to south is very limited, when compared with other conti- situations. The equatorial trough is centered at 5 to 10 N during its most northerly advance in August/September and at 0 to 5°S in February/March (Figure 3-1). During the southern summer, a continental heat low develops over northern Argentina, Paraguay, and Bolivia. Frére et al. (1975) point out that some authors attribute this low to an extension of the equatorial trough, whereas others maintain that it is a separate phenomenon. In either case, the result is the same: an extended area of high instability and heavy rain in the western portion of the study area during the southern summer.

Polar Air Masses

Invasions of the cold polar air mass are common during the southern winter and can produce marked and rapid drops in temperature as the cold front passes northward. The air mass tends to be channeled between the Andean highlands and the central Brazilian shield, frequently reaching the upper Amazon and occasionally spilling over the Orinoco basin into the Caribbean. The cool change, known in Brazil as *friagem* and in Bolivia as *surazo*, may last for 3 to 5 days or, in exceptional cases, up to 15 days. The northerly extent of a typical cold front is shown in Figure 3-1 (Ratisbona, 1976).

Rainfall Patterns

Rainfall patterns follow the movement of the equatorial trough and the development of the continental heat low. They are further modified by interaction with the maritime air masses. Thus, the western equatorial zone has no distinct dry season, but a bimodality may be discerned in the rainfall figures. As one proceeds eastward in the equatorial zone, the dry season becomes more marked and the bimodality less so. The bimodality remains in the southeastern section of the equatorial zone as the *veranico*, a short dry spell that may occur in the middle of the wet summer.

On either side of the equatorial zone, typical tropical patterns of summer rainfalls and dry winter periods are noticed. Rain in the southeastern portion of the study area (Mato Grosso and Goias) appears to be due to winds from the upper Amazon. In this, the upper Amazon behaves more like a maritime zone than a continental one. Indeed, as is pointed out by Ratisbona (1976), the potential evaporation of the equatorial forest, greater than 1300 mm/year throughout the region, is actually higher than that from an ocean surface, due to its lower albedo (percentage reflection of radiation). The drylands of northeast Brazil (including the Caatingas) are the result of insufficient penetration of either the maritime or the moist upper Amazon (equatorial continental) air masses to this intermediate region.

Climatic Classifications

Köppen Classification

Many schemes have been devised to classify the climates of the world, but perhaps the most widely known is that of

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[a] Meteorologist, CIAT.

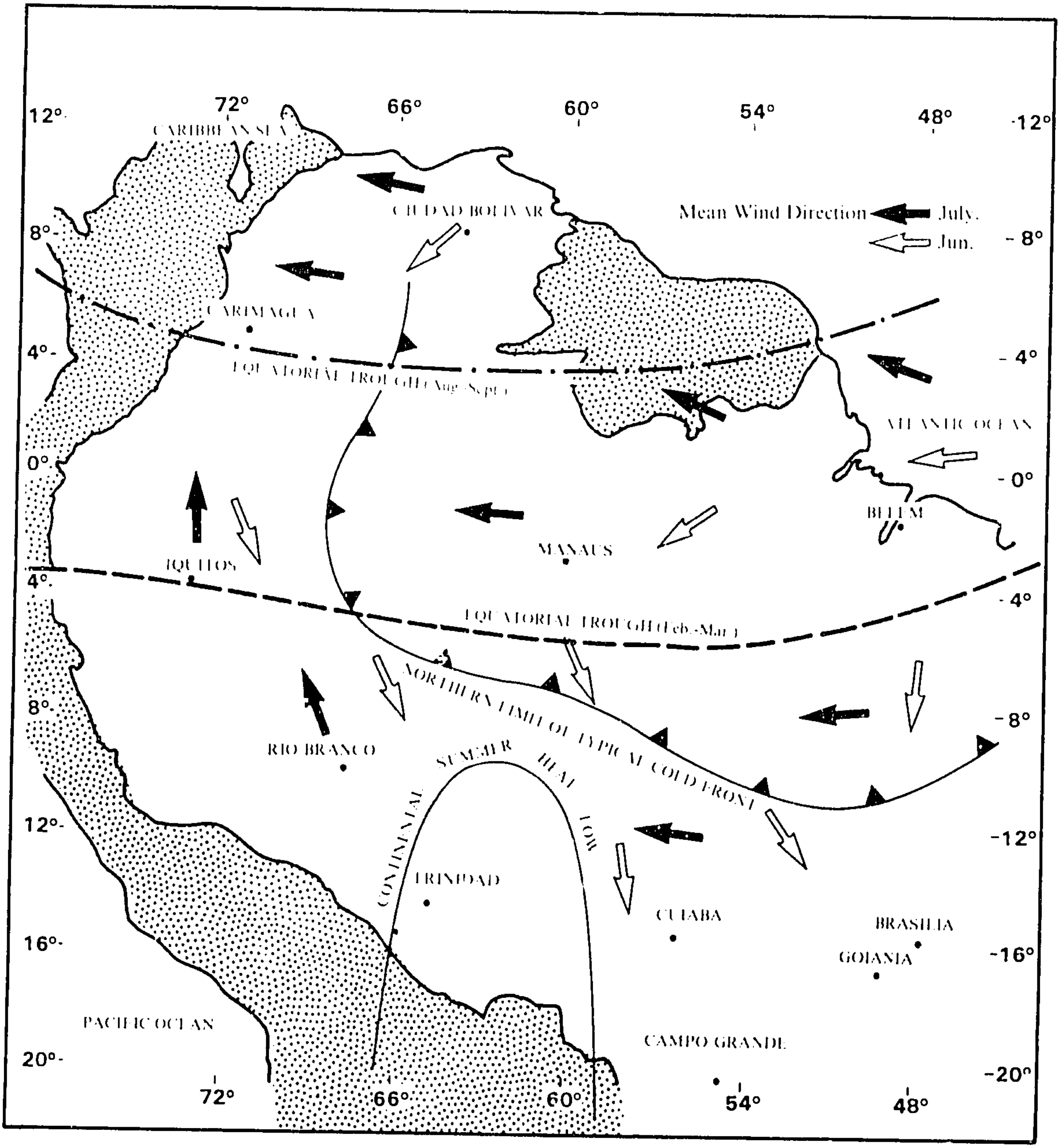
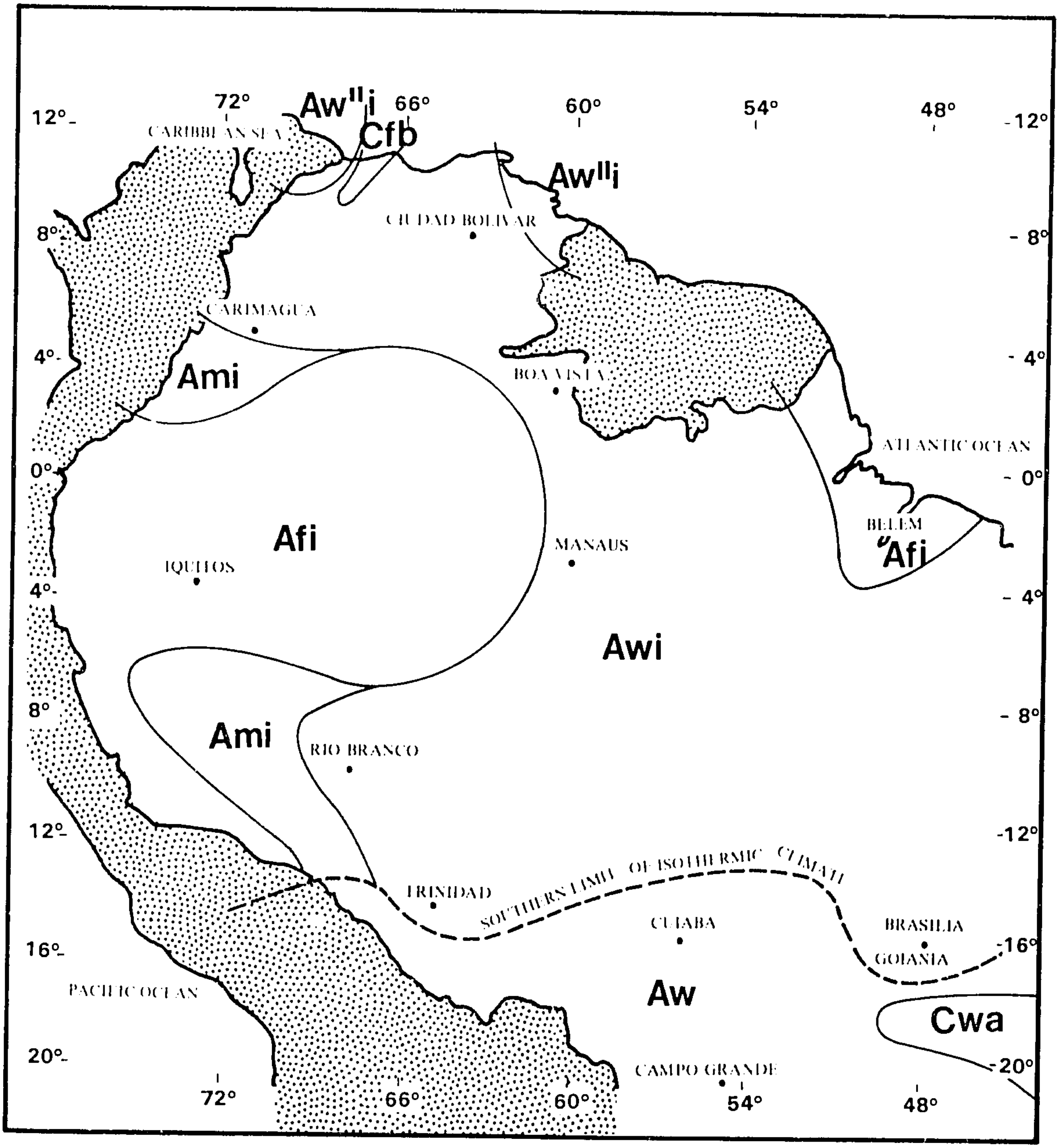


Fig. 3-1 Major determinants of climate througnout the study area, showing mean wind direction and position of the equatorial trough.

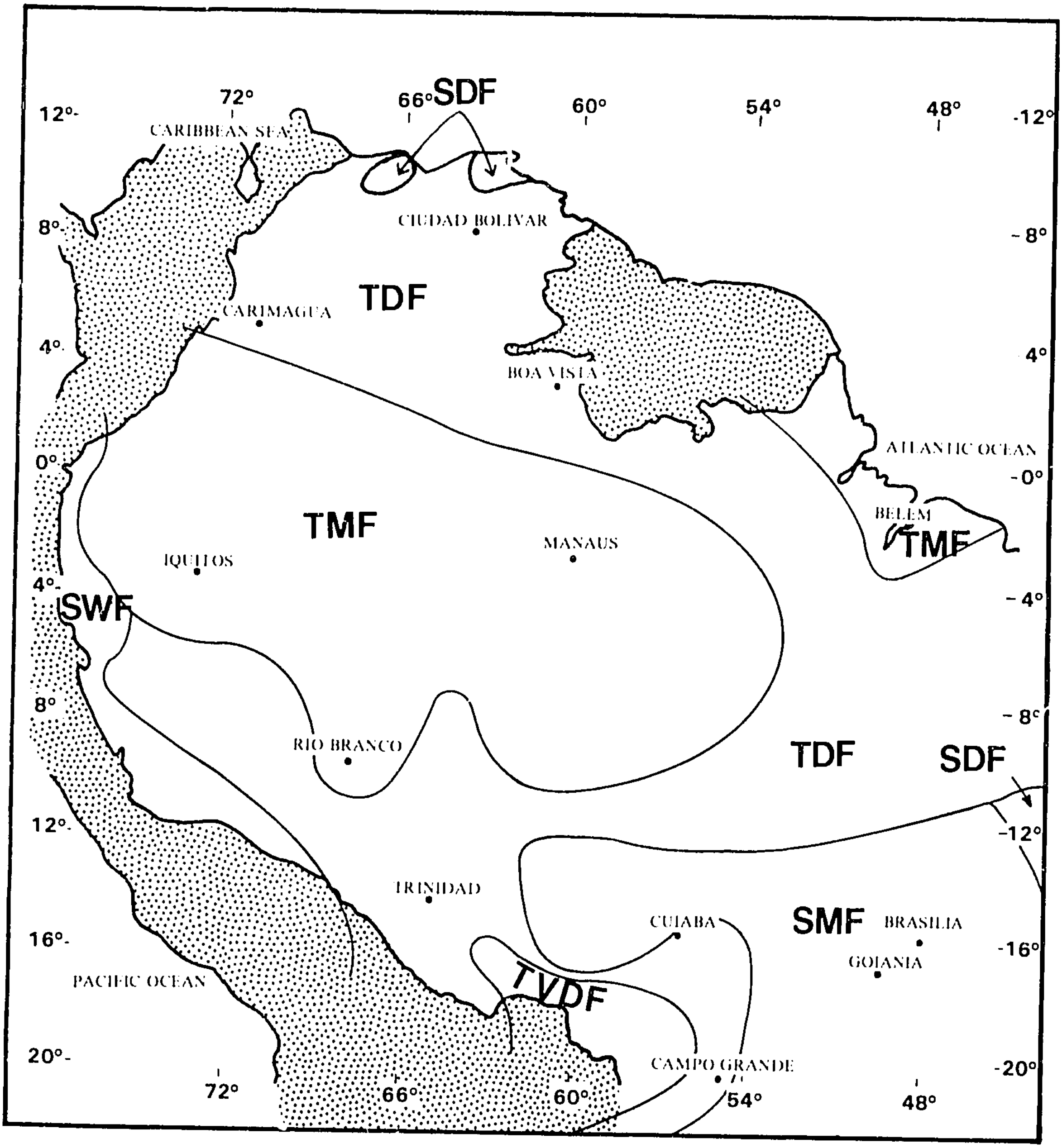


A. = tropical: no month with mean temperature less than 18°C
C. = temperature: some months less than 18°C

f. = rainfall all year round
m. = monsoonal rainfall
w = predominantly winter rainfall

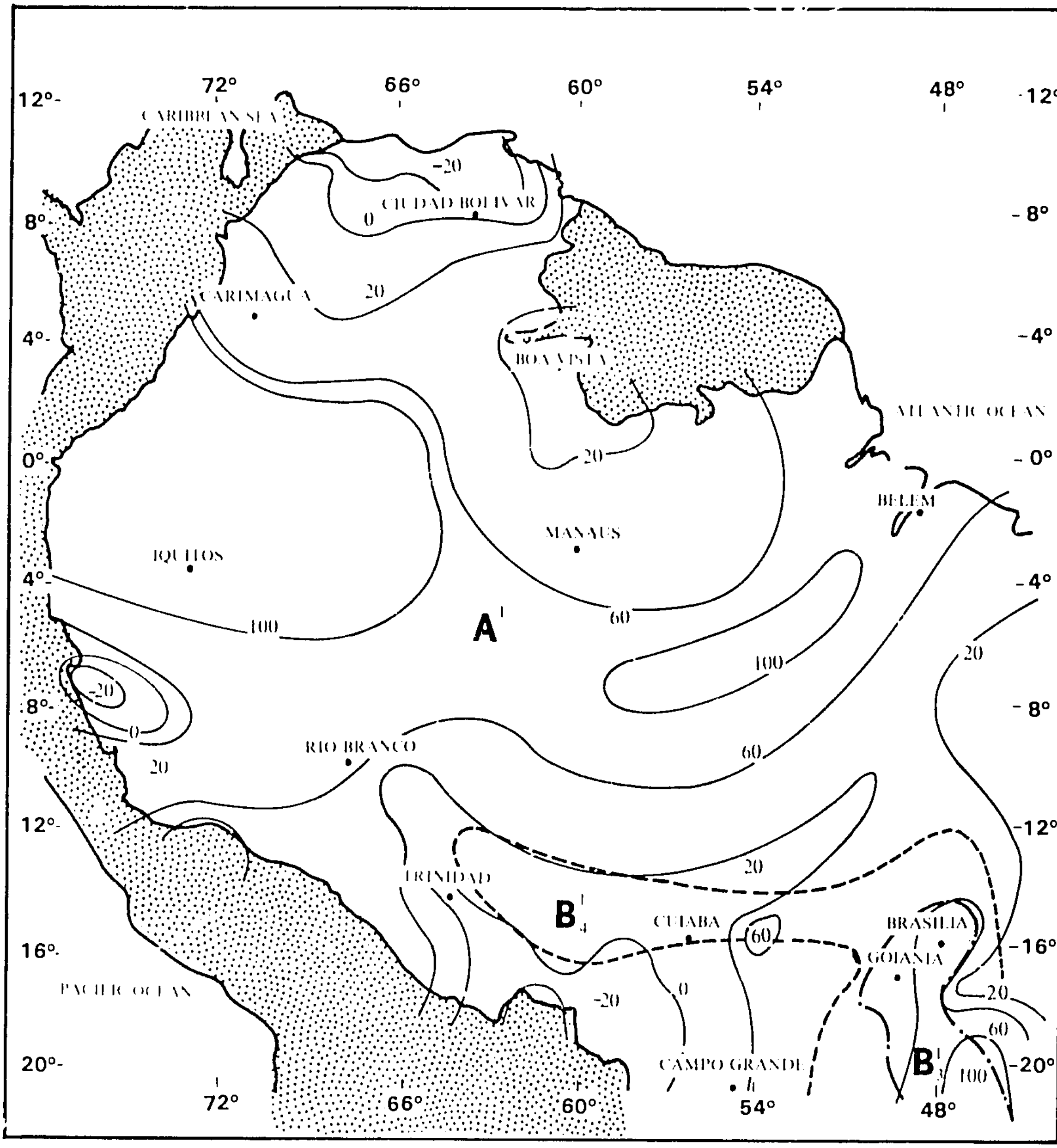
w'' = bimodal rainfall

Fig. 3-2 Köppen climatic classification of the study area.



TMF = Tropical Moist Forest
TDF = Tropical Dry Forest
TVDF = Tropical Very Dry Forest
SWF = Subtropical Wet Forest
SMF = Subtropical Moist Forest
SDF = Subtropical Dry Forest

Fig. 3-3 Holdridge life zone classification of the study area.



A¹ = Megathermal: thermal efficiency > 1150 mm

B¹₄ = Mesothermal: thermal efficiency 1000–1150 mm - - -

B¹₃ = Mesothermal: thermal efficiency 860–1000 mm -.-.-.-

Fig. 3-4 Thornthwaite moisture index isolines and thermal provinces in the study area.

Köppen (see Stringer, 1972). Figure 3-2 classifies the area in the Land Systems Map according to this system. This classification is based on rainfall and temperature regimes and separates the region into two areas: north and south. The separation lies at about 15°S—the line between the northern isothermic climate types (less than 5°C difference between the warmest and coolest months) and the southern climate types with cooler winters (more than 5° difference). The upper Amazon is differentiated as **Af**, that is, as having no dry season. It is flanked by smaller zones of **Am** where the dry season is short enough so that no serious moisture deficit is encountered. The rest of the area has one marked dry season, or in restricted zones of Venezuela, two dry seasons (denoted w"). Only very small high-altitude areas in Venezuela and Brazil are differentiated by their lower temperatures from the general tropical classification. It is obvious from the figure that this system does not sufficiently delineate the area on the Land Systems Map.

Holdridge Life Zones

The Holdridge (1967) life zone classification (Figure 3-3) is a simplistic scheme, taking into account only the total annual precipitation and the mean annual biotemperature, which, at all points within the Land Systems Map area, is equal to the annual mean temperature. It is clear from Figure 3-3 that the life-zone classification fails to differentiate climates by seasonal variation, and, due to difficulties of nomenclature, fails to account for the tropical rain forest in the upper Amazon.

Thornthwaite Classification

A system much more closely related to the agricultural potential of a region is that of Thornthwaite (1948) (Figure 3-4). Climate is defined in terms of a moisture index (I_m) and thermal efficiency (T/E), which is equal to the potential evapotranspiration (e). Seasonal variations in water supply and temperature (not shown on Figure 3-4) are also used as classifying factors. Thus,

$$I_m = 1/e\,(100s - 60d)$$

where e is the potential evapotranspiration, s is the water surplus, and d is the deficit after allowing for rainfall and stored soil water. And,

$$e = 1.6(10\,t/I)^a$$

where t is monthly temperature (°C), I is the heat index, a is a cubic function of the heat index, and e is the evapotranspiration in cm per month. The sum

$$I = \sum_{j=1}^{12} (t_j/5)^{1.514}$$

defines the heat index (I), where t is the mean temperature of month j.

The Thornthwaite method suffers from the fact that evapotranspiration is estimated from temperature data and is not necessarily universally reliable, but it does allow an estimate in many situations where more accurate formulas cannot be applied. Using this system, the majority of the region in the Land Systems Map is classified as megathermal (thermal index > 1150 mm), with only the highlands of the Brazilian shield falling into the mesothermal (< 1150 mm) class. The moisture index was calculated assuming a 150 mm soil water-holding capacity. The perhumid region, with a moisture index above 100, quite closely follows the actual extent of the tropical rain forest in the upper Amazon. Due to lower evapotranspiration rates in the rather cooler region to the south of the Amazon and east of Manaus, however, there appears to be a second perhumid region, which does not correlate with rain forest. Because no attempt was made to follow topography in the sketch map, the extent and shape of this area are not necessarily realistic depictions. The subhumid areas in Venezuela, the Peruvian foothills, the area around Boa Vista in northern Brazil, and the Brazilian shield are well delineated using this method, however.

Land-Systems Approach to Climate

From the above examples, it can be seen that it is possible to classify the climates of the area in several ways, all similar in some respects and yet different in others. Each of these systems fails, in some way or other, to account for observed patterns of vegetation and/or agricultural potential of the area. For the Land Systems Map, then, it was decided to concentrate on recording characteristics of the environment that would best reflect the range of variation in growing-season potential within the region. This is intended as a description of the region; it is not intended as an alternative climatic classification for general use.

Throughout the tropics, the major determinant of growing season is soil moisture. Normally, long-term mean rainfall is used to determine moisture availability, but this does not take seasonal variation in rainfall into account. The expected seasonal variation within the area on the Land Systems Map ranges from a 10–15% average departure from normal in the Amazon basin and northern regions of the area to a 25–30% departure in the drier eastern Brazilian regions (Biel, quoted by Riehl, 1979). Clearly an estimate of water supply must take this range into account. Therefore, an estimate of dependable precipitation and the best available estimate of potential evapotranspiration were chosen as the starting point for climatic determination for the Land Systems Map.

Meteorological Data Collection and Compilation

Long-term (more than 20-years) data records from over 1100 meteorological stations (Figure 3-5) were initially gathered, and meteorological data sets were compiled as an integral part of the land-resource data base.[b]

Table 3-1, prepared from the computer printout of the climatic data for Luziania (Hancock et al., 1979), located in

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b. This work was carried out as a subcontract to the survey by Hancock, et al. (1979) of Utah State University; it has since been assimilated into CIAT's South American Meteorological Data (SAMMDATA) computer files.

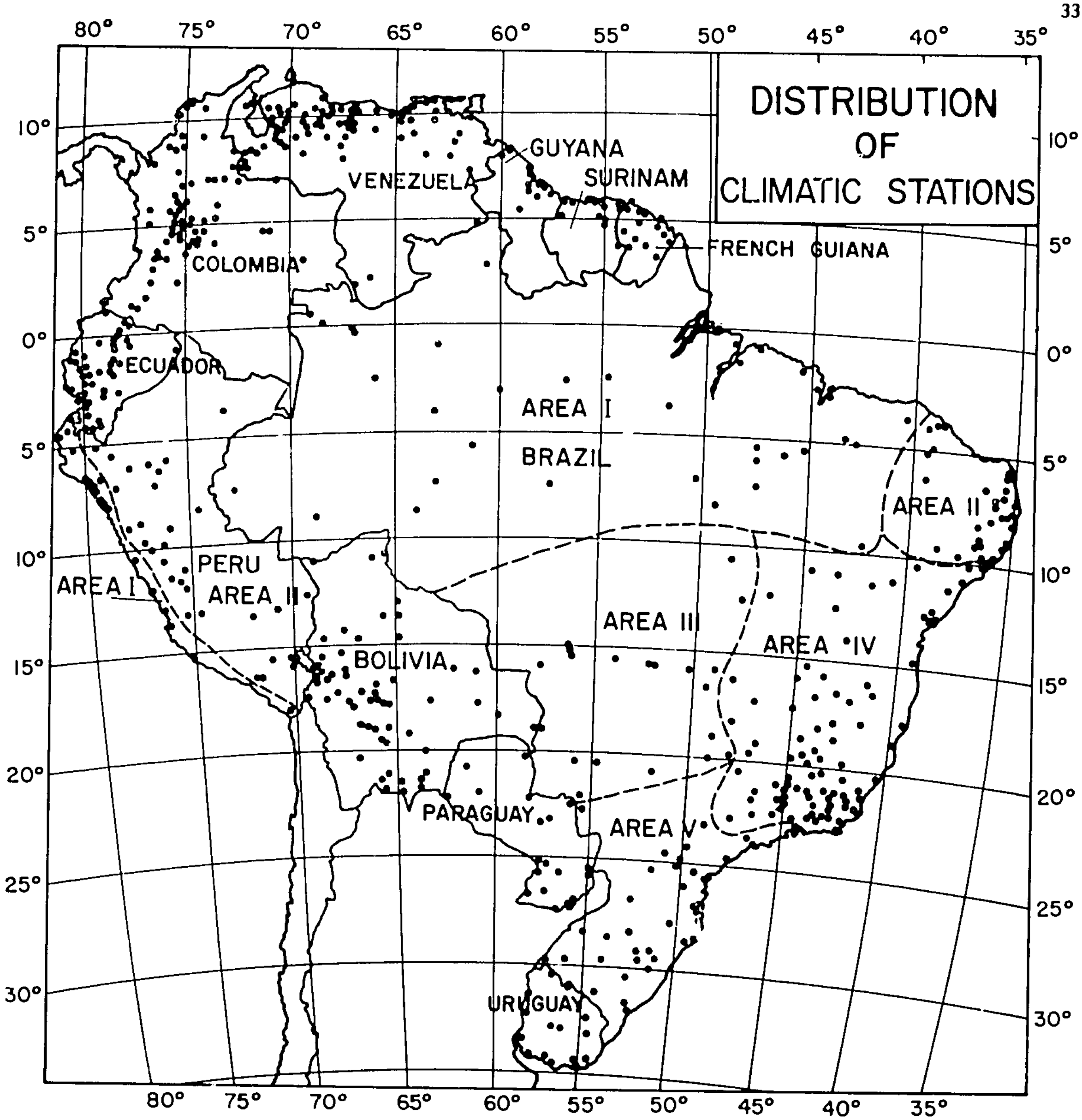


Fig. 3-5 Distribution of meteorological stations (●) and regions for dependable precipitation calculations (country and area boundaries). (Source: Hancock et al., 1979)

Table 3-1. A meteorological data set of Luziania, Central Brazil (16°15'S latitude, 47°56'W longitude, 958 amsl).

Parameter[a]	Jan	Feb	Mar	Apr	May[b]	Jun[b]	Jul[b]
MEAN TEMP (°C)	21.9	22.0	21.7	21.1	19.4	18.3	18.1
MEAN RAD (Langleys/day)	574.	523.	481.	495.	452.	440.	461.
PRECIP (mm)	228.	201.	229.	96.	16.	7.	4.
POT ET (mm)	164.	135.	136.	134.	120.	110.	118.
DEF PREC[c] (mm)	-65.	-66.	-93.	38.	104.	103.	[illegible]
DEP PREC[d] (mm)	141.	123.	142.	53.	0.	0.	0.
MAI[e]	0.86	0.91	1.04	0.40	0.00	0.00	0.00

	Aug[b]	Sep[b]	Oct	Nov	Dec	Annual
MEAN TEMP (°C)	20.0	22.1	22.3	21.9	21.6	20.9
MEAN RAD	512.	526.	529.	527.	475.	500.
PRECIP (mm)	5.	27.	130.	215.	317.	1475.
POT ET (mm)	139.	146.	152.	145.	134.	1632.
DEP PREC[c] (mm)	133.	119.	22.	-70.	-183.	157.
DEF PREC[d] (mm)	0.	7.	76.	132.	200.	
MAI[e]		0.00	0.05	0.50	0.91	1.49

a. In order, refer to mean temperature, mean radiation, precipitation, potential evapotranspiration, precipitation deficit, dependable precipitation, moisture availability index.
b. May to September = dry season.
c. DEF PREC = PRECIP - POT ET.
d. DEP PREC = 75% probability level of precipitation occurrence.
e. MAI = DEP PREC ÷ POT ET.

the savannas of central Brazil, illustrates the meteorological summaries used for drawing the Land Systems Map. The data recorded and calculated are:

MEAN TEMP	—Mean temperature, in degrees Celsius.
PCT SUN	—Percentage of possible sunshine.
MEAN RAD.	—Mean solar radiation, in Langleys per day.
PRECIP.	—Mean precipitation, in millimeters.
POT ET	—Potential evapotranspiration, in millimeters.
DEF PREC	—Precipitation deficit, in millimeters.
DEP PREC	—Dependable precipitation, in millimeters.
MAI	—Moisture availability index.

For some stations, the relative humidity was also estimated and appears on the printout as MEAN R.H.; for others, mean maximum and minimum temperatures are also recorded.

Mean Temperature

When temperature data (MEAN TEMP) were not available for a station, an estimate was made based on data from stations closely related geographically and by taking into account the relationship between elevation and temperature. Temperature decreases by an amount of about 0.0055 times the elevation in meters, or 5.5°C for every 1000 meters of increase in elevation.

Mean Solar Radiation

When solar radiation data (MEAN RAD.) were not available for a station, estimates were made from solar radiation maps developed by Loft et al. (1966), or were computed from a multiple-regression equation using such values as longitude, latitude, and precipitation. The solar radiation (*RS*), in Langleys per day, was converted to equivalent millimeters of evaporation per month (*RSM*) by correcting for the number of days in the month (*DM*) and the latent heat of vaporization of water (*L*) as:

$$RSM = DM \times RS/L.$$

The average *L* value for a month was calculated from the mean monthly air temperature in degrees celsius (*TMC*) by the equation:

$$L = 595.9 - 0.55 \times TMC$$

Potential Evapotranspiration

Potential evapotranspiration (POT ET) was calculated to determine the water balance and growing seasons. It is usually referred to as the water consumption of an extended surface of 8- to 15-cm tall, green grass cover that is actively growing and completely shading soil well supplied with water. However, Monteith (1973) notes that "experience on experimental sites ranging from field plots to large catchments has shown that the restriction to short green cover is unnecessary." An accurate estimate of POT ET is a most useful climatic parameter in helping to judge the agricultural potential of an area, especially in comparing similarities and differences in climatic regimes and predicting irrigation and drainage needs.

From physical considerations, it is well recognized that air temperature, radiation balance, humidity, and wind speed are all necessary factors in estimating evaporation from a surface (Penman, 1963). Many workers have shown that empirical relationships using only temperature are inadequate, but that

Table 3-2. Regression coefficients for determining dependable precipitation, by location.

Region/Country	Area	A value	B value
Central America		-23.0	0.84
South America			
Brazil	I	-20.0	0.85
	II	- 9.0	0.57
	III	-23.0	0.79
	IV	-11.0	0.67
	V	-11.0	0.67
Bolivia		-10.0	0.69
Colombia		-25.0	0.84
Ecuador		- 5.0	0.64
French Guiana		-25.0	0.84
Guyana		-14.0	0.77
Paraguay		-10.0	0.69
Peru	I	- 1.0	0.18
	II	- 5.0	0.70
Surinam		-14.0	0.77
Uruguay		-10.0	0.69
Venezuela		-14.0	0.77
Caribbean Islands		-23.0	0.84

if radiation estimates are included, an acceptable estimate can be obtained for sites where complete information is lacking.

Hargreaves' (1977a) equation based on solar radiation and temperature was used to calculate POT ET; values of POT ET (Hargreaves' *ETP*) in millimeters per month are given by his equation:

$$ETP = 0.0075 \times RSM \times TMF$$

in which *RSM* is incident solar radiation, expressed as equivalent millimeters of evaporation per month, and *TMF* is the mean monthly temperature in degrees Fahrenheit. Hargreaves (1977b) has shown that his equation compares favorably with other equations that give acceptable estimates of POT ET.

Precipitation Deficit

The precipitation deficit (DEF PREC) is simply the difference between the mean precipitation (PRECIP) and the POT ET.

Dependable Precipitation

Dependable precipitation (DEP PREC), at the 75% probability of precipitation occurrence, is the amount of precipitation that will be equaled or exceeded in 3 out of 4 years. The probability distribution of monthly rainfall amounts is known to be skewed markedly toward the lower values. For this reason, some workers, for example Frére et al. (1975), have used a log normal distribution to estimate the dependability of rainfall. A better approximation is the gamma distribution; although it is rather more trouble to calculate, the gamma distribution can now be done readily with the aid of a high-speed computer. Hancock and his collegues at Utah State University have produced gamma-distribution estimates of dependable precipitation for many stations in the area shown in the Land Systems Map. However, in order to be able to fit the distribution, a large number of years of record must be available. Unfortunately, many stations in the area have an insufficient period of record. It was noticed (Hancock et al., 1979), however, that there is a strong linear relationship between the mean monthly rainfall and dependable precipitation if the sample is restricted to a climatically uniform area. It is thus possible within each subarea to estimate dependable precipitation (P_d) from mean rainfall (P_m) by a simple equation:

$$P_d = a + b\,P_m$$

The coefficients a and b were estimated by the Utah group from the existing gamma distributions. These estimates are shown, by region, in Table 3-2; the regions themselves are indicated in Figure 3-5.

The linear relationship was used to estimate dependable precipitation for all stations in the study area using as a base the mean rainfall data given in Wernstedt (1972).

Moisture Availability Index

The moisture availability index (MAI) is a moisture adequacy index at the 75% probability level of precipitation occurrence. It is defined as:

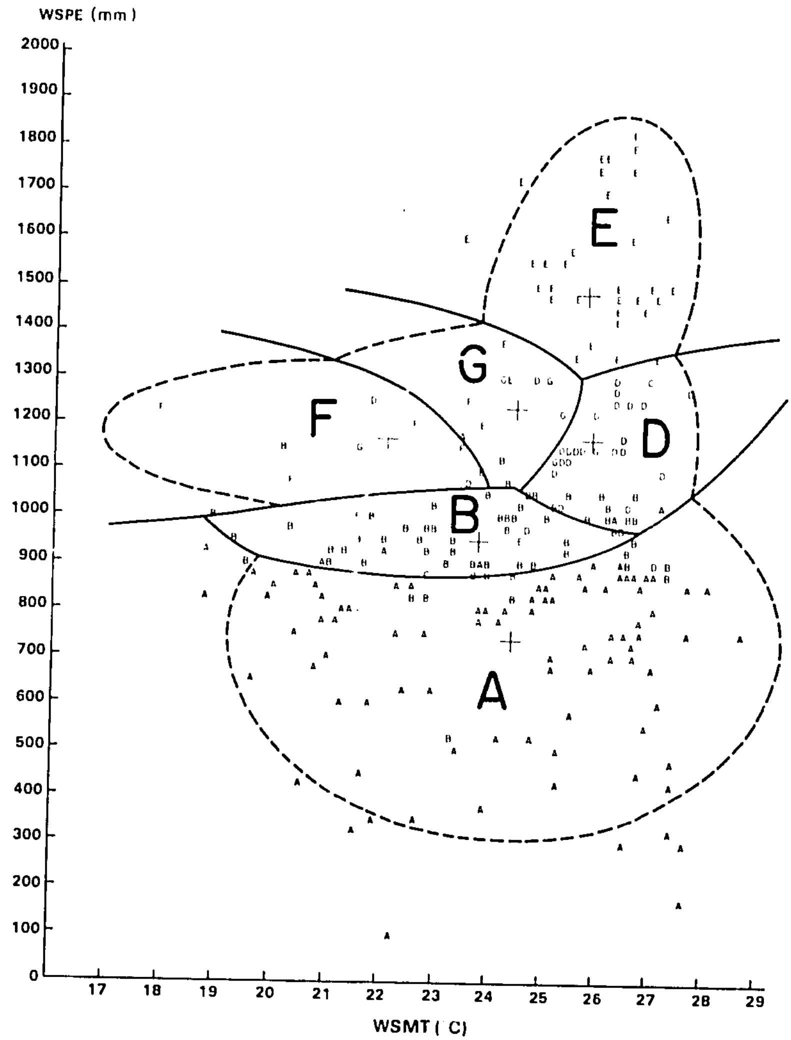
$$MAI = DEP\ PREC \div POT\ ET$$

An MAI value of 1.00 means that dependable precipitation equals potential evapotranspiration.

The MAI concept was introduced by Hargreaves in 1972 to develop a classification that includes soil-moisture adequacies. He proposed that MAI be adopted as a standard index for measuring water deficiencies and excesses and suggested the following classifications:

MAI value	Category
0.00 to 0.33	Very deficient
0.34 to 0.67	Moderately deficient
0.68 to 1.00	Somewhat deficient
1.01 to 1.33	Adequate
1.34 and above	Excessive

Hargreaves showed that there is a good relationship between MAI and crop production when soil moisture is adequate for



Cluster Code	Climatic subregión
A	Deciduous forest
B	Well-drained savanna
D	Tropical semi evergreen seasonal forest
E	Tropical rain forest
F	Subtropical semi-evergreen forest
G	Subtropical evergreen forest

Fig. 3-6 Cluster diagram of vegetation classes throughout tropical South America in terms of total wet-season potential evapotranspiration (WSPE) and wet-season mean monthly temperature (WSMT). (Source: Cochrane and Jones, 1981).

a week or more and recommended a level "less than 0.34" to define a dry month. A wet month, then, was defined as one with an MAI greater than 0.33, bearing in mind that this level may be too low for soils with very low moisture-holding capacities.

Moisture Availability Index and Soil Moisture

Interestingly, the MAI, if qualified by the corollary "when soil moisture is adequate for a week," would describe soil-moisture availability in terms of the climatic potential to both supply and extract soil moisture at a given location during a given period of time, as well as imply the ability of a soil to store and supply water. In this sense, the criterion would be more sensitive for a given soil during periods of high potential evapotranspiration than during periods with lower potential evapotranspiration; further, it would be more critical for soils with low moisture-holding capacities. Therefore, the need to take soil moisture-holding capacities into account in relation to the water balance at a given time of the year must be emphasized. Soil moisture-holding capacities are defined in Chapter 6.

Meteorological Data Sets

Part 2 of the *Computer Summary* (Volume 3) contains a range of meteorological data sets representative of those for the land systems in the Land Systems Map. These were originally compiled by Hargreaves and his coworkers for the land-systems study (Hancock et al., 1979). The CIAT SAMM-DATA (South America Meteorological Data) computer file currently includes over 4000 data sets from stations throughout tropical America, many of which were adapted from Hargreaves' data file. These stations are indexed by names and geographical coordinates to help delineate and describe land systems.

Climate and Physiognomic Vegetation Patterns

In spite of the large number of meteorological data sets, a problem arose for the Amazonian region and parts of Central Brazil in that the distances between meteorological stations with long-term data were often too great to enable acceptable extrapolations.

In an attempt to overcome the problem of extrapolating climatic patterns between meteorological stations separated by large distances, it was decided to investigate the dependency of the natural vegetation on climate (Cochrane and Jones, 1981).

Vegetation Classes

Physiognomic vegetation classes, as defined in Chapter 4, were used to describe the vegetation of the land facets of the land systems. Map 2 (see Map Plates) provides a picture of the major vegetation classes throughout the region. It was made by assigning the vegetation class of the major land facets to the land systems and by compiling computer printouts. The vegetation classes include poorly drained savannas, well-drained savannas, tropical rain forest, tropical semi-evergreen seasonal forest, tropical deciduous forest, caatinga, and others (including subtropical and submontane forests, swamp forests, and other vegetation classes). These are briefly described in Chapter 4. The term "well-drained savannas" covers those vegetation types referred to in Brazil as "Cerrados," described in detail by Eiten (1972). The definitions of forest types follow the descriptions by Eyre (1968).

Discriminant Analyses of Meteorological Data

A vegetation class was assigned to each of 251 meteorological data sets, from stations spaced as evenly as possible throughout the region, on the basis of the native vegetation growing on the well-drained soils in their vicinities. Sixty-one meteorological stations were located throughout the savannas, 38 in tropical semi-evergreen seasonal forests, 49 in tropical rain forests, 84 in deciduous forests, 8 in subtropical semi-evergreen forests, and 11 in subtropical evergreen forests. Many combinations of different climatic parameters from the data sets, including the number of wet months, wet-season mean monthly temperatures (WSMT), wet-season radiation, wet-season potential evapotranspiration (WSPE), and dry-season moisture availability (DSMA) (an index of the severity of the dry season, in contrast merely to its length), were then examined through discriminant analyses, both parametric and nonparametric, to see if they followed the vegetation classes.

Vegetation and Wet-Season Potential Evapotranspiration

Figure 3-6 summarizes the investigation of the dependency of the vegetation classes on WSPE (wet-season mean potential evapotranspiration) and WSMT (wet-season mean monthly temperatures). The observations were computer plotted in the WSPE × WSMT space, and clustering of the vegetation classes can readily be seen. To delineate the classes, the lines of equiprobability of assignment were manually plotted between the various populations, by graphically finding the intersects of successive confidence elipsoids.

The posterior probability of correct assignment for the vegetation classes was estimated as:

Computer cluster codes (from Figure 3-6)

A	Deciduous forest	.91
B	Well-drained savanna	.68
D	Tropical semi-evergreen seasonal forest	.71
E	Tropical rain forest	.87
F	Subtropical semi-evergreen forest	.67
G	Subtropical evergreen forest	.60

The poorly drained savannas (C) could not be included in this analysis because there were records from only two sites.

Using the nonparametric technique of nearest neighbor classification described by Cover and Hart (1967) as implemented by Barr et al. (1976), the data set was divided into two randomly selected halves and each subset used both as a calibration set and a test set. The two sets of results were then combined to form estimates of the probability of correct classification. These were A = .77; B = .73; D = .41; and E = .88. F and G contained no correct classifications due to the small sample size.

WSPE and Well-Drained Savannas

To check the possible variation of WSPE between well-drained savannas with different wet-season lengths, the 61 meteorological data sets from the stations located in the savannas were subdivided into three groups with 6, 7, and 8 months of wet season, respectively, and the total wet-season POT ET values and the wet-season average monthly POT ET values of the groups were compared. Table 3-3 shows that there is no significant difference between the total wet-season POT ET values for savannas having a 6-, 7-, or 8-month wet season ($P > .2$). On the other hand, it shows that the monthly average wet-season POT ET values are significantly different ($P < .001$). The monthly average wet-season POT ET values decrease with an increase in the length of the wet season.

It is clear that the WSPE throughout the well-drained savanna regions is virtually constant. In Figure 3-6, the group of well-drained savannas (cluster code B) falls in a compact band right across the center of the cluster diagram, indicating that they can be differentiated on WSPE alone. Indeed, the range of WSPE experienced is remarkably small in spite of considerable difference not only in wet-season length, but also in wet-season temperatures.

Climatic Potential for Growth of Vegetation

For any given month, providing that MAI is high enough to allow relatively unrestricted water availability, the actual evapotranspiration would closely follow the POT ET under the natural vegetation cover. Therefore, the WSPE approximates the annual consumptive water use of the vegetation. As such, the WSPE is a proxy estimate of the amount of annual energy the savanna vegetation can use for growth in the absence of irrigation. It follows, therefore, that the savannas occupy a well-defined habitat delimited by the climatic potential for growth; this potential is greater than that of deciduous forests but less than that of evergreen and semi-evergreen forests. Subtropical vegetation classes, although dependent on WSPE, appear to be further differentiated, as expected, by growing-season temperature. The group of deciduous forests (cluster code A) is a composite group. Caatingas, the thorn scrub of northeast Brazil, may be differentiated from this group using the dry-season moisture availability index (DSMA), as shown by Figure 3-7. The DMAI indicates the intensity of the dry season, as opposed merely to its length. It is the mean monthly moisture availability index of the dry-season months (those with an MAI < 0.34), corrected to run from zero to 1, where 1 = an average dry season monthly MAI of 0.33; thus "zero" is the most severe rating.

Further work needs to be carried out to examine the climate-vegetation interrelationships more thoroughly; nevertheless, the finding that WSPE regimes follow major vegetation classes provides for a better understanding of these interrelationships. In the context of tropical South America, with its rapidly expanding agricultural frontiers, where as often as not little or no recorded climatic data are available, it is evident that the natural vegetation growing on well-drained soils can be used as a guide to extrapolating climatic patterns.

Climatic Subregions

The WSPE regimes within the major vegetation zones were consequently used to help define climatic subregions (Map 3). Together with the length of the wet season and the WSMTs, they provide a convenient subdivision of the region into five main and two less-defined climatic subregions, summarized in Table 3-4. WSPE approximates the total annual energy available for plant growth, assuming that the soils hold sufficient moisture to enable nonstress growth for at least a week under the prevailing POT ET regimes. Further, only the natural rainfall at the 75% probability level is considered, without supplemental irrigation.

Table 3-3. Total wet-season potential evapotranspiration (POT ET) values and monthly average wet-season POT ET values, according to the number of wet season months of the well-drained savannas.

	Length of wet season		
	6 months	7 months	8 months
Meteorological data sets (no.)	13	39	9
Total wet-season POT ET[a]			
Mean (mm)	904.7	969.4	976.1
Variance	1696	2528	2115
S.D.	42.86	50.94	48.78
Monthly average wet season POT ET[b]			
Mean (mm)	150.8	138.3	122.1
Variance	47.13	49.77	33.05
S.D.	6.146	7.147	6.097

a. t-test probability of difference between means: 0.2 (not significant).
b. t-test probability of difference between means: 0.001 (very highly significant).

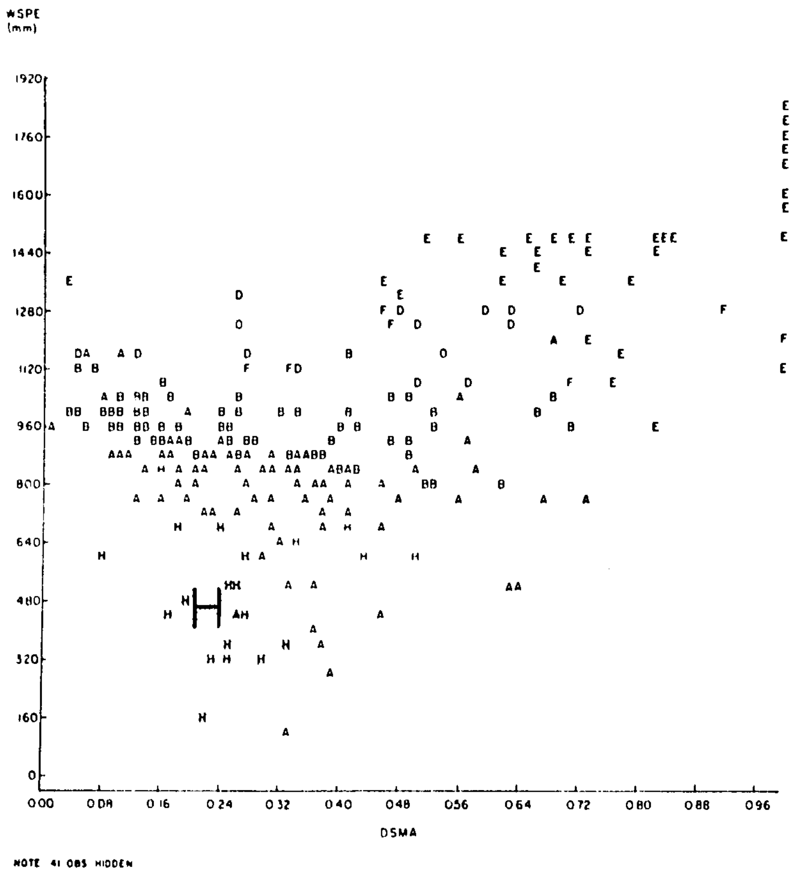


Fig. 3-7 Plot of total wet-season potential evapotranspiration (WSPE) by the dry season moisture availability index rating (DSMA).

Table 3-4. Climatic subregions of the central lowlands of tropical South America.

Climatic subregion code	Climate: WSPE[a] (mm)	Climate: Wet months[b] (no.)	Climate: WSMT[c] (°C)	Subregion name
a	> 1300	> 9	> 23.5	Tropical rain forest
b	1061-1300	8-9	> 23.5	Semi-evergreen seasonal forest
c	900-1060	6-8	> 23.5	Isohyperthermic savanna[d]
d	900-1060	6-8	< 23.5	Isothermic savanna[d]
e	< 900	< 6	> 23.5	(Semi-)deciduous forest
f	-	-		Subtropical vegetation[e]
o	-	-		Other[f]

a. WSPE: total wet-season potential evapotranspiration, the sum of the potential evapotranspiration of the wet months.
b. Wet months are months with a moisture availability index (MAI) > 0.33%.
c. WSMT: wet-season mean monthly temperature.
d. Terms not used in the strict sense in accordance with U.S. Soil Taxonomy (Soil Survey Staff, 1975).
e. Other vegetation on predominately poorly drained or seasonally flooded lands.
f. Nonclassified, or submontane or subtropical forests.

Table 3-5. Climatic data sets of sites located in each of the major climatic subregions of the central lowlands of tropical South America.

Parameter[a]	Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Climatic subregion a: Tropical rain forest Site: Cruz do Sul, AC, Brazil. Lat. 7 38'S, Long. 72 40'W, 170 masl													
MEAN TEMP	24.4	24.6	24.4	24.2	24.1	23.4	22.9	23.8	24.5	24.6	24.7	24.6	24.2
MEAN R.H.	92.	92.	92.	89.	80.	73.	74.	77.	89.	94.	87.	96.	86.
PCT SUN	30.	30.	31.	36.	50.	57.	56.	53.	36.	28.	40.	23.	39.
MEAN RAD	390.	391.	386.	384.	413.	418.	425.	451.	405.	372.	447.	339.	402.
PRECIP	246.	244.	269.	241.	138.	104.	47.	86.	147.	251.	216.	241.	2230.
POT ET	118.	108.	117.	112.	124.	120.	124.	135.	119.	113.	132.	103.	1426.
DEF PREC	-128.	-136.	-152.	-129.	-14.	16.	77.	49.	-28.	-138.	84.	-138.	-804.
DEP PREC	189.	187.	209.	185.	97.	68.	20.	53.	105.	193.	163.	185.	
MAI	1.60	1.74	1.78	1.65	0.78	0.57	0.16	0.40	0.88	1.71	1.24	1.79	
Climatic subregion b: Semi evergreen seasonal forest Site: Manaus, AM, Brazil. Lat 3 8'S, Long. 60 1'W, 48 masl													
MEAN TEMP	25.9	25.8	25.8	25.8	26.4	26.6	26.9	27.5	27.9	27.7	27.3	26.7	26.6
MEAN R.H.	88.	89.	89.	88.	81.	74.	71.	63.	67.	76.	78.	85.	79.
PCT SUN	38.	36.	37.	38.	48.	56.	59.	67.	63.	54.	51.	43.	49.
MEAN RAD	420.	415.	418.	404.	426.	441.	462.	525.	541.	509.	491.	443.	458.
PRECIP	276.	277.	301.	287.	193.	99.	61.	41.	62.	112.	165.	228.	2102.
POT ET	132.	118.	131.	123.	135.	136.	149.	172.	173.	167.	155.	142.	1732.
DEF PREC	144.	-160.	-170.	-164.	-58.	37.	88.	131.	111.	55.	-11.	-86.	-370.
DEP PREC	215.	215.	236.	224.	114.	64.	32.	15.	33.	75.	120.	174.	
MAI	1.62	1.83	1.80	1.82	1.06	0.47	0.22	0.09	0.19	0.45	0.78	1.22	
Climatic subregion c: Isohyperthermic savanna Site: Conceição do Araguaia, PA, Brazil. Lat. 8 15'S, Long. 49°12'W, 90 masl													
MEAN TEMP	25.1	24.9	25.2	25.6	25.6	25.1	24.9	26.0	26.7	25.8	25.6	25.2	25.5
MEAN R.H.	88.	89.	88.	79.	65.	48.	44.	54.	70.	83.	83.	89.	73.
PCT SUN	38.	37.	38.	50.	66.	79.	82.	74.	60.	46.	45.	36.	54.
MEAN RAD	437.	431.	428.	453.	470.	488.	510.	530.	521.	479.	477.	427.	471.
PRECIP	253.	252.	263.	163.	60.	8.	7.	15.	64.	163.	196.	227.	1671.
POT ET	135.	119.	132.	137.	147.	146.	156.	167.	162.	150.	144.	132.	1727.
DEF PREC	-118.	-133.	-131.	26.	87.	138.	149.	152.	98.	-13.	-51.	-95.	56.
DEP PREC	195.	194.	204.	119.	31.	0.	0.	0.	34.	119.	146.	173.	
MAI	1.45	1.63	1.54	0.87	0.21	0.00	0.00	0.00	0.21	0.79	1.01	1.31	
Climatic subregion d: Isothermic savanna Site: Luziania, GO, Brazil. Lat. 16°15'S, Long. 47 56'W, 958 masl													
MEAN TEMP	21.9	22.0	21.7	21.1	19.4	18.3	18.1	20.0	22.1	22.3	21.9	21.6	20.9
MEAN R.H.	72.	78.	79.	61.	52.	41.	38.	43.	63.	75.	79.	87.	64.
PCT SUN	59.	52.	51.	69.	76.	84.	87.	83.	67.	55.	50.	40.	64.
MEAN RAD	574.	523.	491.	495.	452.	440.	461.	512.	526.	529.	527.	475.	500.
PRECIP	228.	201.	229.	96.	16.	7.	4.	5.	27.	130.	215.	317.	1475.
POT ET	164.	135.	136.	134.	120.	110.	118.	139.	146.	152.	145.	134.	1632.
DEF PREC	-65.	-66.	-93.	38.	104.	103.	114.	133.	119.	22.	-70.	-183.	157.
DEP PREC	141.	123.	142.	53.	0.	0.	0.	0.	7.	76.	132.	200.	
MAI	0.86	0.91	1.04	0.40	0.00	0.00	0.00	0.00	0.05	0.59	0.91	1.41	
Climatic subregion e: (Semi-)deciduous seasonal forest Site: Ibipetuba, BA, Brazil. Lat. 11°1'S, Long. 44 31'W, 434 masl													
MEAN TEMP	24.6	24.6	24.6	24.5	23.4	21.9	21.5	22.3	24.9	26.3	25.5	24.8	24.1
MEAN R.H.	56.	65.	73.	56.	46.	44.	45.	38.	52.	59.	69.	74.	56.
PCT SUN	73.	65.	57.	73.	81.	83.	82.	87.	76.	71.	61.	56.	72.
MEAN RAD	621.	578.	520.	535.	503.	478.	489.	557.	579.	596.	568.	546.	547.
PRECIP	125.	145.	136.	73.	12.	1.	1.	1.	7.	53.	158.	198.	910.
POT ET	189.	159.	158.	157.	149.	132.	138.	160.	172.	189.	171.	167.	1942.
DEF PREC	64.	14.	23.	84.	137.	131.	137.	159.	165.	136.	13.	-31.	1032.
DEP PREC	72.	86.	80.	38.	0.	0.	0.	0.	0.	25.	94.	121.	
MAI	0.38	0.54	0.50	0.24	0.00	0.00	0.00	0.00	0.00	0.13	0.55	0.72	

a. MEAN TEMP: mean temperature (°C); MEAN R.H.: mean relative humidity (%); PCT SUN: percentage of possible sunshine (%); MEAN RAD: mean solar radiation; PRECIP: mean precipitation (mm); POT ET: potential evapotranspiration (mm); DEF PREC: precipitation deficit (mm); DEP PREC: dependable precipitation (mm); MAI: moisture availability index.

Approximately 27% of the region falls into the tropical rain forest subregion, (climatic code a) mainly in the western half of the Amazon basin. The semi-evergreen seasonal forests, (climatic code b) characterized by the narrow range of an 8- to 9-month wet season, occupy 38% of the area, most of it in Brazil east of Manaus. The isohyperthermic savannas (climatic code c), 16% of the region, are well-drained native grasslands surrounded by forest vegetation. They include parts of the Brazilian Cerrados, the northern and western Bolivian *pampas*, the eastern Llanos of Colombia, a large part of the central Llanos of Venezuela, and parts of the Rupununi plains and the Boa Vista and Amapa Cerrados of Amazonia. Climatic subregion d, the isothermic savannas, comprises mainly the central plateau areas of the Cerrados of Brazil; these differ from the Llanos in terms of a cooler temperature regime. They occupy 5% of the region. Climatic subregion e is comprised of areas covered with deciduous vegetation.

The characterization of climatic subregions does not take into account the differences between well-drained and poorly drained savannas. This fundamental difference between savannas has led to a lot of confusion in the past concerning the nature of savannas; poorly drained savannas are found in climatic subregions with 2 to 6 months of dry season, and a wide range of WSPEs, as the edaphic circumstance of waterlogging overrides the climatic effect. Table 3-5 shows a meteorological data set from a site in each of the climatic subregions.

Soil-Moisture Stress and the *Veranicos*

In considering the relationship between WSPE and vegetation, it has been noted that soil-moisture stress is described in terms of the climatic potential to supply and extract soil moisture at a given location during a given period of time, and the ability of well-drained, medium-textured soils to store and supply water. In soils that have less than the medium capacity to store plant-available water, such as sandy Spodosols and many Oxisols, vegetation can quickly suffer moisture stress. Such situations occur both in the Amazon basin and in the Brazilian Cerrados. In Amazonia, Alvim and Silva (1980) note that areas of *campinarana* vegetation (a type of low, open forest) are prevalent on sandy soils with very low moisture-holding capacities, surrounded by soils with higher moisture-holding capacities covered in semi-evergeen seasonal forests. (It may be noted that many of these *campinarana* areas also suffer from a wet-season hydromorphic condition.)

The *veranicos* are erratic, but often prolonged (10- to 20-day) periods with no rainfall commonly occurring during the "wet-season" months of January and February in the Cerrados (well-drained savannas) of Central Brazil. They are often cited as the cause of considerable yield reductions in shallow rooting annual crops.

Veranicos can usually be identified from the monthly meteorological data sets as comparative differences between the MAI values of the peak wet-season months of December to March. For example, a meteorological data set for Luziania (see Table 3-1) shows lower MAI values in January and February than in December or March; nevertheless, the actual monthly MAI values for all 4 months are well above the value 0.33 used to signify a dry month. This would suggest that the moisture-stress condition resulting in reduced crop yields is not only a climatic problem but also a soil problem; a function of shallow rooting in soils with low moisture-holding capacities. In fact, it has recently been demonstrated in the Cerrados Center (CPAC, EMBRAPA) near Brasília that this moisture-stress condition can be obviated in soybeans growing in Oxisols if deeper rooting is encouraged by applying single superphosphate to help overcome soil Al toxicity and P and Ca deficiency conditions (E. Wagner, CPAC, pers. comm.).

Monthly MAI values and the soil moisture-holding capacity rating, with or without a rating for soil chemical factors including Al toxicity and P and Ca deficiencies as given by the present study, have recently been used to form a preliminary zonification of the propensity of the Cerrados of Brazil to be affected by the wet-season drought periods.

A Fresh Approach to Climatic Zoning

Although the authors of this study do not intend to put forward a universal climatic classification on the basis of their analyses, the wet-season potential evapotranspiration (WSPE) concept has provided a fresh approach for zoning climatic subregions throughout lowland tropical America for nonirrigated, perennial crop production. It is leading to a better understanding of the region and has provided CIAT a basis for defining broadly comparable climatic conditions for the selecting, testing, and transferring of new pasture plant accessions (CIAT, 1980b). This is described in Chapter 1. The concept is compatible with the recently developed theory of unifying principles for water movements in biological tissues, including plants (Cochrane 1983, 1984). Studies, including those recently published by Ranzani (1978), will help to define more precisely the ability of the different soils to supply soil moisture and improve the water-balance estimates for specific agricultural systems.

PHOTO PLATES

With these photographs, you may take a trip through the various and distinct regions in the central lowlands of tropical South America. You can readily note the differences in topography, vegetation, climate, and soils and see some of the traditional land-use systems.

Amazon Basin

Plate 1 Colonist intercultivating cassava, maize, and beans (barely noticeable), 50 km south of Santarém in eastern Amazonas, Brazil.

Plate 2 Poorly drained savannas of the Isla de Marajó, Brazil, in the mouth of the Amazon.

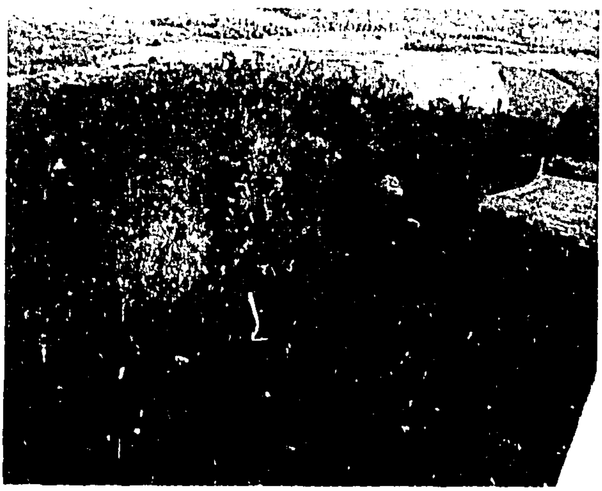


Plate 3 Tropical semi-evergreen seasonal forest near Altamira, southeast Amazonas, Brazil.

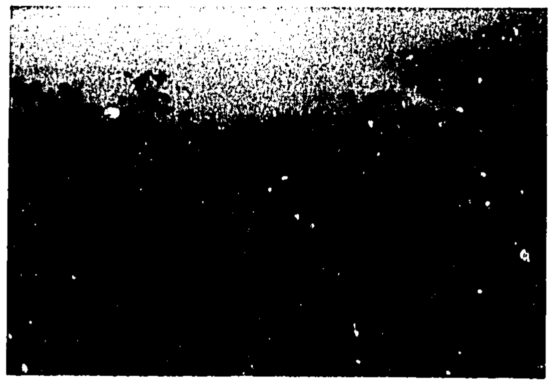


Plate 4 The Amapá well-drained savannas near the mouth of the Amazon, Brazil.

Plate 5 An Oxisol (Haplustox) 45 km south of Santarem in eastern Amazonas, Brazil.

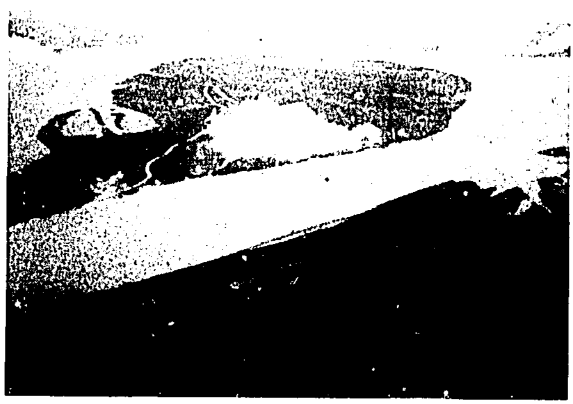


Plate 6 *Varseas*, or seasonally flooded lands, near Manaus, Brazil. Junction of the Negro River with the Amazon River in the background.

Plate 7 Tapping rubber (*Hevea brasiliensis*) in Amazonas, Brazil. Contrary to what is recorded in some literature, rubber-tapping techniques have been used only by local Indians since pre-colonial times to extract latex from the giant *Hevea* trees.

Plate 8 Tropical rain forest, Tefe, Brazil; junction of Tefe River with Amazon River in western Amazonia.

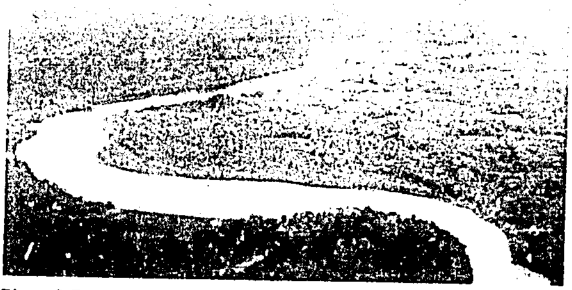


Plate 9 Tropical rain forest, largely cutover, near Yurimaguas, Peru.

Plate 10 Indian cultivation near the Huallaga River near Yurimaguas, Peru.

Plate 11 River transport of Pôrto Velho, Rondônia State, Brazil.

Plate 12 Colonization in Rondonia State, southwest Amazonia, Brazil. Unnecessary destruction of productive natural rubber and Brazil nut groves has taken place in recent years by overzealous colonists clearing land for food-crop (mainly rice) production.

Plate 13 The Humaita wetland savannas near Pôrto Velho, Brazil.

Plate 14 A mature nut tree (*Bertholletia excelsa*) in semi-evergreen forest near Riberalta in northeast Bolivia.

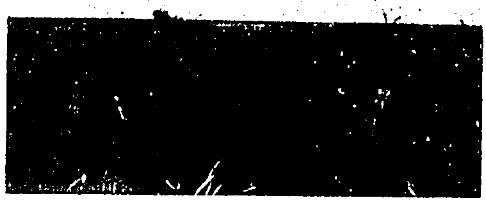


Plate 15 Well-drained savannas in southern Amazonia.

Brazilian Shield

Plate 16 The Alcantillados tablelands showing the red Oxisols, about 100 km east of Rondopolis, Central-West Brazil.

Plate 17 The Central Brazilian highland plateau near Anápolis, 160 km south of Brasilia.

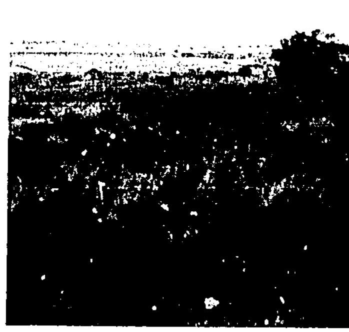


Plate 18 Looking across the rolling plateau surface of Land System No. 49 from the airport at Rio Verde, central Brazil.

Plate 19 On-the-ground view of tropical (semi-)deciduous forest 200 km west of Imperatrix in western Amazonas, Brazil.

Plate 20 Campo limpo (almost pure grass savanna) on the central plateau, Brazil.

Plate 21 Campo cerrado (open savanna) near Anápolis, central Brazil.

Plate 22 Cerrado (intermediate savanna) near Planaltina, central Brazil.

Plate 23 Cerradão (closed savanna) near Planaltina, central Brazil.

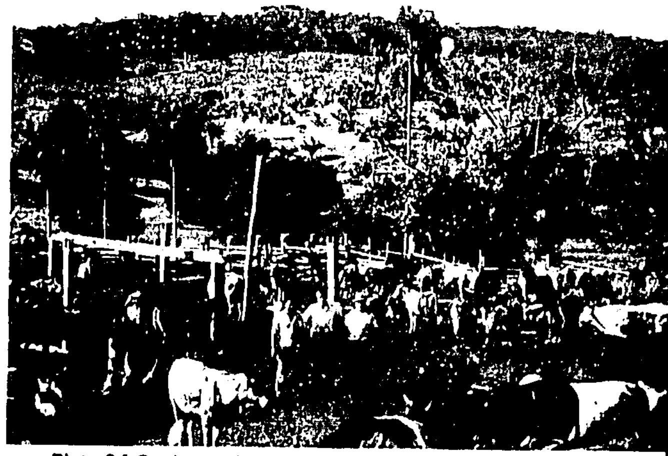


Plate 24 Cattle ranching near San Javier, Bolivia, on the Brazilian shield.

Plate 25 An Acrustox profile, Centro de Pesquisa Agropecuária dos Cerrados, Central Brazil.

Plate 26 The Cerrados Center, Centro de Pesquisa Agropecuária dos Cerrados, Central Brazil.

Plate 27 Agriculture on the Brazilian shield near Rio Verde.

Plate 28 Excessive lime applications in south Mato Grosso, Brazil.

Plate 29 Caatinga vegetation in western Bahia, Brazil.

Plate 30 The Entisol (sandy) savanna lands of the Parecis tableland of western Brazil.

Andean Foothills

Plate 31 Andean foothills near Villavicencio, eastern Colombia.

Plate 32 Phosphorus deficiency in Dwarf Cavendish bananas growing with coffee, near Pereira, Colombia.

Plate 33 Andean foothills forming a backdrop of the eastern Colombian plains, or Llanos, near Villavicencio, Colombia.

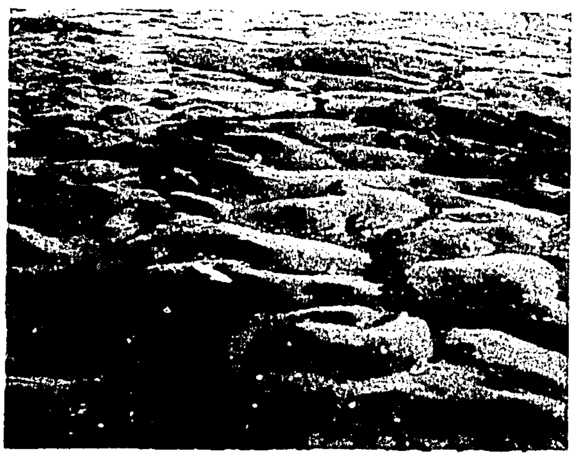


Plate 34 Rolling foothills, mainly cleared of tropical rain forest, near Florencia, eastern Colombia.

Mojos Pampas

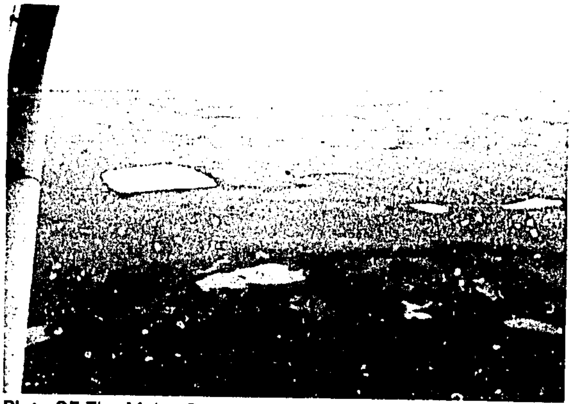


Plate 35 The Mojos Pampas of eastern Bolivia showing typical "square" lakes, a little north of the city of Trinidad.

Plate 36 Studying Ultisols near Reyes, Mojos Pampas, Bolivia. In the background, a typical island of forest on higher ground may be noted.

Plate 37 Cattle doing well near Reyes in the Mojos Pampas of Bolivia.

Plate 38 An aerial view of the "raised beds" used by pre-Columbian inhabitants of the Mojos Pampas, Bolivia, to elevate crop production above the wet-season water table.

Orinoco Basin

Plate 39 Farming with irrigation on the Orinoco plains 60 km south of San Tomé toward Ciudad Bolívar, Venezuela.

Plate 40 Savanna lands on Oxisols near San Tomé, Orinoco plains, Venezuela.

Plate 41 The well-drained *(altillanura)* savannas of eastern Colombia near Carimagua, as seen on the ground.

Plate 42 Carimagua in the eastern Colombian Llanos, showing the lowland (isohyperthermic) savanna site of ICA-CIAT. Note the presence of lower, poorly drained lands.

Plate 43 A more broken part of the well-drained savannas of eastern Colombia, south of the Muca River.

Plate 44 Laterite (hardened plinthite) outcrop near Carimagua, eastern "high" plains *(altillanuras)*, Colombia.

Plate 45 The Casanare wetland (Ultisol) savanna in Orocué, eastern Colombia.

Pantanal

Plate 46 Junction of the poorly drained and better drained lands in northeast Pantanal, Brazil.

Plate 47 The Brazilian "Pantanal," 50 km northeast of Corumba.

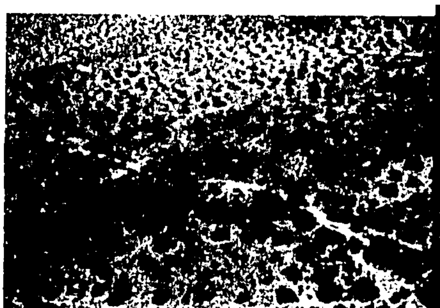


Plate 48 Better drained lands (but still hydromorphic) in the northern Pantanal, 50 km west of Rôndonopolis, western Brazil.

Plate 49 The Brazilian "Pantanal," 150 km northeast of Corumba, showing the typical "colored lakes". The colors are attributed to differences in the lake's microflora.

Plate 50 Close-up view of the "colored lakes" of the Pantanal, Brazil.

Paraná Basin

Plate 51 Burning Cerrados on sandy soils (Entisols) 150 km of Três Lagoas, Brazil.

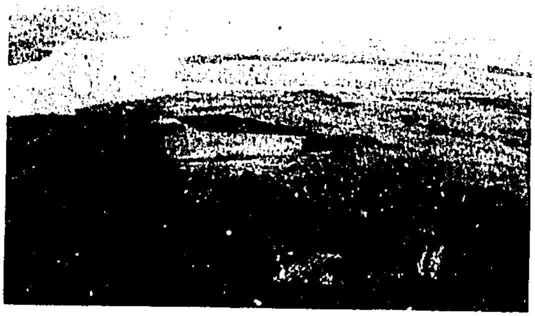


Plate 52 The Paraná River, Brazil, 100 km upstream from the Paranaiba dam, flanked by Eutrustox soils.

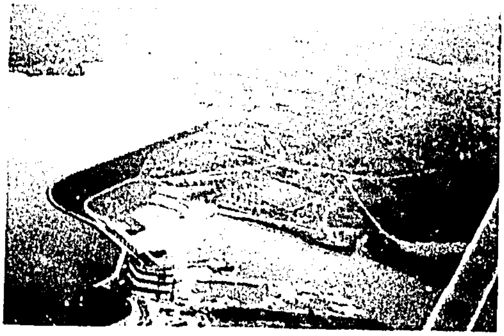


Plate 53 The Paranaiba hydroelectric dam on the Paraná River, Brazil.

Plate 54 At Foz do Iguacú, the color of the water is indicative of the excessive erosion ocurring in southern Brazil.

Plate 55 The Mearim River, near its junction with the Paraná River, passing through an area of good agricultural lands in Brazil, mainly Alfisols.

Chapter 4. LANDSCAPES

From north to south, the region in the Land Systems Map extends from the Panamanian isthmus to southern Brazil; from east to west it reaches from the Atlantic Ocean to the Andean foothills. It covers a large part of the watersheds of the Orinoco, Amazon, and Paraná—South America's three major river systems. Its physiography is molded from geological formations spanning nearly 1000 million years: from the Precambrian shields of central Brazil and the Guyanas rich in granites, micas, and gneiss to the alluvial deposits of many rivers that occurred in the recent epoch. Between these extremes there is a rich diversity of landscape formation on sedimentary, metamorphic, and volcanic deposits with a gamut of ages and materials. These include shales from the Devonian to Tertiary periods; mudstones and sandstones of the recently uplifted Andean foothills and their more recent andesitic volcanic ash mantling in the equatorial region; mudstones and sandstones of the Orinoco, Amazon, and the western Paraná basins dating from the Tertiary and Quaternary eras; and an extensive Cretacean tufa (volcanic) capping over parts of the Precambrian-shield region of southern Brazil (Mozart Parada and Maia de Andrade, 1977).

This chapter describes the topography and vegetation classes used as the bases for delineating land facets in the Land Systems Map.

Geology

The Brazilian shield, visible as the plateaus of central Brazil and the higher lands of eastern Bolivia, and its more northern equivalent, the Guyana shield, seen mainly in southern Venezuela, date to the Precambrian era. They support the oldest land surfaces in South America. Nevertheless, in some places, outcrops of hard granitic rock give these regions a more broken topography than that often associated with old surfaces. The landscapes of the two shields are separated by the much younger Tertiary, Quaternary, and Recent sediments of the Amazon basin. Continental drift theory suggests that these shields were once a part of the African continent.

The Brazilian shield extends at a relatively shallow depth from the northern plains of eastern Bolivia (at a depth of about 600 m at Trinidad) to the sub-Andean piedmonts. According to Schlatter and Nederlof (1966), Bolivia can be divided into a tectonically higher northern half and a deeper southern half, separated by a tectonic belt or "fault line" extending from Arica, Chile, on the Pacific coast, to the "elbow" of the Andes in the environs of the village of Buena Vista about 80 km to the north of the city of Santa Cruz, and continuing eastward across the continent. This phenomenon, considered in relation to the tremendous centrifugal forces caused by the spinning of the world around its axis over the eons, might provide a possible explanation for the directional change in the lie of the Andes. North of Buena Vista, the Andes swing from a northwest to southwest direction, resulting in a considerable effect on climate.

Schlatter and Nederlof consider that the Andean uplift started in mid-Tertiarian times. Movements were spirogenic, and two major Neogene depositional basins were formed: the Altiplano Trough, sandwiched between the Andes, and the Eastern Foredeep. Both received sediments mainly from the Andes.

At the end of the Pliocene or possibly the start of the Pleistocene era, the main Andean uplift created the high Andean Cordilleras. These are the result of largely vertical uplift with block faulting (a Germanotype style) and asymmetric folds. They are in a stage of active erosion.

Erosion is particularly noticeable in the sub-Andean foothills, which in many places show evidence of very recent uplifting. Erosion, particularly in parts of Peru and Bolivia, is taking place in spite of the forest cover; it is dramatic where soft sandstones and conglomerates are found in the foothill region.

Hydrology

The Orinoco, Amazon, and Paraná river systems drain most of the region; they provide waterways for transport and fishing and are an immense resource for power generation. The Amazon river system is navigable for large, seagoing ships as far inland as Manaus, and for quite large vessels as far inland as Porto Velho, the capital of Rondônia State in western Brazil, and to Iquitos and beyond in Perú. Small riverboats penetrate much further.

It is unfortunate for Bolivia that rapids (rocks belonging to the Brazilian shield formation) make the principal Amazonian tributaries, the lower Beni and Madeira rivers, impassable to river craft. To overcome this problem, a railway was built during the height of the rubber boom to link the cities of Guajará Mirim and Porto Velho; this was abandoned in 1966 but is now being rebuilt because road transport has not proven economic in this part of our energy-short world. A hydroelectric power station was recently constructed near Paranaiba on the Paraná river, and immense power reserves exist at Iguaçu, the site of the world's largest power complex under construction on the lower Paraná river (see Photo Plate

53). The erosion in southern Brazil, and the need for urgent control measures, is indicated by the color of the water in the photograph (see Photo Plate 54).

Major hydrological disasters could well take place in the coming years over parts of the watersheds of the Orinoco and, especially, the Amazon rivers, unless the present tendency to encourage colonization in unstable foothill regions is discontinued. The so-called *carretera marginal de la selva* (marginal jungle road), presently projected to follow along the Andean foothills, should be relocated well into the plains to help avoid the deforestation of erodable lands by colonists.

Physiographic Regions

Map 4 (see Map Plates) summarizes the major macrophysiographic regions identified on the Land Systems Map, the differences among which may be appreciated from the photographs in the Plates.

Amazon Basin

This is the lowland region of Amazonia between the sub-Andean foothills and the Brazilian and Guyanian shields. (See Photo Plates 1–15.) It is drained by many tributaries of the Amazon river. The land surfaces are predominantly plains or peneplains exhibiting various patterns of dissection and recent terrace formations. A large part of the region, especially in the northwest, is poorly drained; some areas, particularly in the vicinity of large rivers, are susceptible to annual flooding. Most of the region is still covered with native vegetation, although considerable destruction of forest has taken place in recent years.

Brazilian Shield

This refers to the elevated and exposed Precambrian shield region of Central Brazil and is characterized by old, stable plateau surfaces. (See Photo Plates 16–30.) A large part is still covered in native vegetation, mainly savannas locally called "Cerrados." However, considerable development has taken place during the last 20 years with the establishment of Brazil's administrative capital, Brasilia, located virtually in the epicenter of this unit. The formation extends into eastern Bolivia.

Elbow of the Andes

This unit has been delineated to emphasize the fault line across the South American continent extending eastward from the "elbow" of the Andes near Buena Vista nestling in the sub-Andean foothills of Bolivia. Apart from physiographic implications, the region has climatic characteristics transitional from the tropics to the subtropics.

Andean Foothills

This region defines the sub-Andean foothill region. (See Photo Plates 31–34.) It is particularly important as many of the foothills are susceptible to erosion. The indiscriminant clearing of native vegetation from the foothills is already aggravating flooding problems in the Amazon Basin and Mojos Pampas region of Bolivia.

Guyana Shield

This refers to the elevated and rugged Precambrian shield region north of the Amazon river. It is still mainly covered by native vegetation—forest and savannas.

Mojos Pampas

This is an extensive area of wetland savannas in the eastern plains of Bolivia, allegedly formed from the infill of a geologically postulated ancient lake between the Andes and the Brazilian shield. (See Photo Plates 35–38.) Apart from being a major cattle-producing area (Photo Plate 37), it is both geologically and archeologically unique. The presence of hundreds of "square" lakes (Photo Plate 35) has baffled geologists for years; current theory postulates that they are an effect of faulting in the underlying Brazilian shield. The presence of "raised beds" (Photo Plate 38) in many sites (Denevan, 1964) has presented an enigma to archeologists. The senior author believes that pre-Columbian peoples cultivated their food crops on these raised beds simply to raise them above the high, wet-season water tables of the region. It is interesting to speculate that their major grain crop was probably Job's tears (*Coix lacryma* Jobi), as this crop is still cultivated by some of the indigenous peoples in the region.

Orinoco Basin

This is the lowland drainage basin of the Orinoco river and its tributaries. (See Photo Plates 39–45.) It is largely covered by savannas on both poorly and well-drained lands, but includes some forests, particularly those abutting the western edge of the Guyana shield and in the northeast.

Pantanal

This is an area in western Brazil mainly along its border with Bolivia. As the name suggests, it is a lower, poorly drained savanna region. Nevertheless, landscape differences and grades of seasonal inundation exist.

Paraná Basin

This region includes a large part of the watershed for the Paraná river found in southern Brazil. (See Photo Plates 51–55.) It is largely made up of savanna and some deciduous forest covering dissected plain surfaces. There are extensive areas of sandy soils in the western portion of these plains.

Physiographic Units

Within the physiographic regions, physiographic units were identified to separate distinctive landscapes, using locally recognizable names. As the land systems were delineated, they were assigned numbers identifying them with these physiographic units. These are listed by country in the glossary to Part I of the *Computer Summary* (Volume 3). Figure 4-1 illustrates their use to make a physiographic map of Central-West Brazil. They present a picture of the major landscape differences within any one country or region. However, for agricultural production considerations, the land systems per se must be considered.

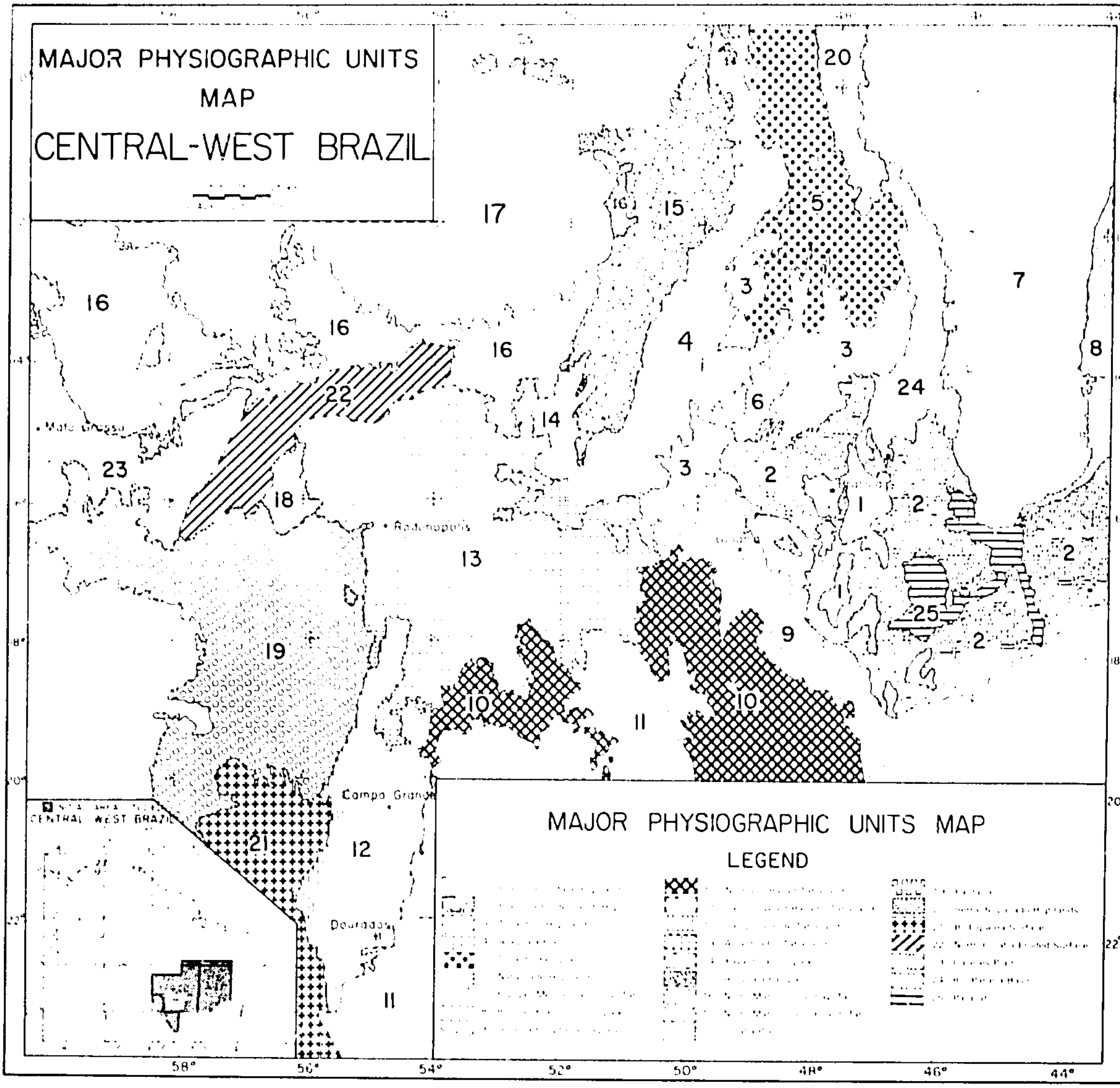


Fig. 4-1 Physiographic units map of Central-West Brazil.

Land Systems, Land Facets, and Mapping Scales

The description and coding of the landscape features have been described in Chapter 2. The subdivision of the land systems into land facets emphasizes that landscape is not constant, but continually varying. As practical farming has to cope with a variation in land surfaces and soils, the description of the land facets within a land system is clearly important.

It should be remembered that there may be lesser variations in topography, vegetation, and soils within a land facet; however, some level of generalization must be accepted in making an inventory of land resources. This is inherent in all but the most detailed large-scale maps, such as individual farm maps. Therefore, the generalization made in classifying the soils of the land facets according to their predominant soils is no more serious than those currently accepted in soil mapping. In fact, the emphasis given to describing land systems in terms of facets adds to the usefulness and precision of this study.

For very small-scale maps, further generalizations are quite acceptable. As the mapping scale becomes smaller, the degree of detail is diminished. It is quite permissible, therefore, to depict the topography, vegetation, and soils of the major land facets as those predominating over a region. This is useful to provide an overview of major features—to rephrase an old saying, "to see the forests and not the trees." The computerization of the study facilitated the production of such overview maps.

It also facilitated quantification of properties. Because quantification is made on the basis of the land facets, however, the figures reflect a greater degree of precision than the mapping units based on the land-system subdivisions.

Topography

Map 5 is a computer-based map summarizing the topography of the region.

Poorly Drained Lands

Approximately 21% (170 million ha) of the region is poorly drained; 82% of these poorly drained lands (139 million ha) is covered with forests and the remainder by native savannas.

The vast extent of poorly drained forest lands along the Andean foothills and northwest Amazonia imposes a natural barrier to agriculture. Nevertheless, the seasonally flooded Lands or *várzeas* (see Photo Plate 6) of major river systems often have naturally fertile soils, and it is likely that increasingly important areas will be brought into more intensive production of crops, including wetland (paddy) rice and jute, in the not too distant future.

The poorly drained savanna lands have been used successfully since colonial times for extensive cattle production. Significant areas are found in the Brazilian Pantanal (see Photo Plates 46–50); the Bolivian Pampas de Mojos (Photo Plates 35–38); the Casanare plains of northeast Colombia (Photo Plate 45), which extend into southwest Venezuela as the Apure plains; the island of Marajó at the mouth of the Amazon river (Photo Plate 2); the Humaitá plains north of Porto Velho in Rondônia in Brazil's southwest Amazonia; parts of the Amapá savannas near the mouth of the Amazon river on its northern side (Photo Plate 1); parts of the Boa Vista savannas in northern Brazil; and the contiguous Rupununi savannas of Guyana.

Well-Drained Lands

About 79% (649 million ha) of the region is reasonably well drained. The major part of this area, 508 million ha, is covered by forest, and the remaining 141 million ha is covered by savannas. Approximately 77% of the well-drained lands (497 million ha) has slopes less than 8%, and 23% (152 million ha) has slopes greater than 8%. The relatively flat lands are often closely dissected by small streams. In fact, over 86% of the entire area has perennial streams at less than 10 km intervals and 39% less than 5 km apart (see Photo Plate 43).

Topography and Climatic Subregions

Table 4-1 provides a summary of the topography within the broad climatic subregions described in Chapter 3. It is based on computer printouts.

There is a significantly higher proportion of poorly drained lands in subregion A, the tropical rain forests. Even so, 70% of these areas are well drained; of these, 128 million ha have slopes less than 8%. With the notable exception of some areas in the sub-Andean foothills, such as the Florencia region of Colombia (see Photo Plate 34) and the Yurimaguas region in the low Selva of Peru (see Photo Plate 9), most of these lands are still covered by native tropical rain forest vegetation. Variations in physiography are common and picturesque along the narrow sub-Andean foothills (see Photo Plates 31,

Table 4-1. Topography of the climatic subregions of the central lowlands of tropical South America.

Climatic subregion code	Subregion name	Area (million ha) in each topography class: Flat, poorly drained	Well-drained: <8% slope	Well-drained: 8-30% slope	Well-drained: >30% slope	Total area (million ha)	Total area (%)
a	Tropical rain forest	65	128	20	4	217	27
b	Semi-evergreen seasonal forest	50	189	64	5	308	38
c	Isohyperthermic savanna	31	76	13	9	129	16
d	Isothermic savanna	0	33	6	4	43	5
e	(Semi-)deciduous forest	23	62	10	8	103	12
f	Subtropical vegetation[a]	1	9	1	0	11	1
o	Other[b]	0	0	2	6	8	1
	Total area (million ha)	170	497	116	36	819	
	Percentage of total area	21%	61%	14%	4%		

a. Other vegetation on predominantly poorly drained or seasonally flooded lands.
b. Nonclassified, or submontane or subtropical forest.

33, 34). Between the Andean foothills and the Precambrian shield much of the landscape is uniform and gently undulating, although it is often interspersed with extensive areas of poorly drained lands.

By far the largest area of well-drained lands is found in subregion B, the tropical semi-evergreen seasonal forests (see Photo Plates 3, 5, 14). In central, eastern, and southern Amazonia, these forests are largely intact, although sizeable areas, especially in Rondônia state of Brazil's southern Amazonia, have been cut down in recent years (see Photo Plate 12).

About 73% (189 million ha) of the well-drained lands of subregion B are relatively flat, with slopes less than 8%. The landscape tends to be less variable than in other subregions. Nevertheless, there are major physiographic differences; a large part is closely dissected by the many tributaries of the Amazon river.

Subregion C is largely defined by the well-drained isohyperthermic savanna lands. Some extensive areas of flat lands are found, such as the *altillanura* plains along the south bank of the Meta river (3–4 × 10^6 ha) in Colombia's eastern plains (see Photo Plates 41–43), but large tracts of these lands are strongly dissected.

Subregion D is comprised of the isothermic savannas, mainly confined to the higher (greater than 900 m) plateau lands of Central Brazil, and the cooler southern limits of Brazil's "Cerrados," which contain extensive tracts of flat lands dissected by small valleys (see Photo Plates 16, 17, 18, 21, 23, 26, 27).

Subregion E covers a wide range of topographies.

Vegetation

The Land Systems Map and Figure 3-6 (Chapter 3) summarize the distribution of the natural, physiognomic vegetation classes over the region. The use of physiognomic terms does not imply any preconceived ecological or climatic conditions; the description of the savanna and forest classes used throughout the study strictly follow those quantitatively defined terms used by Eiten (1968, 1972) for tropical well-drained savannas and Caatinga and by Eyre (1968) for tropical forests. Only the classification "seasonally inundated pampas" has not been defined in a physiognomic sense; these *pampas* refer to any lowland tropical savanna or grassland with soils that suffer from prolonged periods of waterlogging.

Savannas

According to Bernal Diaz (1975), "savanna" is a Carib Indian word signifying "treeless plain." In modern usage, its meaning has been extended. Eiten notes that "The range in structural forms in cerrado is completely continuous in the sense that stands can be found in any region which may be ranged in a series from arboreal, through all grades of scrub and structural savanna, to (usually) pure grassland of the cerrado type." This continuity was recognized by many early travelers and particularly emphasized by Smith (1885). The classifications used by Eiten for savannas, or Cerrados, are summarized as follows.

Campo limpo. Grassland with tall visible woody plants essentially absent (see Photo Plate 20), and whose flora is made up of practically the same species as the ground layer of *campo cerrado*. (Note that the use of *campo limpo* here is for a variation of the Cerrado flora.) Sometimes, when a Cerrado grassland has a few, very scattered, low but conspicuous shrubs or acaulescent palms, it is distinguished as *campo sujo*.

Campo cerrado. Includes several forms with total woody plant cover rather open or sparse (see Photo Plate 21), that is, less than 30–40% cover, such as:

a. Quite open scrub
b. Low arboreal, quite open woodland
c. True physiognomic savanna, i.e., scattered medium-tall or low trees, or shrubs, or usually both trees and shrubs intermixed, over a continuous or slightly open layer of grasses, herbs, dwarf shrubs, and semishrubs.

Cerrado (strict sense). Includes several forms with the total woody plant cover closed down to about 30–40% (see Photo Plate 22), such as:

a. Closed or semi-open low arboreal forms (canopy generally less than about 7 m tall).
b. Closed or semi-open scrub forms (canopy generally less than about 3 m tall), the elements of which may be definitely shrubby, arboriform, or the two mixed.
c. Closed or semi-open scrub mixed with scattered trees of various heights. The trees may be emergents and form a single upper layer or, usually, rise to varying heights along with varying heights of scrub elements so that the upper surface of the vegetation is "hilly."

Cerradão. Medium-tall arboreal form with a closed or semi-open canopy (see Photo Plate 23) (but not less than 30–40% tree crown cover).

Forests

The following descriptions briefly identify the tropical forest classifications (see Plates), as used by Eyre.

Tropical rain forest. Most trees are evergreen in habit, casting their leaves and growing new ones continuously and simultaneously (see Photo Plates 8–10). Some may shed all their leaves for a short period at irregular intervals. Large trees may develop plank buttresses, although these are more common in areas with impeded drainage. The trunks of certain trees, especially "lower story" trees, such as cacao, may bear flowers and fruit. This phenomenon is termed "cauliflory," and the bark of such trees is usually very thin. Palms may be present, but not in the great numbers found in poorly drained areas.

A tropical rain forest is usually well over 30 m in height. Statistical appraisal would indicate that it has a three-tiered structure. Under the often-open upper canopy may be found a layer of smaller trees, and, in turn, below this, a lower "story." Trees in the different layers are frequently specifically adapted to particular niches within the microclimatic and structural complex of the forest, and are not necessarily simply immature forest giants. Thus, trees in the lower forest layers largely consist of species adapted to reduced light conditions.

Usually a large number of tree species exists in any one area. These commonly belong to the Rosaceae, Compositae, and Leguminosae families. Lianes and epiphytes are common.

The shrub layer is poorly developed (often just a few ferns and seedlings), and, for this reason, it is usually quite easy to walk through a tropical rain forest.

Tropical semi-evergreen seasonal forest. These forests generally have a two-layered structure, may reach heights of 25 m or considerably more when growing on inherently fertile soils, and possibly 20 to 30% of the upper canopy trees lose their leaves in the dry season. Apparently, many of the evergreen species of the upper layer are facultatively deciduous. In other words, they have the ability to lose their leaves in an extreme dry season. A high proportion of the lower story trees are evergreen.

This type of forest differs from the tropical rain forest in other respects. Fewer trees are buttressed. In the early winter season, many species produce flowers, especially the lower layer trees that tend to be small-leaved.

Tropical semi-deciduous seasonal forest. This forest (see Photo Plate 19) has two strata. The upper at about 15 m is predominantly deciduous. Evergreen trees are common in the lower layer at 4 to 10 m.

Tree species differ considerably from those found in semi-evergreen seasonal forests. They have more gnarled trunks (as opposed to the straight trunks of the semi-evergreen seasonal forests); they branch quite near the ground and have umbrella-shaped canopies, or canopies with distinct horizontal strata, as compared with the compact, conical, or rounded crowns of the wetter forest. Bottle trees, Acacia species, and giant cacti are usually present. The bottle tree flowers about late April to May with the late rains, fruits, then sheds its leaves. Some palms that appear to withstand drought may also be present. A high proportion of the trees are microphyllous. The forest tends to be poor in lianes.

Herbaceous plants, especially grasses, are scantily represented on the forest floor, although spiny plants, particularly Bromeliaceae species, may be very common.

These forest classes correspond to those growing on well-drained soils. The various sub-seres (modification), ecotone characteristic (gradations between two groups), and features worthy of special note of any one type of vegetation are not reflected in the vegetation coding. When very different sub-seres due to natural phenomena were found, e.g. hydroseres (vegetation adapted to wet soil conditions), they were classified with the "Other" vegetation classes. When ecotones were found, they were assigned to the closest vegetation class.

Caatinga. Caatinga has been described by Eiten as the thornscrub of northeastern Brazil (see Photo Plate 29). It is not a structural form of Cerrado, but a different coordinate, large-scale vegetation type with different flora; nevertheless, some Caatingas contain a proportion of Cerrados species. Closed scrub is the commonest form of Caatinga, but this vegetation type also occurs in many other structures, all natural in some regions: forest, arboreal woodland, closed shrub (mostly of definite shrubs 2–5 m tall), closed scrub with emergent low trees, open shrub (mostly of definite shrubs 1.5 m tall), shrub savanna (scattered low trees or shrubs over a closed shortgrass layer, the *Serido* form), and others. Many of the shrubs and trees are spiny. Cacti are almost always present, such as tree cacti of the Cereus tribe, low clumps of globular and cylindrical species, and Opuntia. Terrestrial species of bromeliads are very abundant in most Caatingas.

Submontane forests. Submontane forests are found at altitudes between about 1000 and 2000 m. The classifications of Eyre were used and noted on the original coding sheets. These may be summarized in the following way.

- *Sub-montane evergreen forest.* This forest has a two-tiered structure with an open canopy of trees reaching to heights of 15 to 20 m. Ferns are common in the shrub layer. Most of the tree species are either evergreen or only shed their leaves for short periods at irregular intervals.

- *Sub-montane semi-evergreen forest.* This forest is similar in structure to the sub-montane evergreen forest in that it has a double stratum of trees and an open canopy, but is generally lower (13 to 16 m). A noticeable proportion of trees shed their leaves during the June to August period. Leaf shed in some species is preceded by flowering about April, followed by fruiting.

- *Sub-montane deciduous seasonal forest.* This forest usually has a single layer of trees and tends to be open. Heights vary from about 8 to 12 m. Thorny scrub and cacti are common in the shrub layer. Almost the entire forest sheds its leaves for 3 to 5 months of the year.

Table 4-2. Areal extent (%) of the savannas[a] of tropical South America, subdivided on the basis of relative arboreal biomass contents, with major soil chemical constraints.

Low P		Low K		Al toxic (70% Al sat)		Low Ca		Low Mg	
C	85.6	CD	94.3	CD	93.5	C	82.3	CL+CS	77.
CC	82.9	C	90.8	C	57.8	CC	74.0	CC	51.5
CD	81.1	CC	88.5	CC	54.4	CL+CS	61.6	C	21.1
CL+CS	58.0	CL+CS	68.1	CL+CS	40.0	CD	49.0	CD	15.5

a. Brazilian terms commonly used (see Eiten, 1972): CL+CS = campo limpo + campo sujo (grassland with occasional shrubs), CC = campo cerrado (open savanna), C = cerrado (intermediate savanna), CD = cerradão (closed savanna).

Table 4-3. Areas (ha) of human-induced vegetation throughout the central lowlands of tropical South America (from satellite imagery taken during period 1973-76).

Climatic subregion code	Subregion name	Area planted to pastures	Area planted to crops
a	Tropical rain forest	11,697,490	6,959,370
b	Semi-evergreen seasonal forest	20,904,120	11,999,580
c	Isohyperthermic savanna	13,259,220	6,006,850
d	Isothermic savanna	8,738,000	3,571,620
e	(Semi-)deciduous seasonal forest	5,622,700	2,647,440
f	Subtropical vegetation[a]	2,751,320	737,870
o	Other[b]	1,460,510	804,740
	TOTAL	64,433,360	32,727,470

a. Other vegetation on predominantly poorly drained or seasonally flooded lands.
b. Nonclassified, or submontane or subtropical forest.

- *Sub-montane microphyllous forest.* This is a low, 4 to 7 m high, often open forest or scrub. Cacti are common. The density of the vegetation appears to increase with increasing availability of moisture. The forest is relatively leafless for 6 to 8 months of each year.

Vegetation and Soils

Lopes and Cox (1972) reported a soil fertility sequence following the relative arboreal biomass contents of a limited area of the well-drained savannas. However, as shown in Table 4-2, such a sequence was not confirmed by this study, with the exception of Mg, the significance of which may require further investigation, although it is possibly just a coincidence.

Induced Vegetation

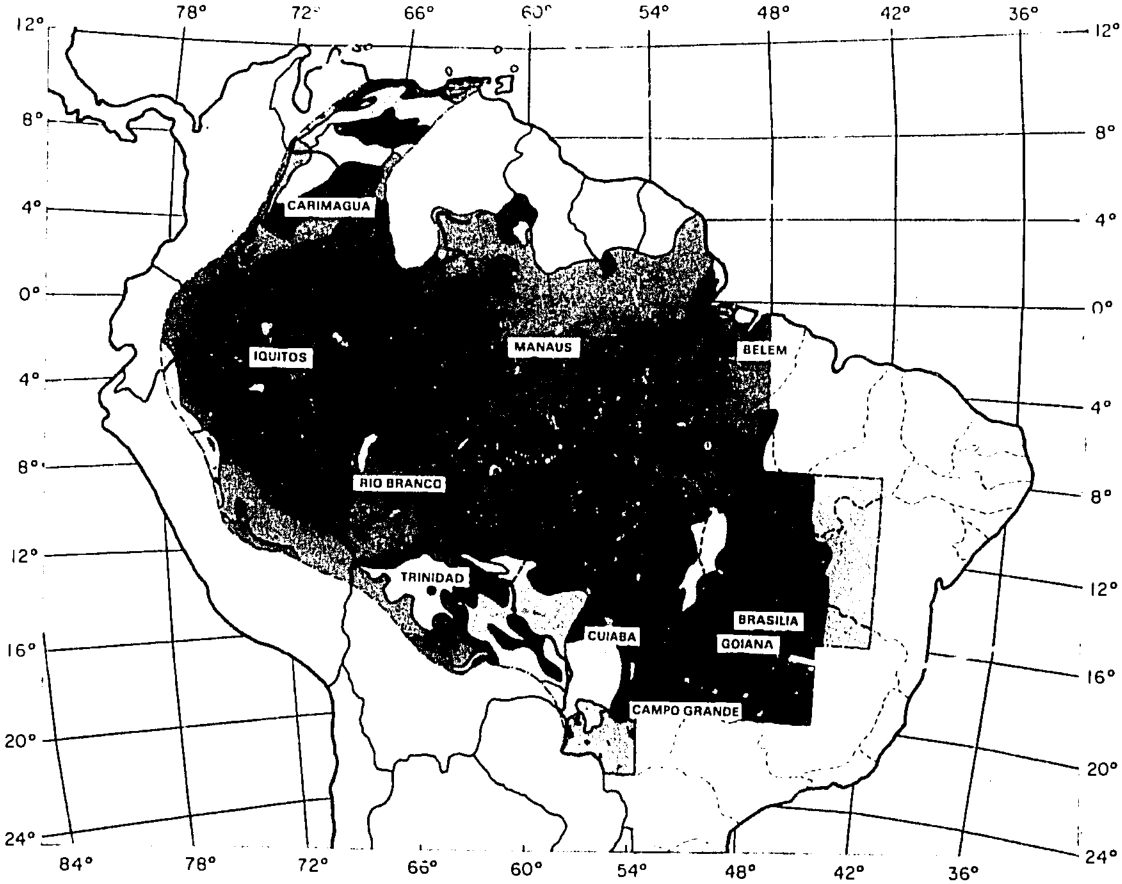
Table 4-3 summarizes the areas of human-induced vegetation throughout the region. It must be noted that these figures were based on imagery taken over the period 1973 to 1976, and as such are very approximate. They do not take into account areas that have been cut over or partially altered; only those areas with obvious signs of vegetation changes. They should be used, if at all, with qualification.

Conclusion

There is no doubt that the 613 million ha of well-drained lands in the region with slopes of less than 30%, from a climate and landscape point of view, represent one of the world's major reserves for crop, pasture, and agroforestry production under rainfed conditions. It follows, therefore, that their soil conditions should be carefully examined.

Map Plates

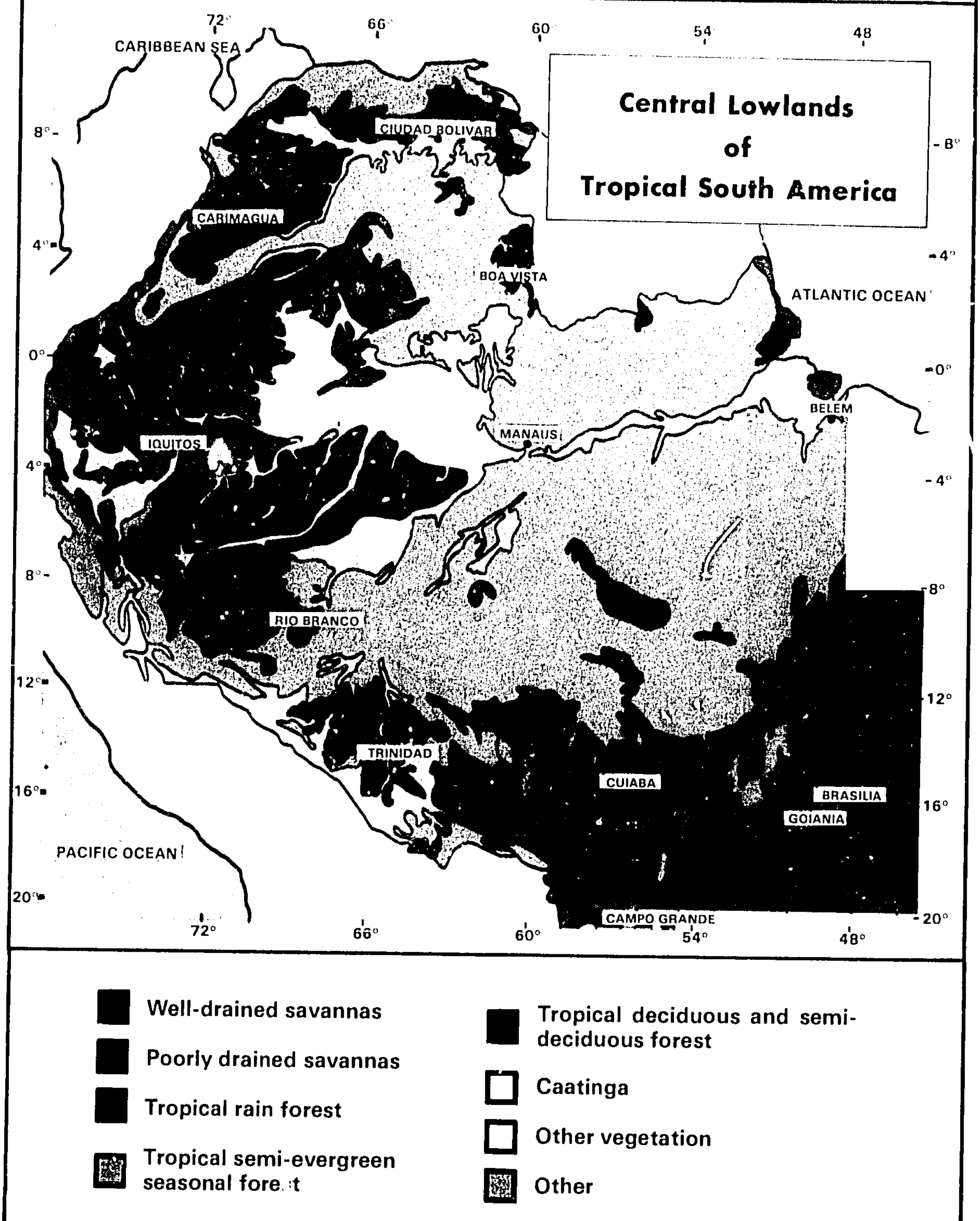
AGROECOLOGICAL ZONES OF TROPICAL PASTURES PROGRAM



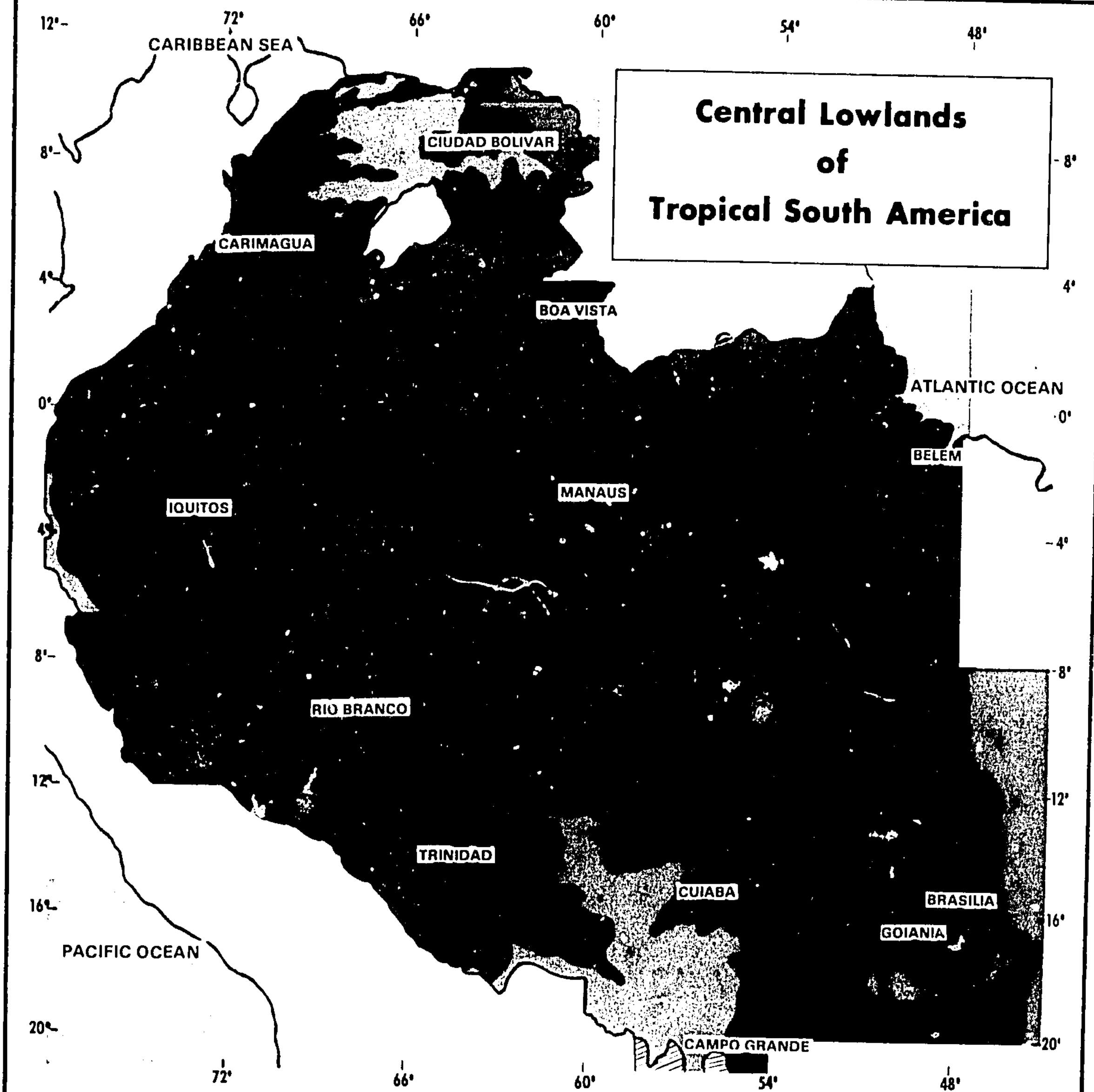
- **Well-Drained Isohyperthermic Savannas** — WSPE[a] 900–1060 mm, 6–8 months wet season, WSMT[b] > 23.5°C
- **Well-Drained Isothermic Savannas** — WSPE 900–1060 mm, 6–8 months wet season, WSMT < 23.5°C
- **Poorly Drained Savannas** (found in lowlands of tropical South America, in varying climatic circumstances)
- **Semi-Evergreen Seasonal Forest** — WSPE 1061–1300 mm, 8–9 months wet season, WSMT > 23.5°C
- **Tropical Rain Forest** — WSPE > 1300 mm, > 9 months wet season, WSMT > 23.5°C
- **Poorly Drained Forest Regions**
- **Deciduous Forests, Caatinga[c] etc**
- **Others[c]**

a. Total wet-season potential evapotranspiration
b. Wet-season mean temperatures
c. Not included within target area of Tropical Pastures Program

NATURAL VEGETATION CLASSES



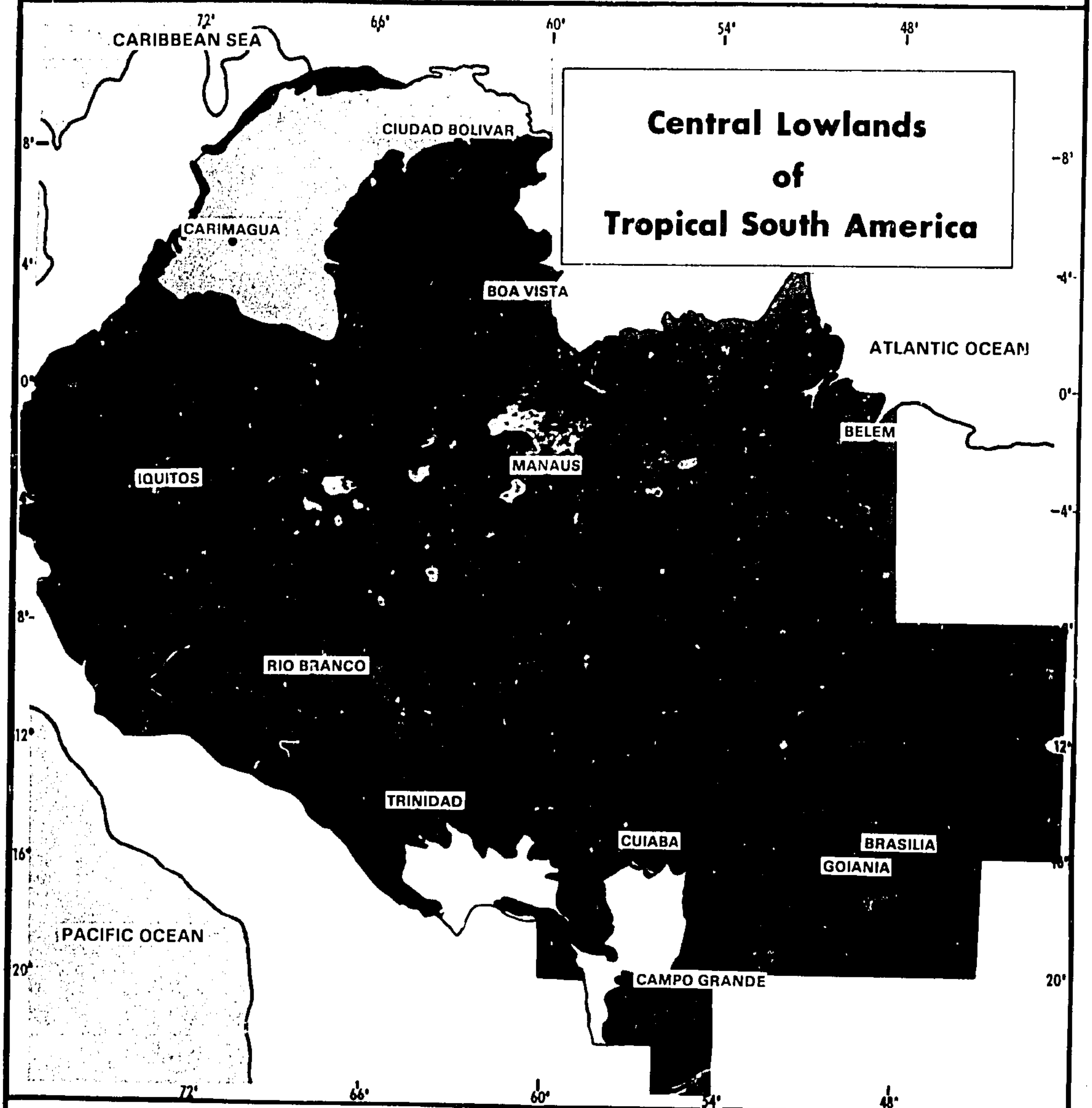
CLIMATIC SUBREGIONS



- **a** WSPE[a] > 1300 mm, > 9 wet mos., WSMT[b] > 23.5°C
- **b** WSPE 1061–1300 mm, 8–9 wet mos., WSMT > 23.5°C
- **c** WSPE 900–1060 mm, 6–8 wet mos., WSMT > 23.5°C
- **d** WSPE 900–1060 mm, 6–8 wet mos., WSMT < 23.5°C
- **e** WSPE < 900 mm, < 6 wet mos., WSMT > 23.5°C
- **f** Subtropical
- **o** Others

a. WSPE = Total wet-season potential evapotranspiration.
b. WSMT = Wet-season mean monthly temperature.

PHYSIOGRAPHIC REGIONS



A Amazon Basin

B Brazilian Shield

E Elbow of the Andes

F Andean Foothills

G Guyana Shield

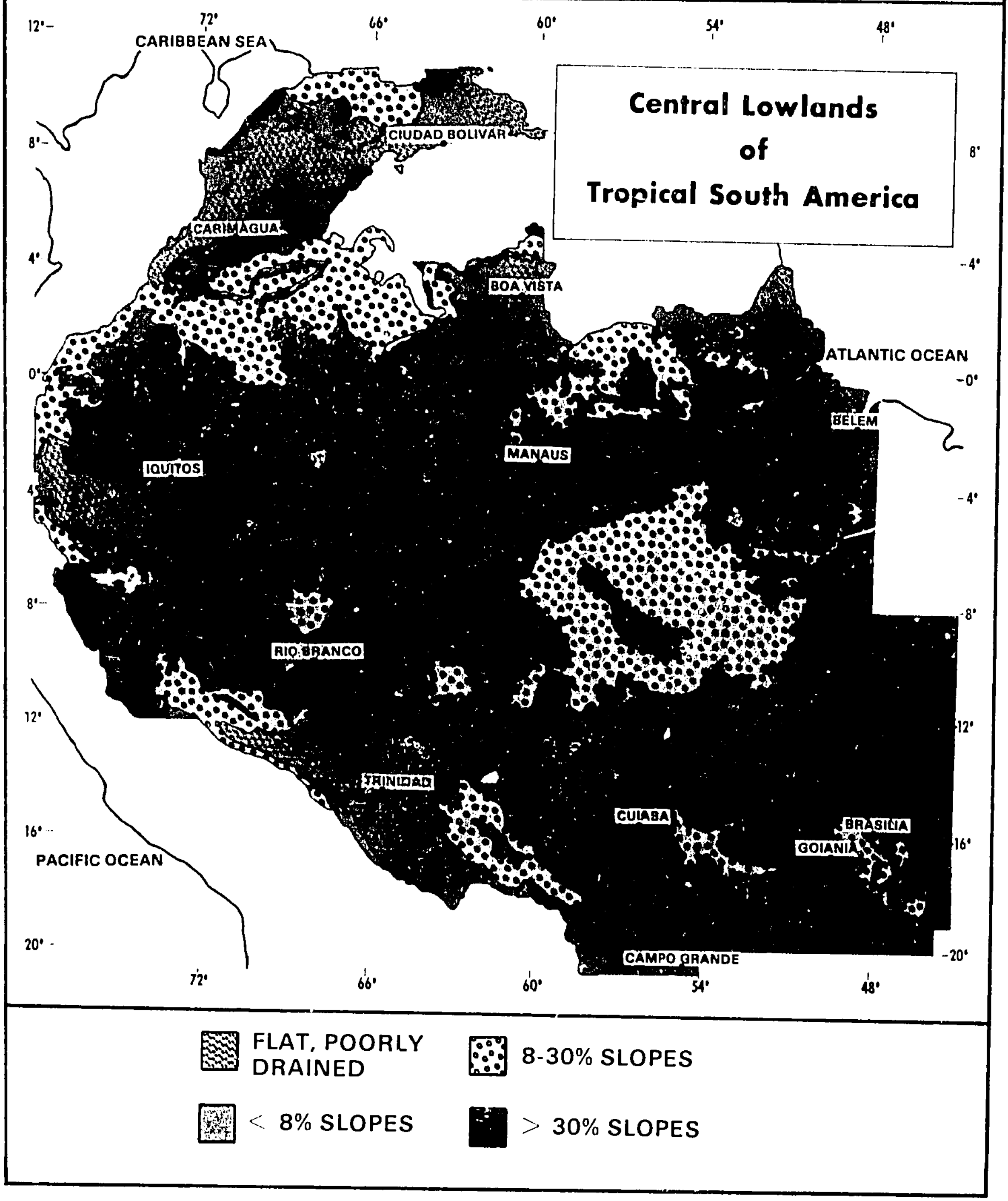
M Mojos Pampas

O Orinoco Basin

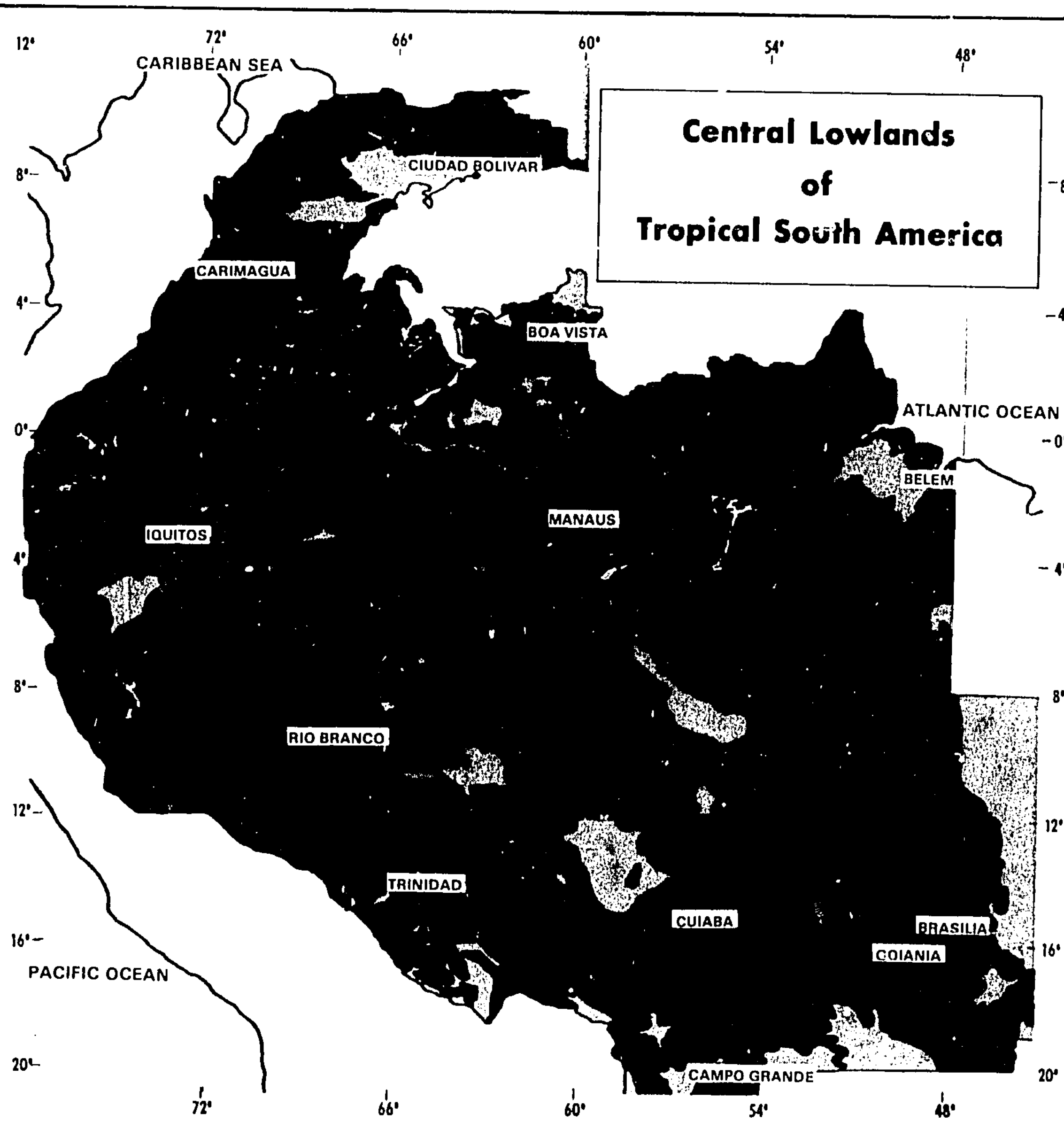
P Pantanal

R Paraná Basin

TOPOGRAPHIC CLASSES

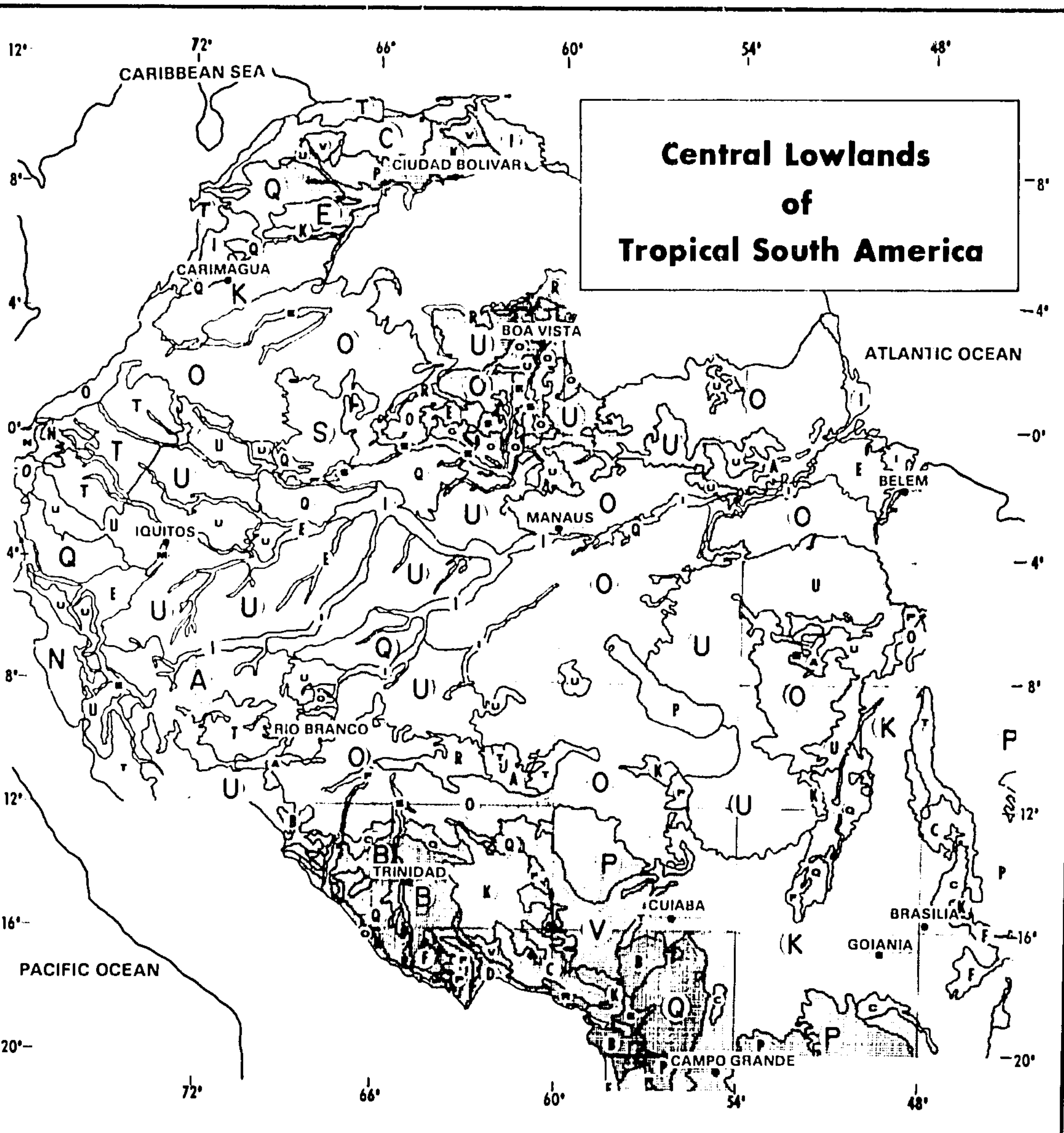


SOIL ORDERS/SOIL TAXONOMY



ALFISOLS
ARIDISOLS
ENTISOLS
INCEPTISOLS
MOLLISOLS
OXISOLS
SPODOSOLS
ULTISOLS

SUBORDER SOIL CLASSES/SOIL TAXONOMY

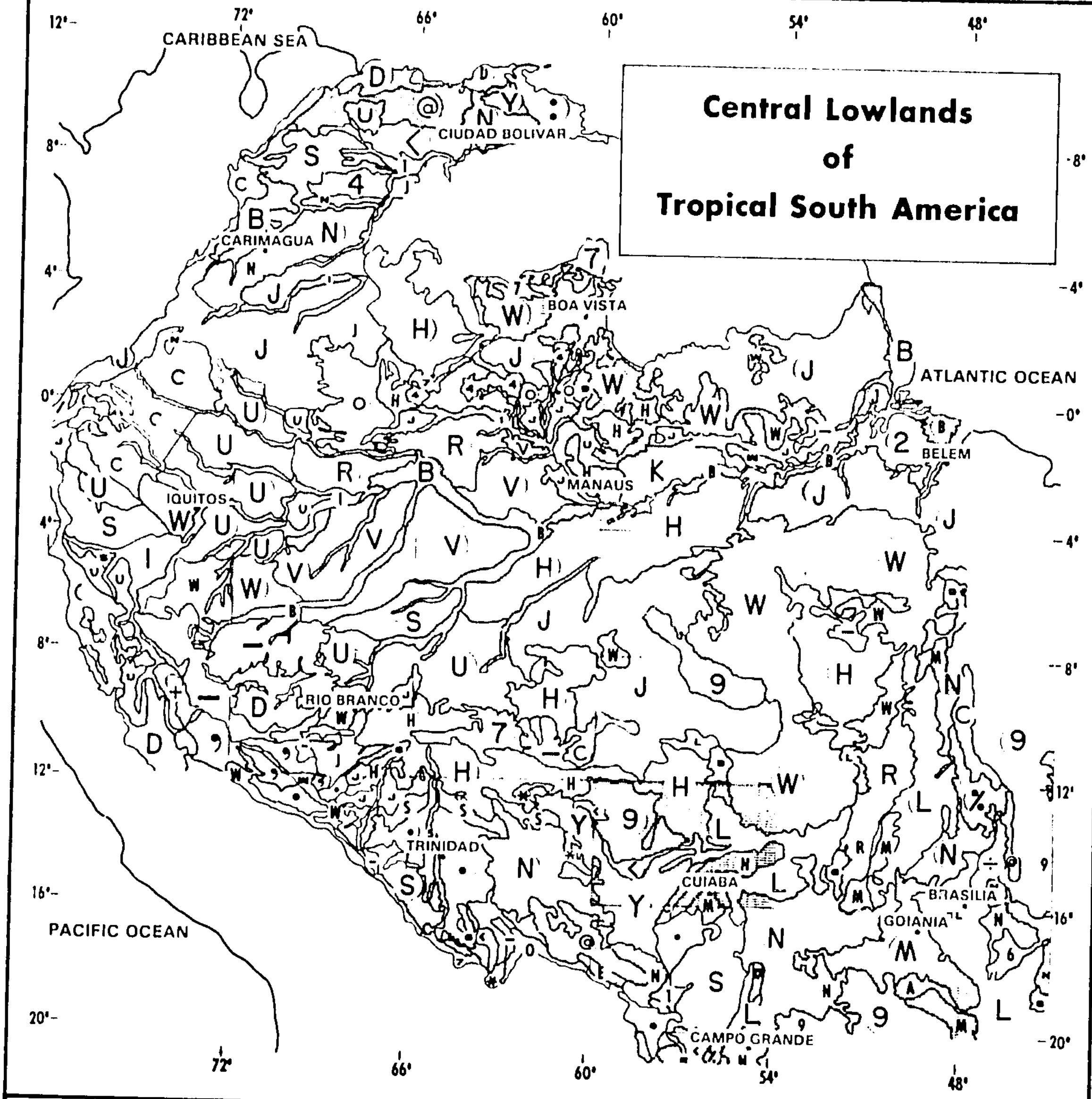


B Aqualfs
A Udalfs
C Ustalfs
X Xeralfs
D Orthids
E Aquents
F Fluvents
R Orthents

P Psamments
N Andepts
I Aquepts
T Tropepts
M Aquolls
G Udolls
H Ustolls

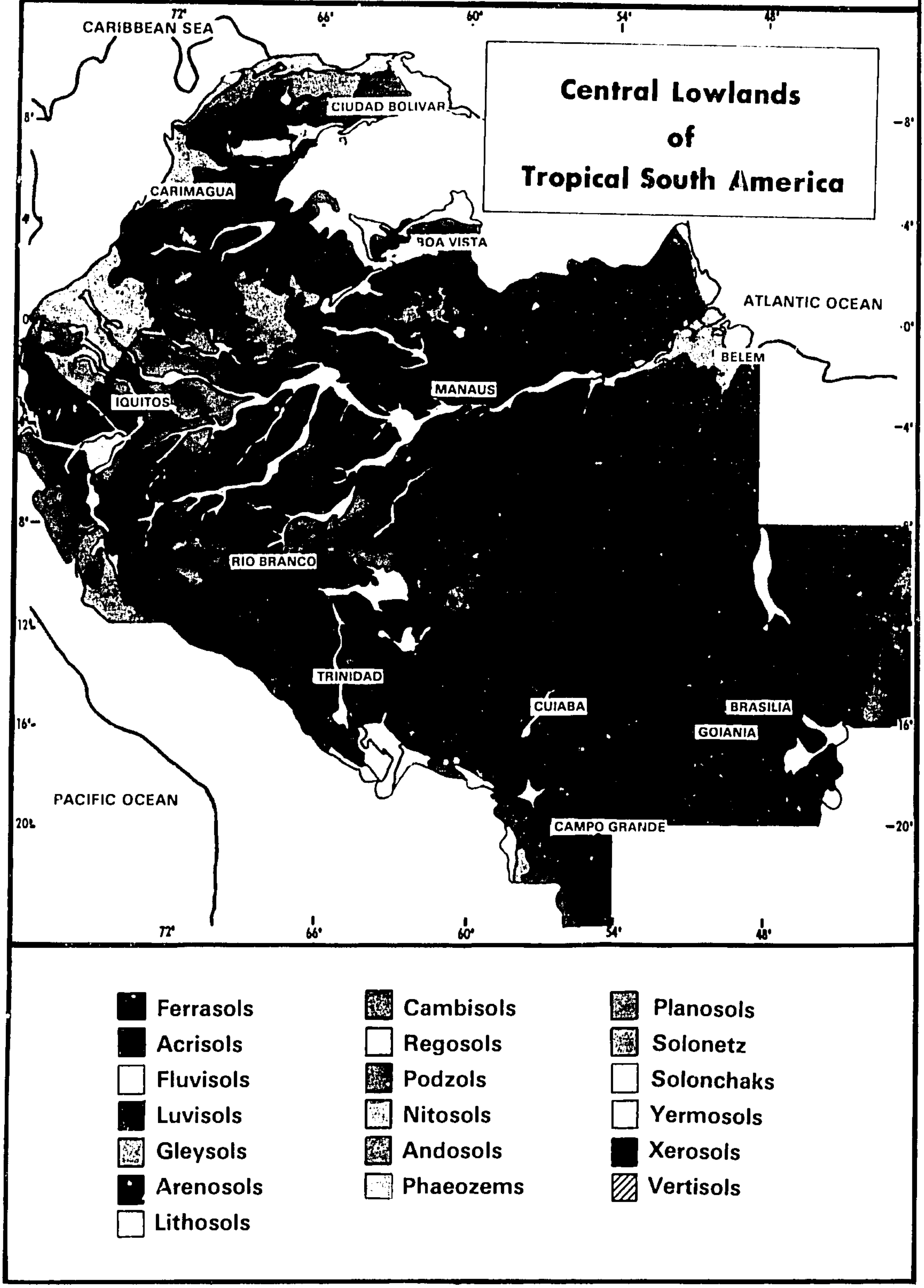
J Aquox
O Orthox
K Ustox
S Aquods
Q Aquults
U Udults
V Ustults

GREAT GROUP SOIL CLASSES/SOIL TAXONOMY

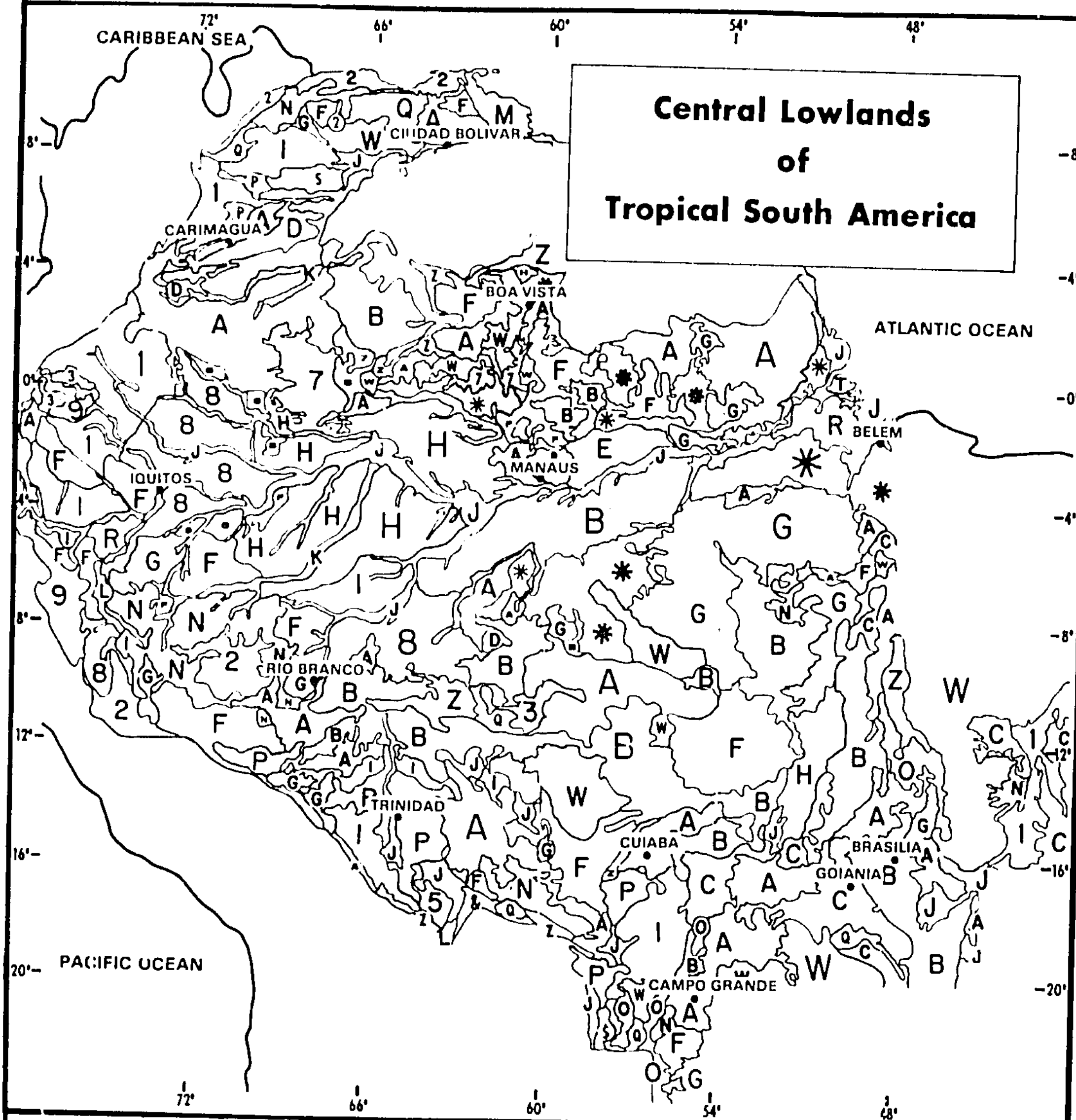


\ Natraqualfs (AAQNA)
· Tropaqualfs (AAQTR)
\+ Hapludalfs (AUDHA)
$ Rhodudalfs (AUDRH)
— Tropudalfs (AUDTR)
@ Haplustalfs (AUSHA)
& Natrustalfs (AUSNA)
Paleustalfs (AUSPA)
% Rhodustalfs (AUSRH)
÷ Tropustalfs (AUSTR)
? Haploxeralfs (AXEHA)
! Camborthids (DORCM)
1 Fluvaquents (EAQFL)
2 Haplaquents (EAQHA)
3 Hydraquents (EAQHY)
4 Psammaquents (EAQPS)
5 Tropaquents (EAQTR)
6 Tropofluvents (EFLTR)
) Ustifluvents (EFLUS)
• Xerofluvents (EFLXE)
7 Troporthents (EORTR)
8 Ustorthents (EORUS)
9 Quartzipsamments (EPSQU)
· Tropopsamments (EPSTR)
· Ustipsamments (EPSUS)
(Dystrandepts (IANDY)
/ Hydrandepts (IANHY)
÷ Haplaquepts (IAQHA)
A Humaquepts (IAQHU)
\# Plinthaquepts (IAQPL)
: Sulfaquepts (IAQSU)
B Tropaquepts (IAQTR)
C Dystropepts (ITRDY)
D Eutropepts (ITREU)
\- Ustropepts (ITRUS)
E Haplaquolls (MAQHA)
F Argiudolls (MUDAR)
; Haplustolls (MUSHA)
G Plinthaquox (OAQPL)
H Acrosthox (OORAC)
I Eutrorthox (OOREU)
J Haplorthox (OORHA)
K Umbriorthox (OORUM)
L Acrustox (OUSAC)
M Eutrustox (OUSEU)
N Haplustox (OUSHA)
O Tropaquods (SAQTR)
P Albaquults (UAQAL)
Q Paleaquults (UAQPA)
R Plinthaquults (UAQPL)
S Tropaquults (UAQTR)
T Hapludults (UUDHA)
U Paleudults (UUDPA)
V Plinthudults (UUDPL)
, Rhodudults (UUDRH)
W Tropudults (UUDTR)
Y Haplustults (UUSHA)
Z Paleustults (UUSPA)
X Rhodustults (UUSRH)
10 Chromuderts (VUDCH)

GENERALIZED SOIL MAP/FAO-UNESCO LEGEND

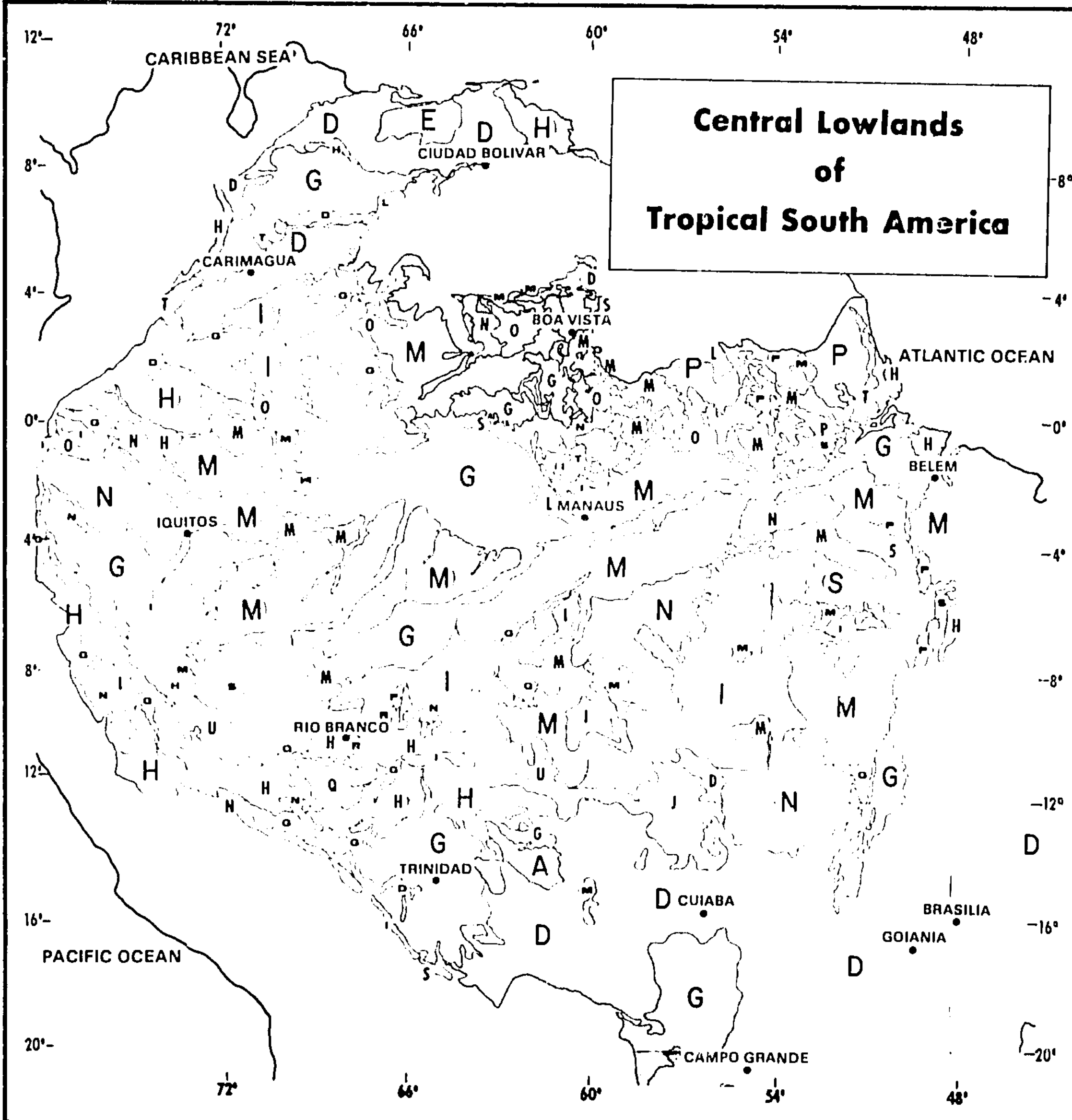


SOIL UNIT MAP/FAO-UNESCO LEGEND



- * Xanthic Ferralsols (Fx)
- A Orthic Ferralsols (Fo)
- B Acric Ferralsols (Fa)
- C Rhodic Ferralsols (Fr)
- D Plinthic Ferralsols (Fp)
- E Humic Ferralsols (Fh)
- F Ferric Acrisols (Af)
- G Orthic Acrisols (Ao)
- H Plinthic Acrisols (Ap)
- I Gleyic Acrisols (Ag)
- J Eutric Fluvisols (Je)
- K Dystric Fluvisols (Jd)
- L Calcaric Fluvisols (Jc)
- M Thionic Fluvisols (Jt)
- N Orthic Luvisols (Lo)
- O Chromic Luvisols (Lc)
- P Gleyic Luvisols (Lg)
- Q Ferric Luvisols (Lf)
- R Eutric Gleysols (Ge)
- S Dystric Gleysols (Gd)
- T Humic Gleysols (Gh)
- U Mollic Gleysols (Gm)
- V Plinthic Gleysols (Gp)
- W Ferralic Arenosols (Qf)
- Y Albic Arenosols (Qa)
- Z Lithosols (I)
- 1 Ferralic Cambisols (Bf)
- 2 Eutric Cambisols (Be)
- 3 Dystric Cambisols (Bd)
- 4 Calcic Cambisols (Bk)
- 5 Eutric Regosols (Re)
- 6 Dystric Regosols (Rd)
- 7 Gleyic Podzols (Pg)
- 8 Dystric Nitosols (Nd)
- 9 Humic Andosols (Th)
- X Luvic Phaeozems (Hl)
- | Haplic Phaeozems (Hh)
- # Dystric Planosols (Wd)
- † Gleyic Solonetz (Sg)
- $ Orthic Solonetz (So)
- @ Gleyic Solonchaks (Zg)
- & Haplic Yermosols (Yh)
- % Luvic Xerosols (Xl)
- 10 Chromic Vertisols (Vc)

SOIL FERTILITY/FCC SYSTEM

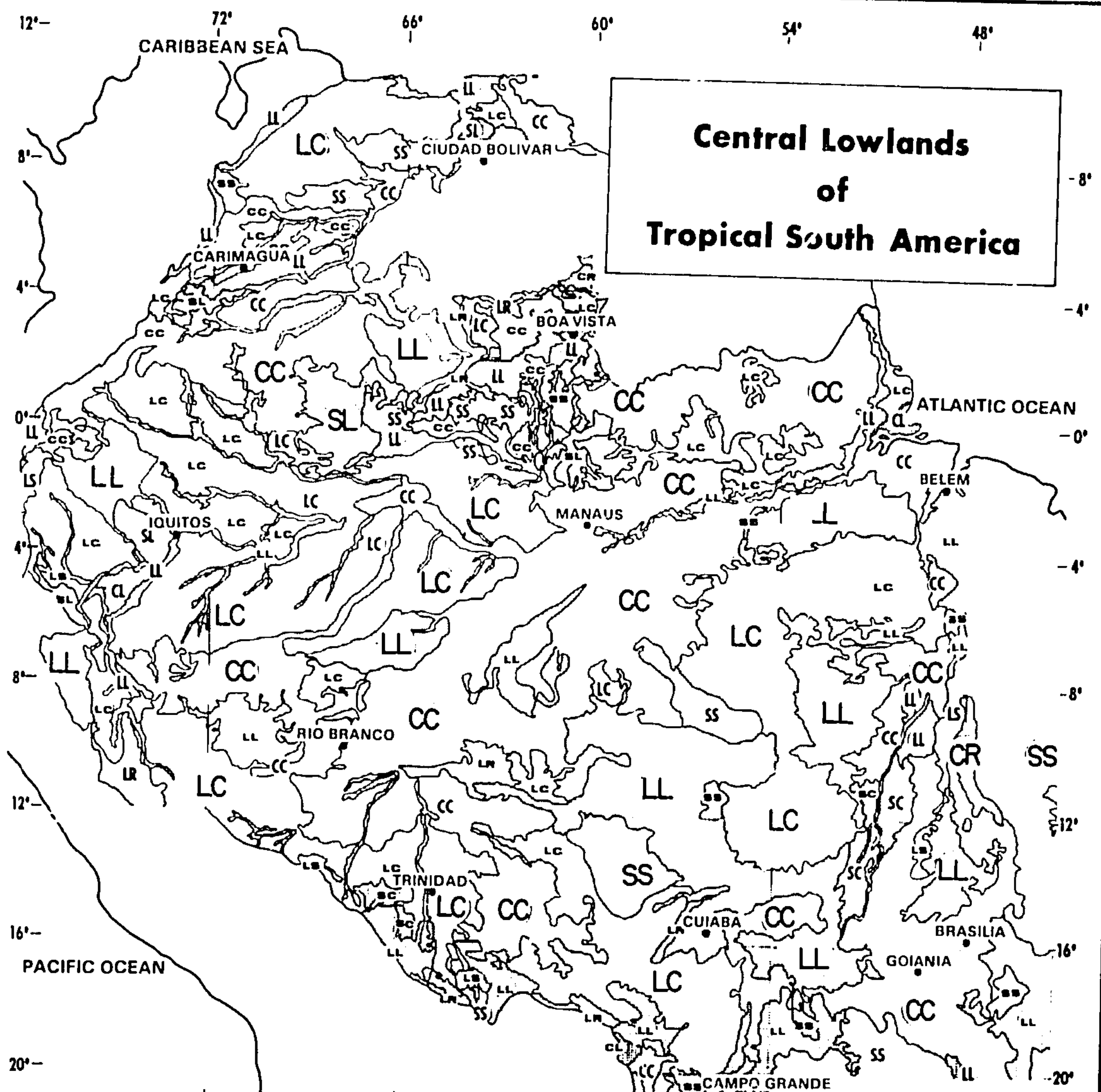


FCC MODIFIERS: a = Al Toxic, d = dry, e = low ECEC, g = gley, h = acid, i = phosphorus fixation, k = potash deficient.

MODIFIER COMBINATIONS:

D = contains "d"
G = constains "g"
H = h
I = ha
J = hae
K = haei
L = hai
M = hak
N = hake
O = hakei
P = haki
Q = hei
R = hi
S = hk
T = hke
U = k

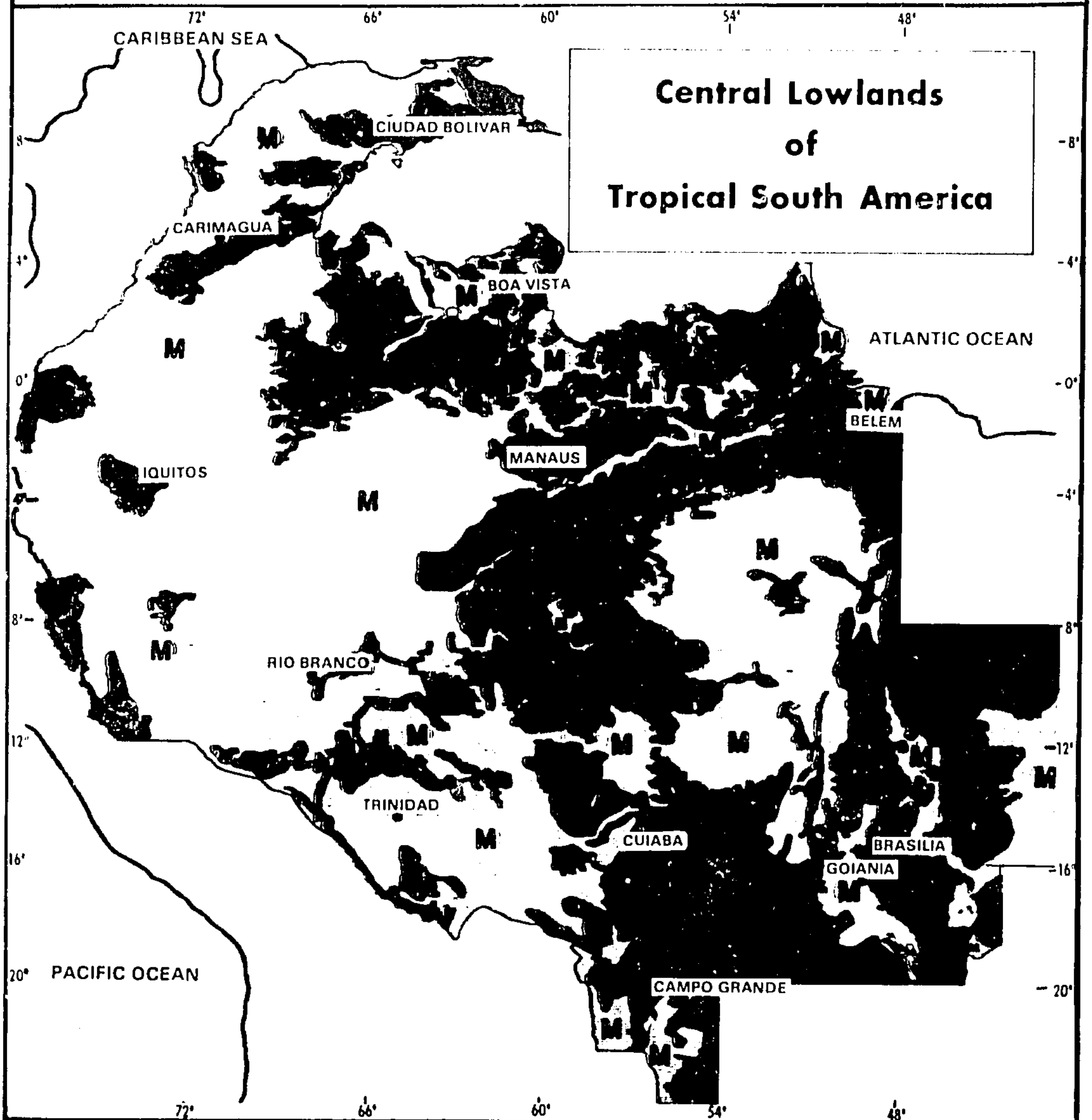
SOIL TEXTURAL CLASSES/FCC SYSTEM



S Sand
L Loam
C Clay
R Rock

NOTE: The first letter of the code indicates topsoil (0–20 cm) texture. The second letter indicates subsoil (21–50 cm) texture.

SOIL MOISTURE-HOLDING CAPACITY

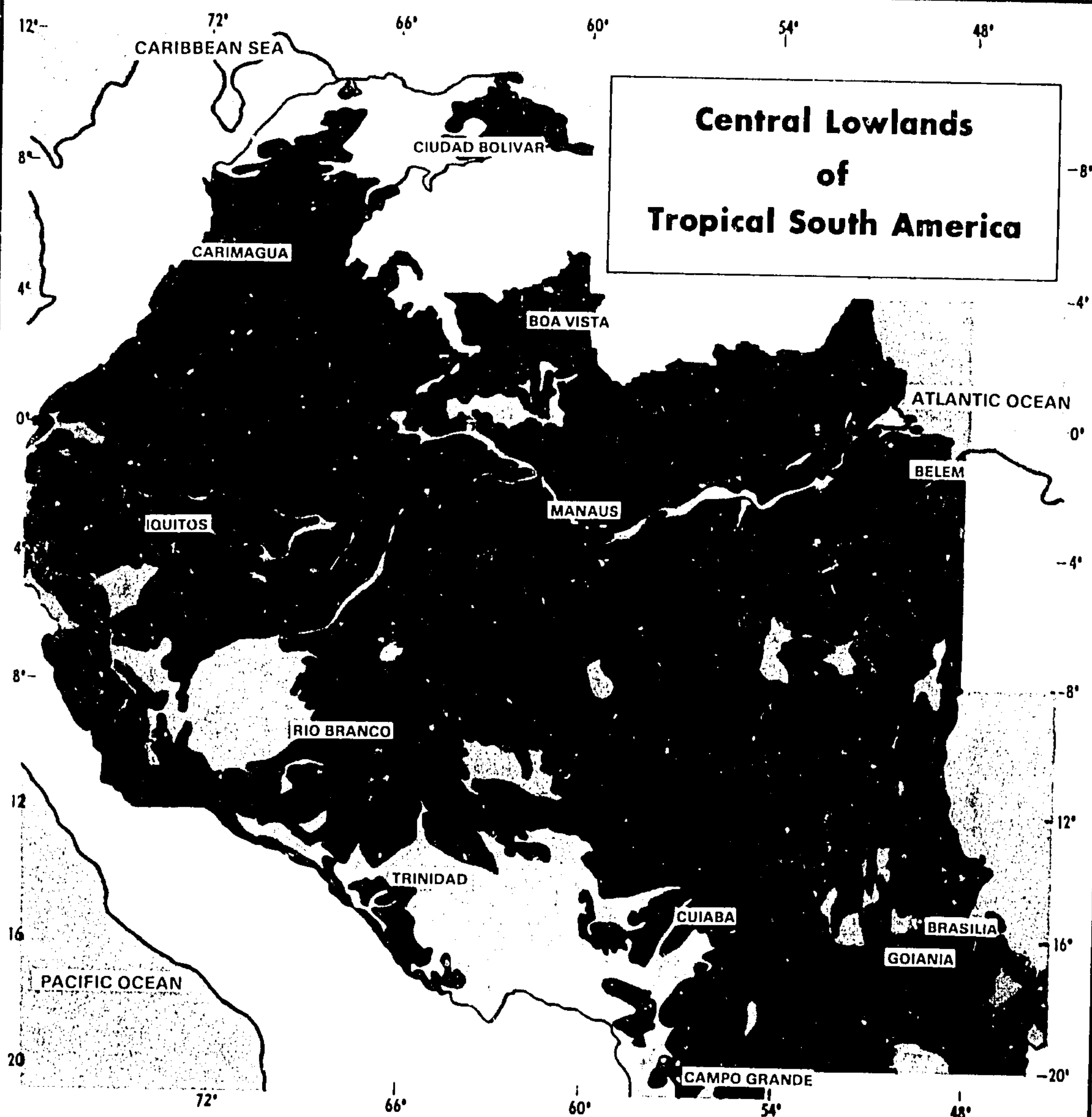


> 150 mm per 100-cm soil depth

M 75–150 mm per 100-cm soil depth

< 75 mm per 100-cm soil depth

pH LEVELS IN TOPSOIL (0–20 cm)

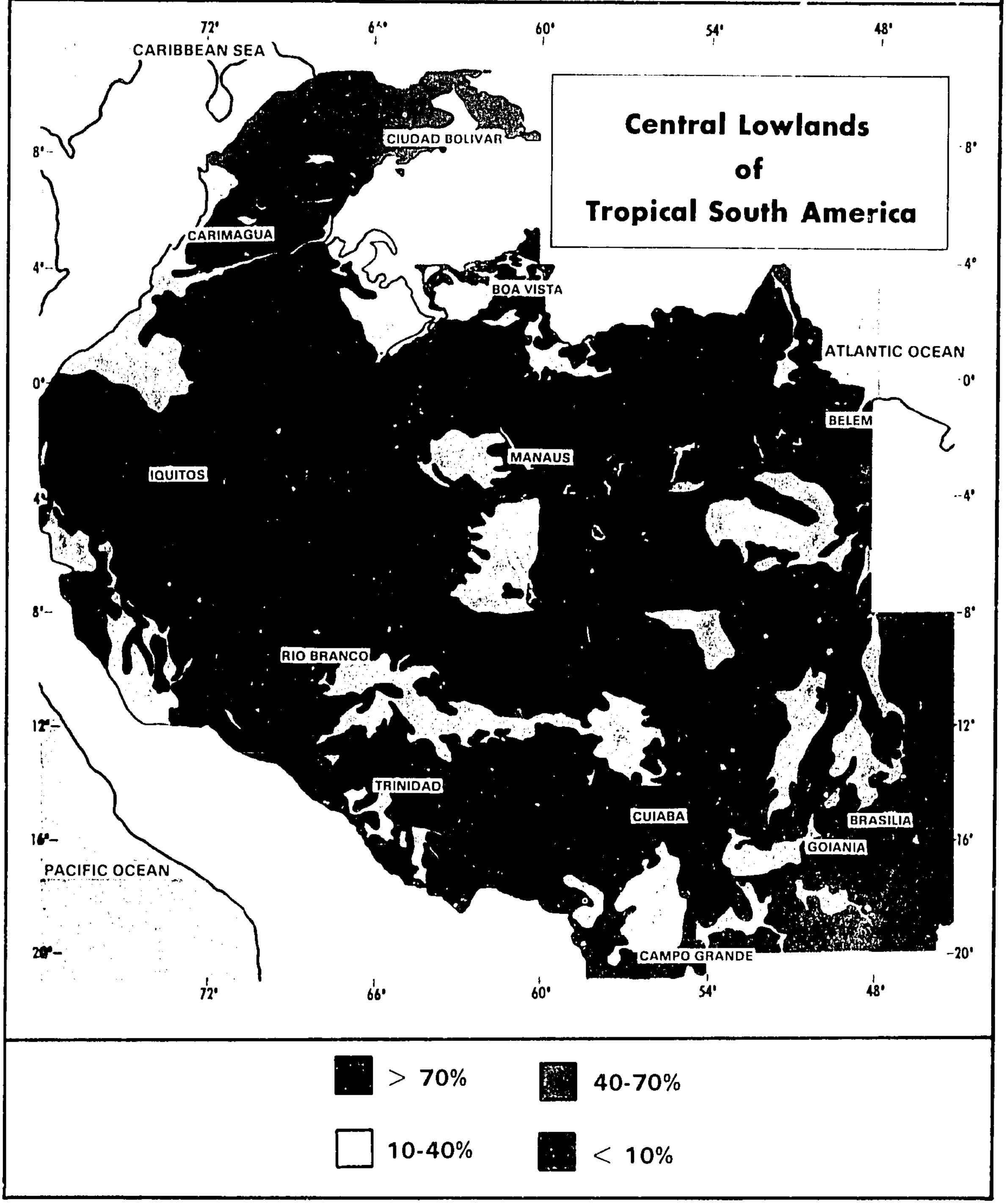


> 7.3

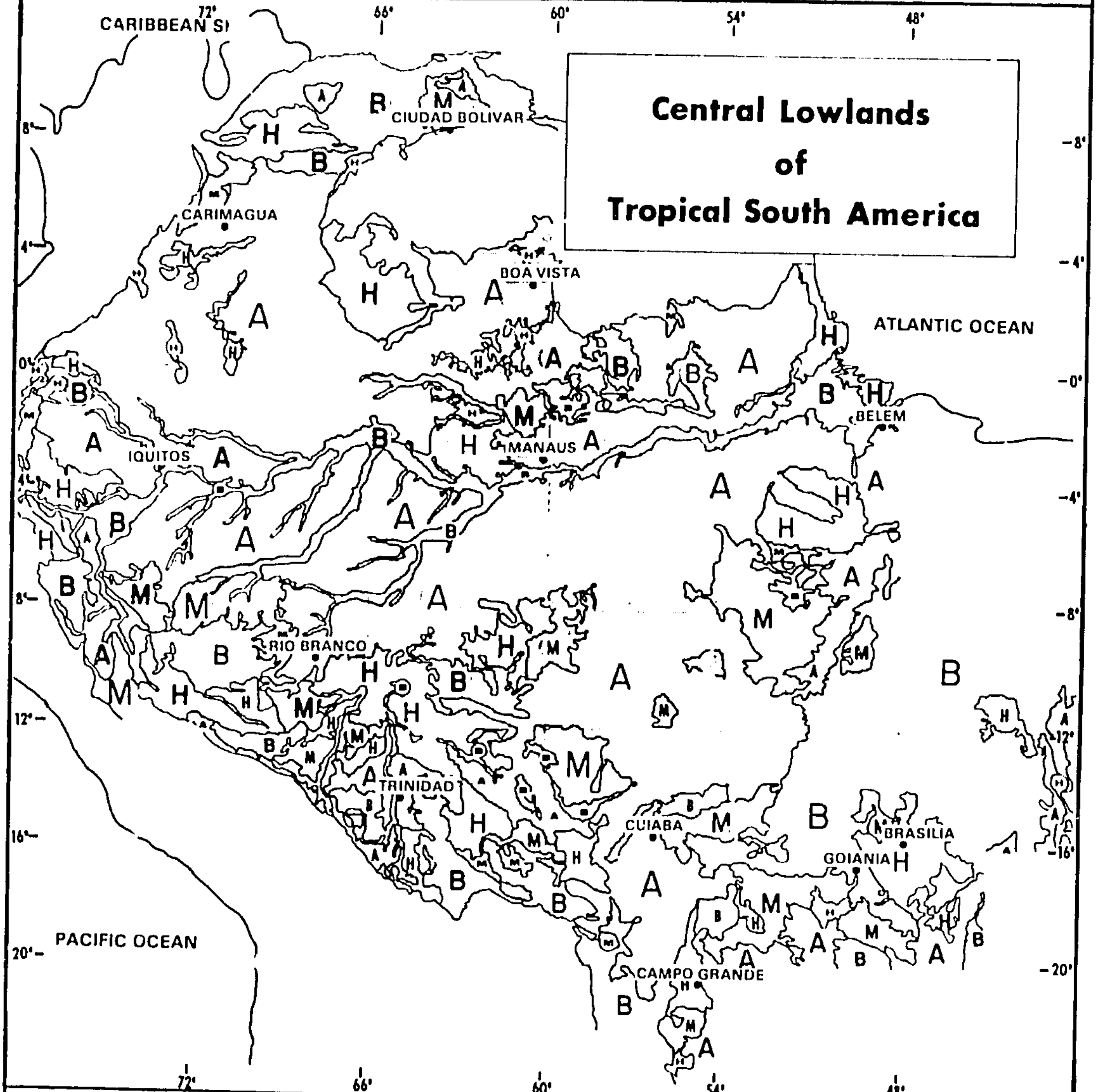
5.3 - 7.3

< 5.3

AL SATURATION LEVELS IN TOPSOIL (0–20 cm)

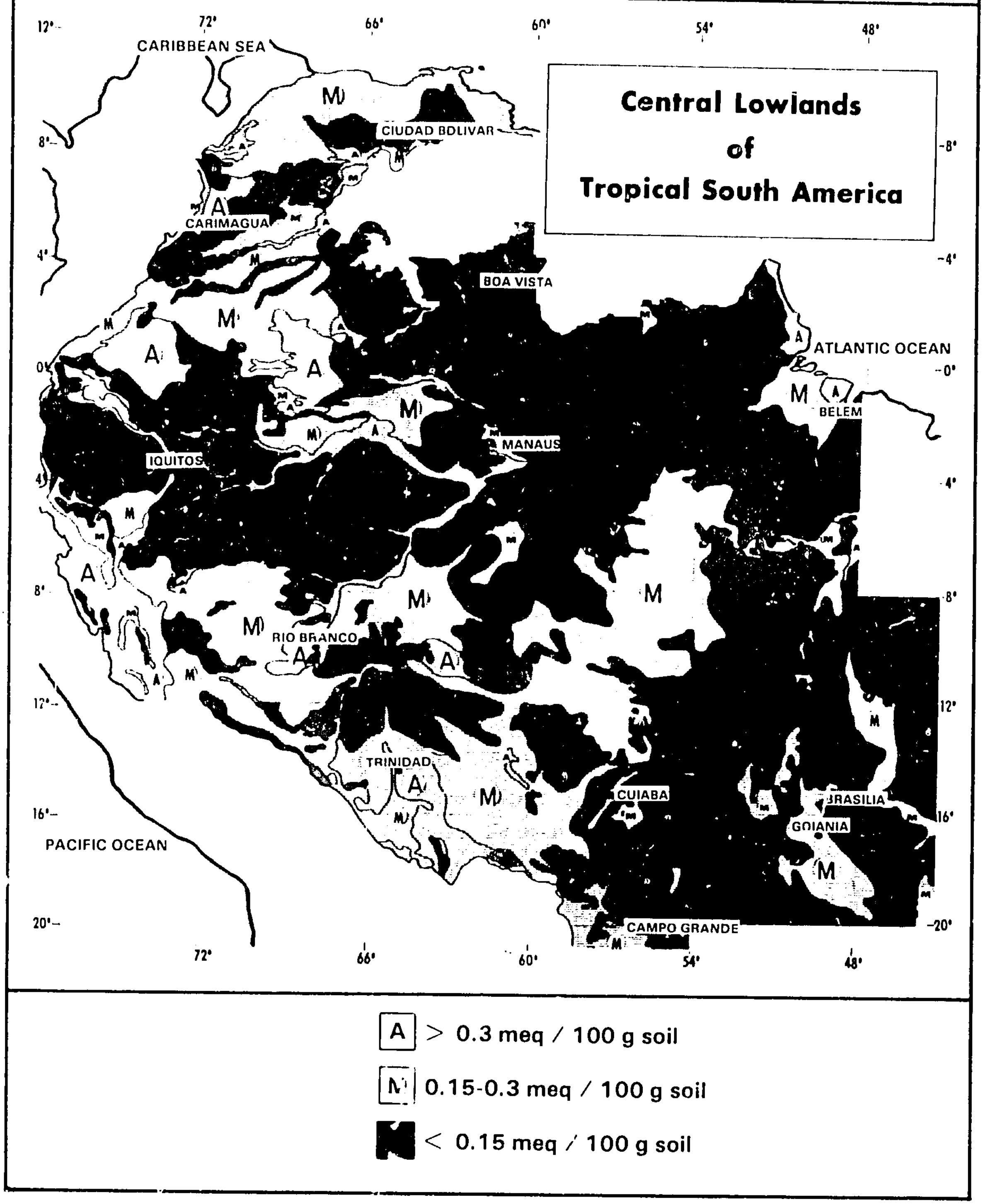


AL SATURATION LEVELS IN SUBSOIL (21–50 cm)

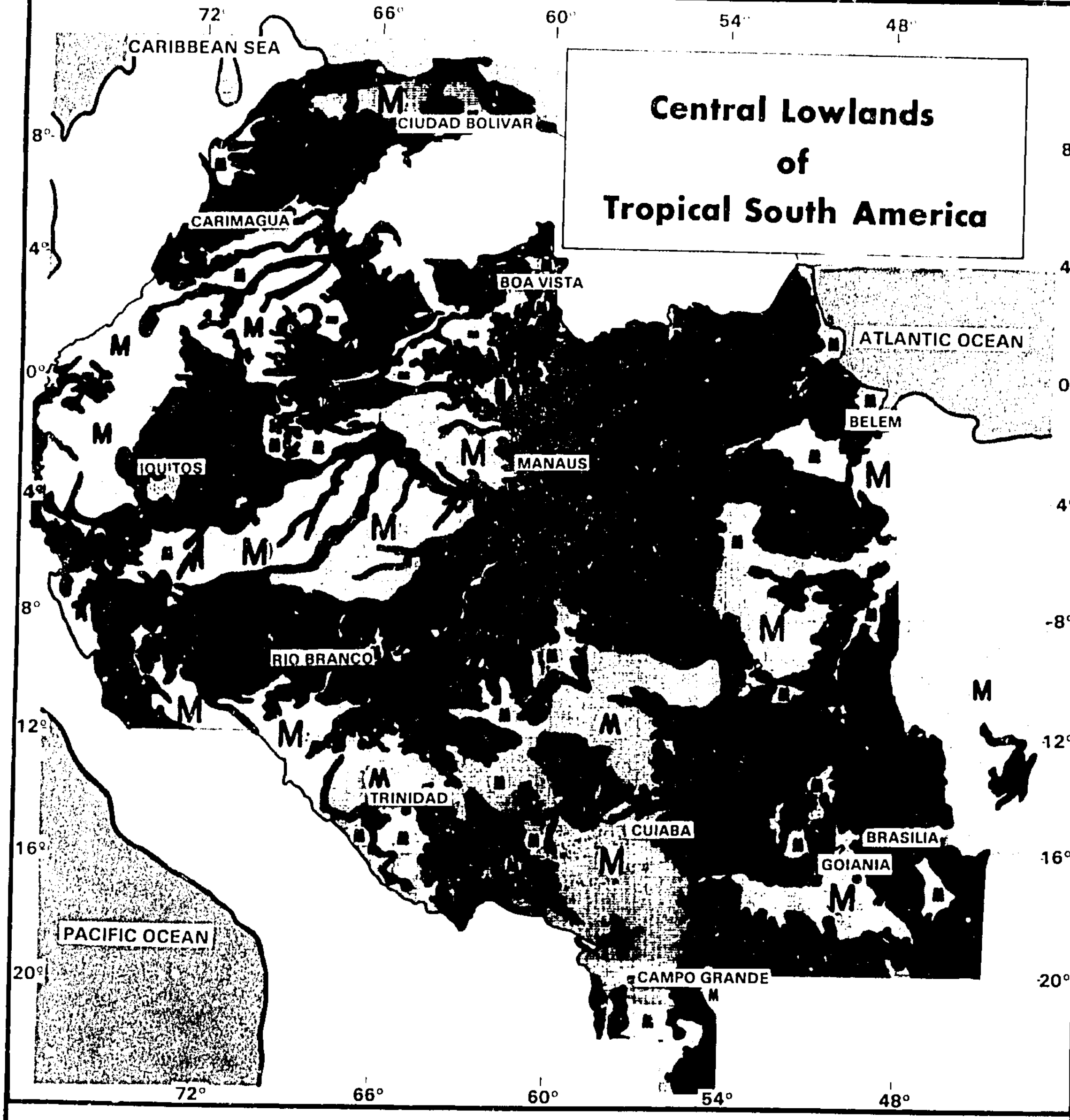


A	> 70%	H	40 - 70%
M	10 - 40%	B	< 10%

POTASH LEVELS IN TOPSOIL (0–20 cm)



Ca LEVELS IN TOPSOIL (0–20 cm)

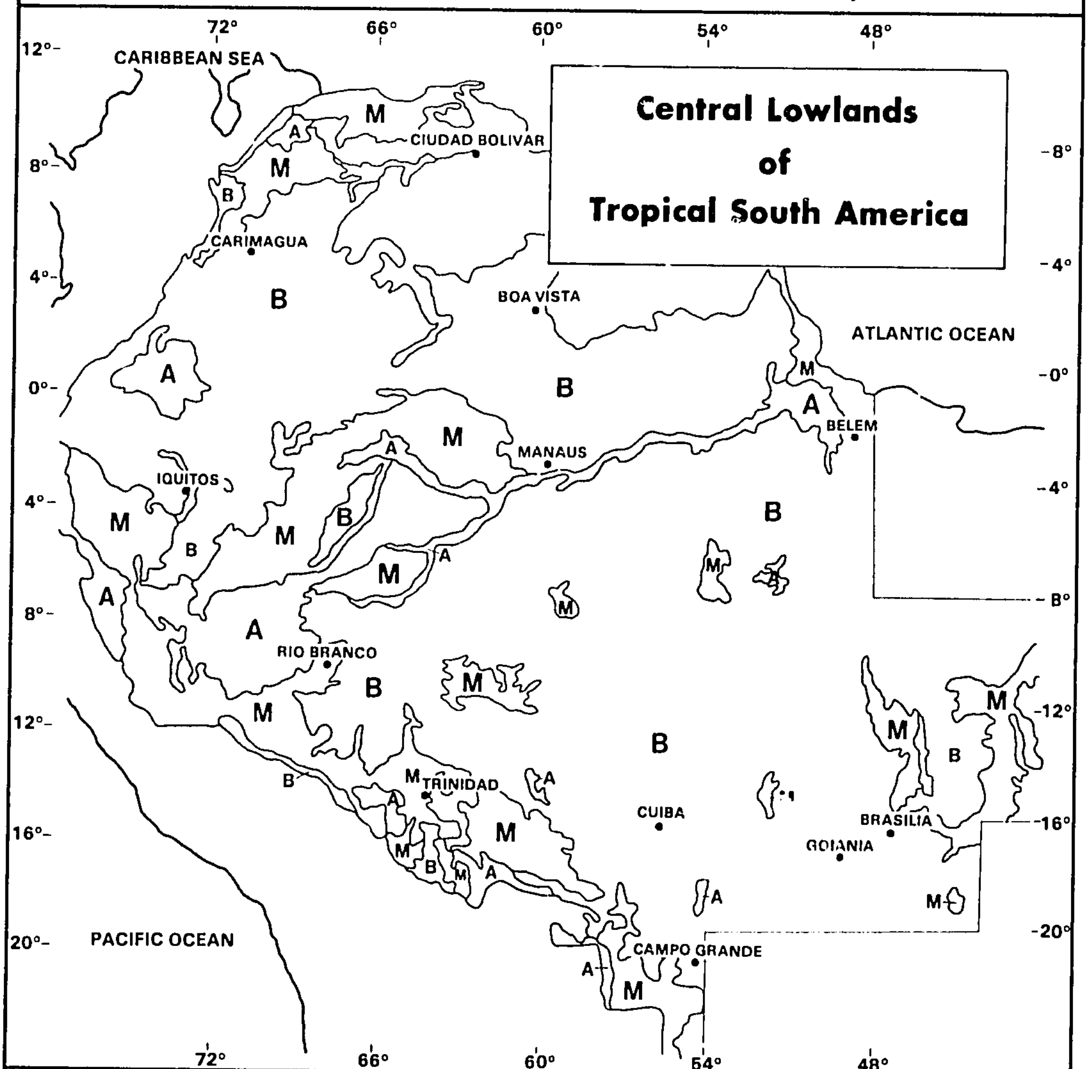


■ > 4 meq/100 g soil

M 0.4–4 meq/100 g soil

■ < 0.4 meq/100 g soil

Ca LEVELS IN SUBSOIL (21–50 cm)

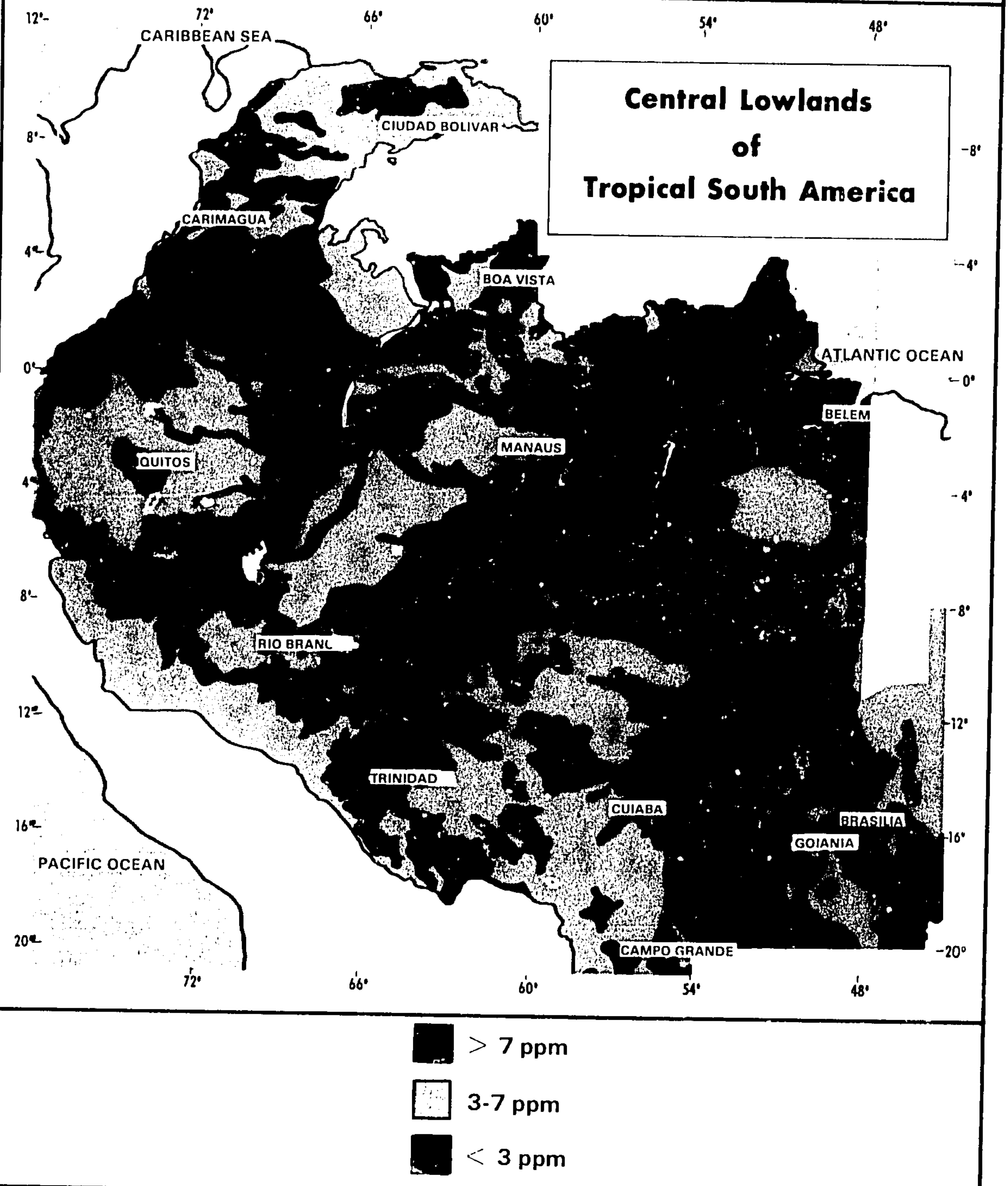


A > 4 meq/100 g soil

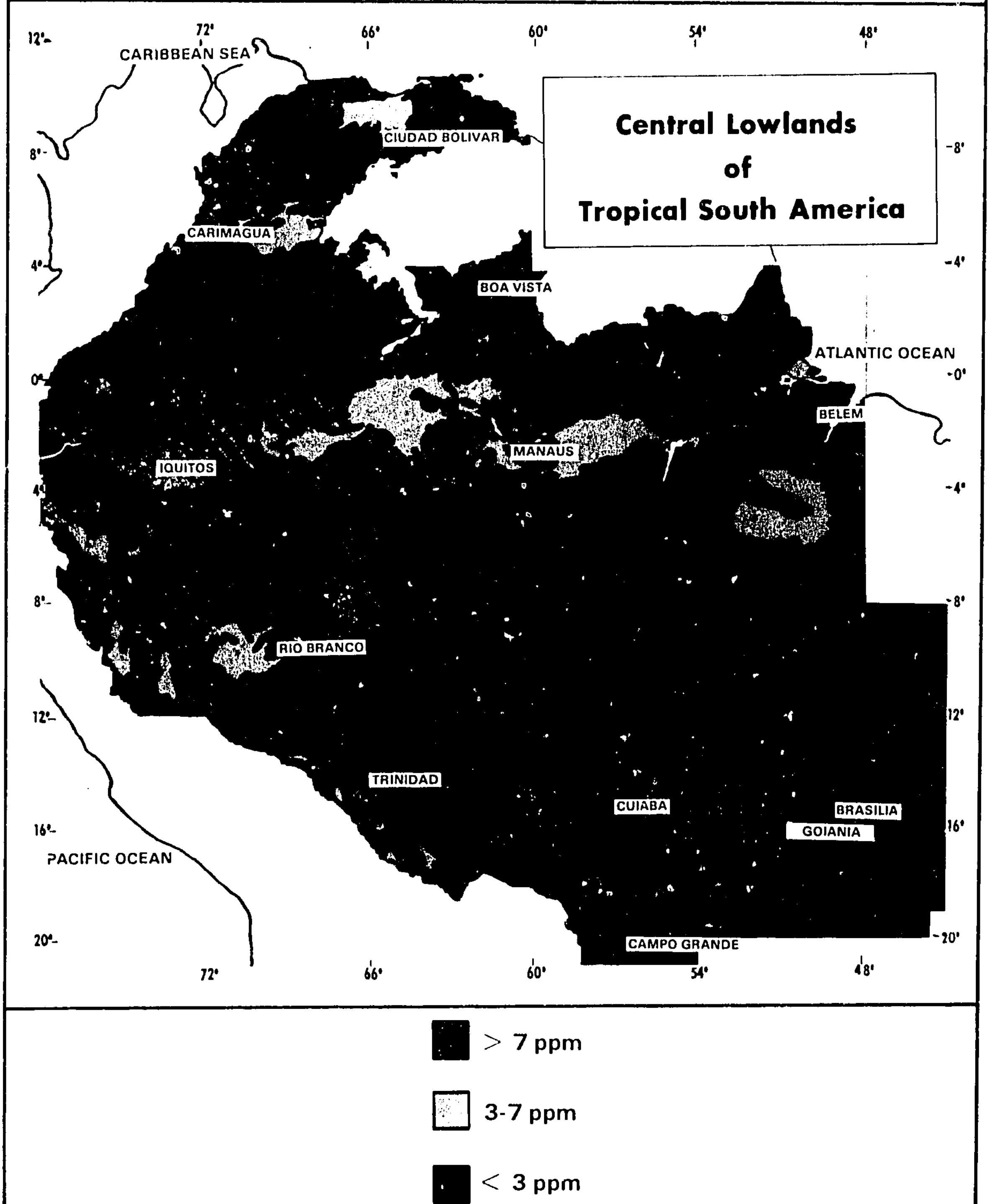
M 0.4–4 meq/100 g soil

B < 0.4 meq/100 g soil

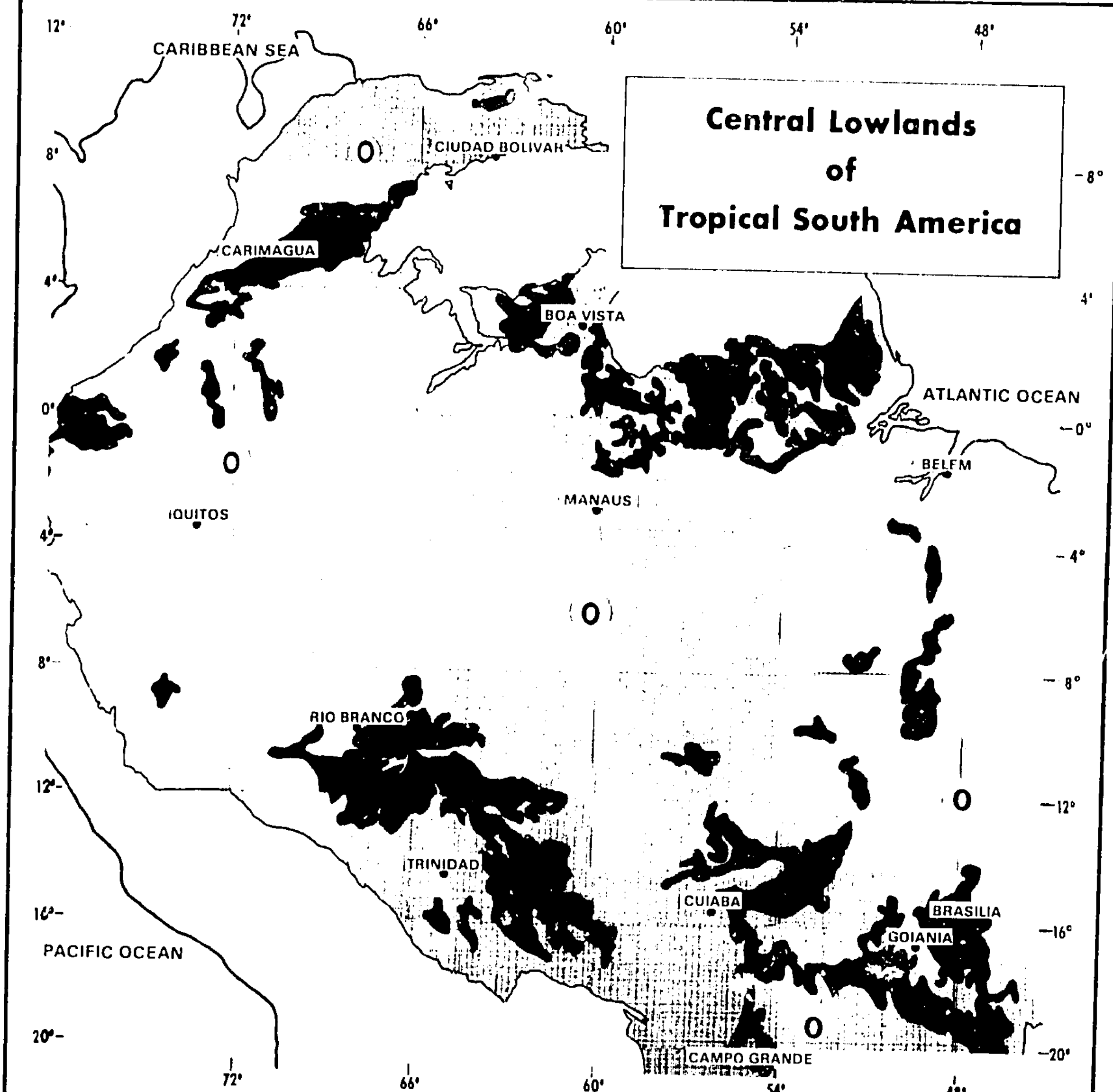
P LEVELS IN TOPSOIL (0–20 cm)



P LEVELS IN SUBSOIL (21–50 cm)



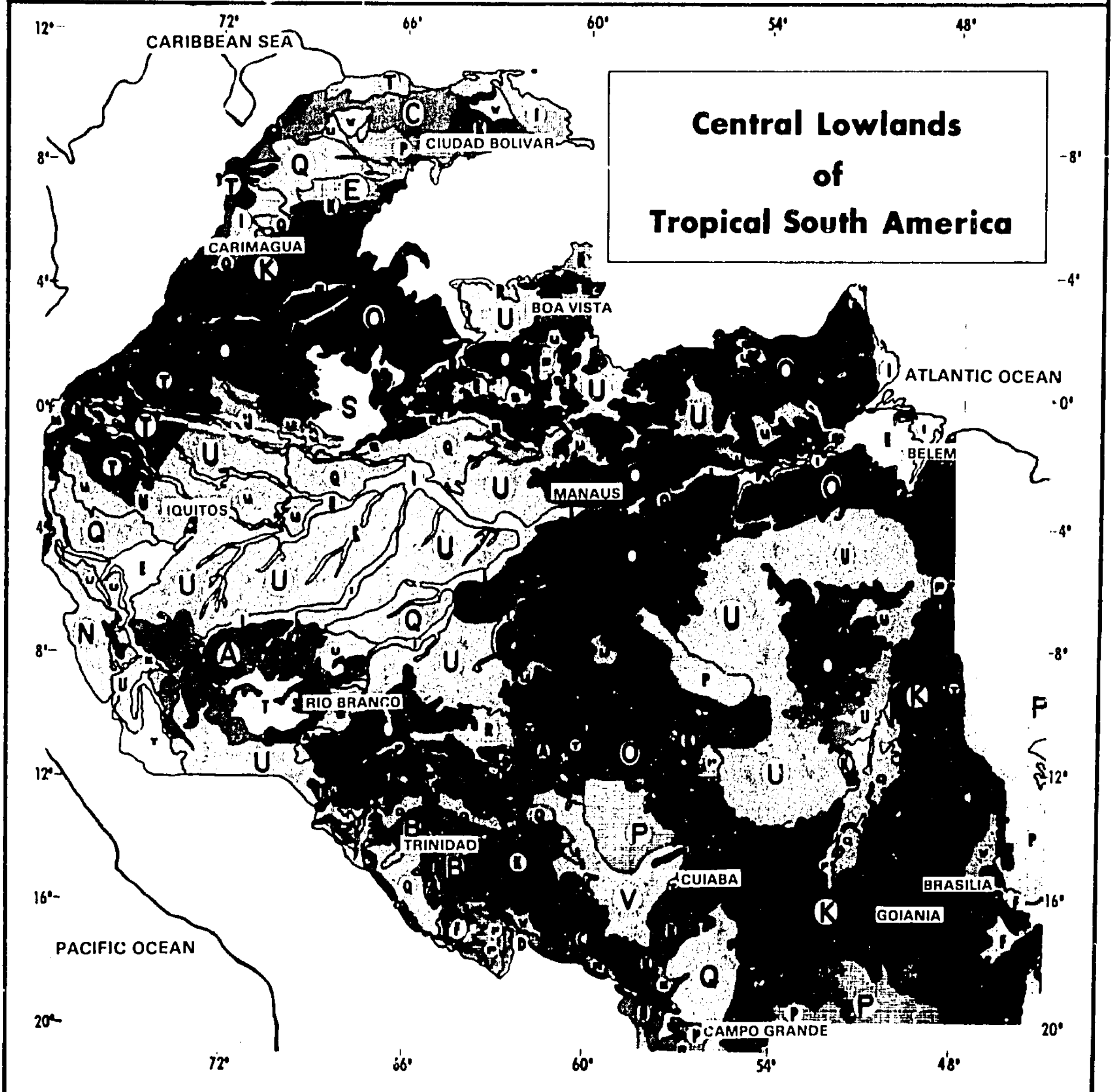
P FIXATION IN TOPSOIL (0–20 cm)



Phosphorus fixation (> 35% clay, % free Fe_2O_3/% Clay > 0.15)

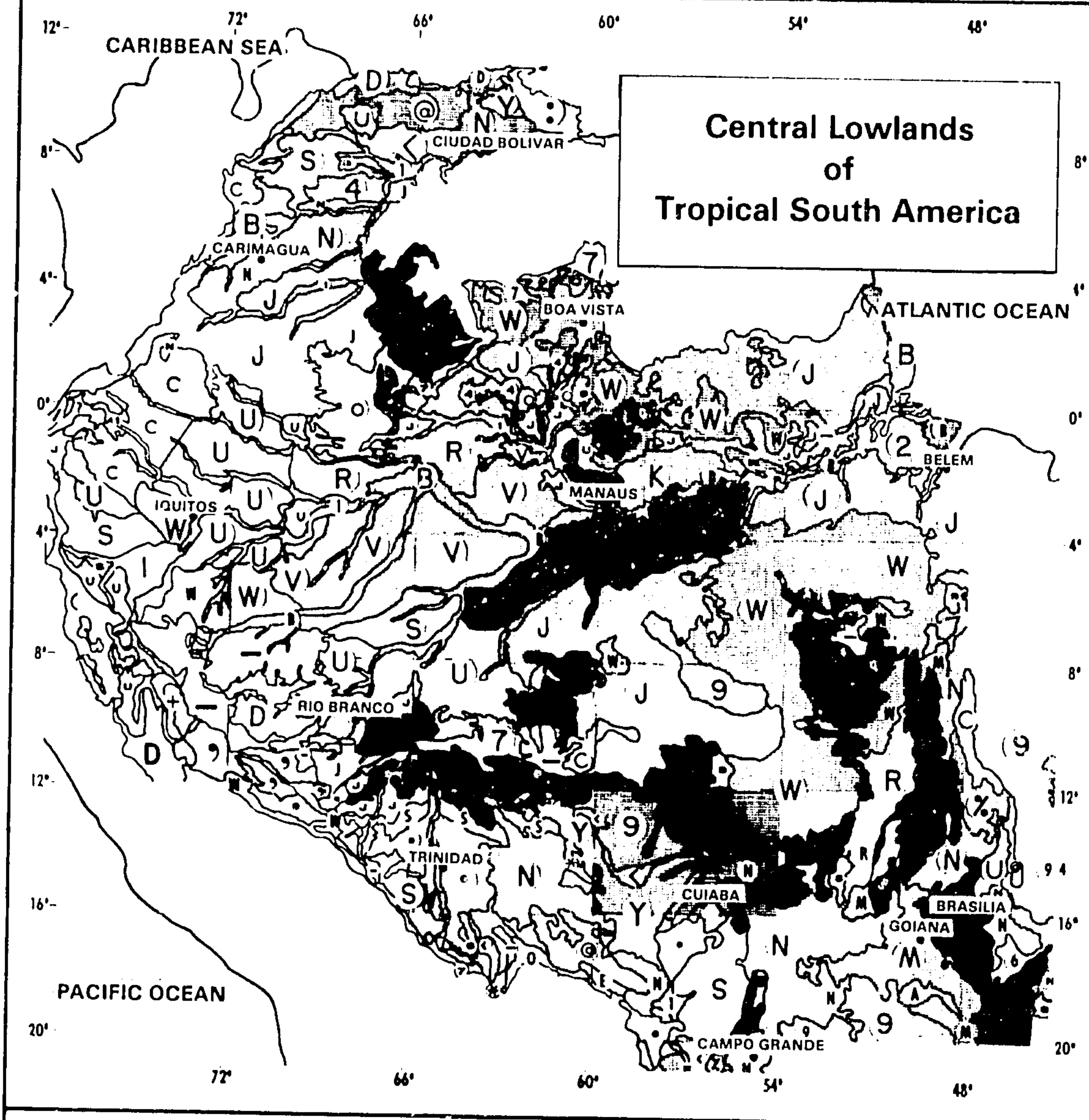
O No or low phosphorus fixation (< than specified for ■)

SUBORDER SOILS WITH POSSIBLE VARIABLE CHARGE



B	Aqualfs	P	Psamments	J	Aquox
A	Udalfs	N	Andepts	O	Orthox
C	Ustalfs	I	Aquepts	K	Ustox
X	Xeralfs	T	Tropepts	S	Aquods
D	Orthids	T	(Dystropepts)	Q	Aquults
E	Aquents	M	Aquolls	U	Udults
F	Fluvents	G	Udolls	V	Ustults
R	Orthents	H	Ustolls		

GREAT GROUP SOILS WITH POSSIBLE NET POSITIVE CHARGE IN SUBSOIL HORIZON



Symbol	Great group	Symbol	Great group	Symbol	Great group	Symbol	Great group
\	Natraqualfs	4	Psammaquents	:	Sulfaquepts	N	Haplustox
.	Tropaqualfs	5	Tropaquents	B	Tropaquepts	O	Tropaquods
+	Hapludalfs	6	Tropofluvents	C	Dystropepts	P	Albaquults
$	Rhodudalfs	)	Ustifluvents	D	Eutropepts	Q	Paleaquults
—	Tropudalfs	•	Xerofluvents	-	Ustropepts	R	Plinthaquults
@	Haplustalfs	7	Troporthents	E	Haplaquolls	S	Tropaquults
&	Natrustalfs	8	Ustorthents	F	Argiudolls	T	Hapludults
¬	Paleustalfs	9	Quartzipsamments	;	Haplustolls	U	Paleudults
%	Rhodustalfs	>	Tropopsamments	G	Plinthaquox	V	Plinthudults
÷	Tropustalfs	<	Ustipsamments	■	Acrorthox	,	Rhodudults
?	Haploxeralfs	(	Dystrandepts	I	Eutrorthox	W	Tropudults
|	Camborthids	/	Hydrandepts	J	Haplorthox	Y	Haplustults
1	Fluvaquents	=	Haplaquents	K	Umbriorthox	Z	Paleustults
2	Haplaquents	A	Humaquepts	■	Acrustox	X	Rhodustults
3	Hydraquents	#	Plinthaquepts	M	Eutrustox	10	Chromudents

Chapter 5.
SOIL CLASSIFICATION

Identification of land facets within land systems was used to bridge the gap between land units and soil units, as facets are often relatively uniform insofar as soil properties are concerned. As emphasized in Chapter 4, although land facets may contain soils with differing properties, some level of generalization must be accepted in making an inventory of land resources. This chapter describes the soil classification systems used to summarize soils and their fertility constraints.

Soil Taxonomy

The soils of the land facets were first classified as far as the Great Group category of Soil Taxonomy (Soil Survey Staff, 1975), then described in terms of their physical and chemical properties. In Soil Taxonomy, soils are not grouped according to those having "similar physical and chemical properties that reflect their response to management and manipulation for use" until the soil Family category is reached. This follows the subdivision of the Great Groups into Subgroups, according to the scheme:

- Order (10 subdivisions)
- Suborder (47 subdivisions)
- Great Group (230 subdivisions)
- Subgroup (970 subdivisions in the USA)
- Family

The Order category separates soils according to their gross morphology by the presence or absence of diagnostic horizons. The Suborder separates the Orders according to criteria that distinguish the major reasons for the presence or absence of horizon differentiation, principally as related to moisture and temperature regimes. The Great Group further separates soils according to the complete assemblage of their several horizons and the most significant properties of the whole soil. However, the Subgroup category is virtually only a separation of the Great Group category, in terms of soils which:

a. Follow the central concept of the Great Group;
b. Are intergrades or transitional forms to other Orders, Suborders, or Great Groups;
c. Are extragrades—soils that have some properties not representative of the Subgroups.

In other words, the separation according to Subgroup is a convenience that does not add much to our knowledge about the characteristics of the soils. For this reason, it was decided to classify soils only as far as the Great Group level, then describe them in terms of their physical and chemical characteristics in such a way as to facilitate the computer grouping and comparison of properties.

The Land Systems Map and its Legend (Volume 2) details the soil classification of the land facets within the land systems to the Great Group level. Table 2-4 (Chapter 2) summarizes the Great Group classes identified. A summary of the land facet soil classification to the Great Group level, together with equivalents according to the FAO legend, is also recorded in Part 1 of Volume 3, the *Computer Summary and Soil Profile Descriptions*. Maps 6, 7, and 8 (see Map Plates) are small-scale maps based on computer printouts illustrating the extent of the soil Orders, Suborders, and Great Groups.

FAO-Unesco Soil Legend

For the convenience of readers accustomed to using the FAO-Unesco soil legend, this soil classification system (FAO-Unesco, 1974) was also used and has been recorded for the land facets within the land systems on the soil classification legend accompanying the Land Systems Map. This has also been coded to facilitate map making. Table 2-5 (Chapter 2) summarizes the major soil classes identified by this system. Soil climate parameters are not inherent in application of the FAO legend. Maps 9 and 10 are small-scale maps of the region using the FAO legend.

Brazilian Soil Classification System

Appendix 1 contains an approximate cross-indexing of the Brazilian soil classification system (Camargo et al., 1975) with Soil Taxonomy and the FAO-Unesco soil legend.

Note on Soil Classification Terminology

Soil classification terminology is regarded by many agronomists as so much gobbledygook, reserved for the special precinct of communication between soil surveyors. Yet, as illustrated by Eswaran (1977), a lot of information concerning soil fertility is available from soil names, particularly in the case of soils classified according to Soil Taxonomy (Soil Survey Staff, 1975). Table 5-1 lists the main soil names used, and what might be deduced from these names, following

Table 5-1. Summary of direct or inferred limiting conditions for Soil Taxonomy taxa identified in the study.

Soil class[a]	Limiting conditions[b]															
	Root res. layer	Text.	Hyd. cond.	Red. cond.	Mois. str.	Low CEC	High Al	Acid sulp.	Anion fix.	Nitr. min.	Vert. prop.	Low min. cont.	Carb. gyps.	Sal. Alk.	Soil temp.	Type char.
A																
AAQ				x												
AAQNA				x										x		
AAQTR				x												
AUD																
AUDHA																
AUDRH									x							
AUDTR																
AUS					x											
AUSHA					x											
AUSNA			x		x									x		
AUSPA					x								x			
AUSRH																
AXE					x											
AXEHA					x											
D					x											
DOR					x											
DORCH					x											
E																
EAQ				x												
EAQFL				x												
EAQHA				x												
EAQHY				x												x
EAQPS		x		x												
EAQTR																
EFL																
EFLTR																
EFLUS					x											
EFLXE					x											
EOR																
EORTR																
EORUS					x											
EPS		x														
EPSQU		x			x							x				
EPSTR		x			x											
H																
HHE																
HHETR																
I																
IAN									x	x						
IANDY							x		x	x						
IANHY									x	x		x				
IAQ				x												
IAQHA				x												
IAQHU				x												

IAQPL	x			x												
IAQSU				x			x	x								
IAQTR				x												
ITR																
ITR[illegible]Y							x									
ITR[illegible]U																
ITRUS					x											
M																
MAQ				x												
MAQHA				x												
MUD																
MUDAR																
MUS					x											
MUSHA					x											
O						x	x		x			x				
OAQ	x			x		x	x		x			x				
OAQPL	x			x		x	x		x			x				
OOR						x	x		x			x				
OORAC						x	x		x			x				x
OOREU						x			x			x				
OORHA						x	x		x			x				
OORUM						x	x		x			x				
OUS					x	x	x		x			x				
OUSAC					x	x	x		x			x				x
OUSEU					x	x			x			x				
OUSHA					x	x	x		x			x				
U							x									
UAQ				x			x									
UAQAL			x	x			x									
UAQPA				x			x					x				
UAQPL	x		x	x			x					x				
UAQTR				x			x									
UUD							x									
UUDHA							x									
UUDPA							x					x				
UUDPL	x		x				x									
UUDRH							x		x							
UUDTR							x									
UUS					x		x									
UUSHA					x		x									
UUSPA					x		x					x				
UUSRH					x		x		x							
V			x								x					
VUD			x								x					
VUDCH			x								x					

a. See Table 2-4.

b. In order, refer to: root restriction layer, texture, hydraulic conductivity, reducing conditions, moisture stress, low cation-exchange capacity, high aluminum content, acid sulphate, anion fixation, nitrogen mineralization, vertic properties, low mineral content, carbonates and gypsum, salinity and alkalinity, soil temperature, type of charge.

SOURCE: Eswaran, 1977.

Table 5-2. Fertility Capability Classification (FCC).

FCC code	Name/condition	Characteristics
	Type[a]	
S	Sandy topsoils	Loamy sands and sands (USDA)
L	Loamy topsoils	< 35% clay but not loamy sand or sand
C	Clayey topsoils	> 35% clay
O	Organic soils	> 30% O.M. to a depth of 50 cm or more
	Substrata Type[b]	
S	Sandy subsoil	Texture as in Type above
L	Loamy subsoil	Texture as in Type above
C	Clayey subsoil	Texture as in Type above
R	Rock or other hard root restricting layer	
	Condition Modifiers[c]	
*g	Gley	Mottles ≤ 2 chroma within 60 cm of surface and below all A horizons or saturated with H_2O for > 60 days in most years
*d	Dry	Ustic or xeric environments; dry, > 60 consequtive days per year within 20-60 cm depth
e	Low CEC	< 4 meq/100 g soil by Σ bases + unbuffered Al < 7 meq/100 g soil by Σ cations at pH 7 < 10 meq/100 g soil by Σ cations + Al + H at pH 8.2
*a	Al toxic	< 60% Al saturation of CEC by (Σ bases and unbuffered Al) within 50 cm < 67% Al saturation of CEC by (Σ cations at pH 7) within 50 cm < 86% Al saturation of CEC by (Σ cations at pH 8.2) within 50 cm; or pH < 5.0 in 1:1 H_2O except in organic soils
*h	Acid	10-60% Al saturation of CEC by (Σ bases and unbuffered Al) within 50 cm; or pH in 1:1 H_2O between 5.0 and 6.0
i	Fe-P fixation	% free Fe_2O_3/% clay > 0.15 or hues redder than 5YR and granular structure
x	X-ray amorphous	pH > 10 in 1N NaF or positive to field NaF^- test or other indirect evidences of allophane dominance in clay fraction
v	Vertisol	Very sticky plastic clay > 35% clay and > 50% of 2:1 expanding clays; COLE > 0.09; Severe topsoil shrinking and swelling
*k	K deficient	< 10% weatherable minerals in silt and sand fraction within 50 cm; or exch. K < 0.20 meq/100 g soil or K < 2% of Σ of bases, if Σ of bases < 10 meq/100 g soil
*b	Basic reaction	Free $CaCO_3$ within 50 cm (fizzing with HCl) or pH > 7.3
*s	Salinity	4 mmhos/cm of saturated extract at 25°C within 1 meter
*n	Natric	> 15% Na saturation of CEC within 50 cm
*c	Cat clay	pH in 1:1 H_2O is < 3.5 after drying, jarosite mottles with hues 2.5Y or yellower and chromas 6 or more within 60 cm

a. Texture is average of plowed layer or 20-cm depth (8"), whichever is shallower.

b. Used if textural change or hard root restricting layer is encountered within 50 cm (20").

c. In plowed layer or 20 cm (8"), whichever is shallower unless otherwise specified by an *.

SOURCE: Adapted from Buol et al. (1975).

Eswaran's approach. In Appendix I, which summarizes equivalent names using Soil Taxonomy, the FAO Legend (FAO-Unesco, 1974), and the Brazilian classification systems, it is evident that the soil names of other classification systems can also be used to obtain an overview of potential soil-nutrient problems.

Soil Fertility Capability Classification

The FCC (Fertility Capability Classification) system proposed by Buol et al. (1975), and incorporated in a slightly modified form as an integral part of the present study, synthesizes key fertility information usually available from soil survey reports. It is considered a technical classification system (Cline, 1949) specifically designed to help soil fertility specialists. Effectively, it systematizes much of what may be gleaned from soil survey reports, particularly those following Soil Taxonomy methodology. It provides a convenient checklist of the major potential problems affecting soil fertility, both physically and chemically speaking. By so doing, it obviates the need for soil fertility specialists to have an in-depth knowledge of soil classification and soil survey methodology.

The FCC system consists of three categorical levels: the Type, Substrata Type, and Condition Modifier. In brief, the Type is the average texture of the topsoil (0–20 cm), the Substrata Type is the average texture of the subsoil (21–50 cm), and the Condition Modifiers refer to chemical or physical conditions. Table 5-2 defines the Fertility Capability Classification (FCC) as proposed by Boul et al. (1975). The Conditioner Modifier constraints, and the minor changes in their definition used in the Land Systems Map, are as follows:

- a: Al toxic. In *The Land Systems Map and its Legend,* "a" is defined as greater than 70% saturation of the ECEC, in contrast with Buol et al.'s 60% level. Plants sensitive to Al toxicity will be affected.
- b: base reaction free carbonate. Rock phosphate and other nonwater-soluble phosphate should be avoided. Potential deficiency of some micronutrients, mainly Mn, Fe, and Zn.
- c: cat clays, potential acid sulphate soils. Drainage not recommended without special practices such as brine flushing (H. Evans, pers. comm.). Might be managed with plants tolerant to flooding and high water tables.
- d: a dry condition. An annual dry season of at least 60 consecutive days. Limitations to soil moisture. Planting dates for annual crops should plan for flush of N at onset of rains.
- e: low CEC. Low ability to retain nutrients for plants, mainly Ca, K, and Mg.
- g: a gley condition in the subsoil as an indication of water saturation within 60 cm of the soil surface.
- h: acid. High soil acidity. Possible need for liming and some trace elements. In *The Land Systems Map and its Legend,* this has been defined as those soils with a pH less than 5.3.
- i phosphorus fixation. Potentially high P-fixation capacity. Requires high levels of P fertilizer. Sources and methods of P fertilizer application should be carefully considered.
- k: K-deficient. Low ability to supply K. In *The Land Systems Map and its Legend,* the level of exchangeable K for this modifier has been reduced to 0.15.
- n: natric. High levels of sodium. Requires special soil-management practices for alkaline soils.
- s: salinity. Presence of soluble salts. Requires special soil-management practices.
- v: vertisol. Clayey-textured topsoil. Tillage is difficult when soil is too moist (or, conversely, too dry), but soils can be highly productive.
- x: x-ray amorphous. Often high P-fixation capacity.

Many of these conditions naturally occur together in the central lowlands of tropical America (Map 11).

The FCC indexes the common information a soil fertility specialist examines when studying soil analytical data for potential limitations. It provides a convenient checklist of potential constraints and is a very handy supplement to the computerized soil chemical data.

Soil Analytical Data

Soil survey reports contain a wealth of soil profile analyses; most national soil laboratories furnish guidelines for interpreting these analyses. A lot of information can be obtained from such data, but they must be interpreted in the light of crop requirements.

In the land-systems study, an innovation was introduced to provide a guide to soil-nutrient levels: levels were detailed in terms of crop requirements. For example, P levels are described as low (inadequate for most crops except those tolerant to low levels), medium (inadequate for crops requiring high levels of the nutrient), and high (adequate for most crops). This approach should provide a clearer idea of soil nutrient levels, particularly for the fertility specialist faced with choosing basic field trial treatments and developing fertilizer recommendations for new genetic materials, especially those purported to have partial tolerance to toxic elements, such as Al and Mn, or to produce satisfactorily with low levels of soil nutrients such as P.

Summary of Soils of the Region

Soil Geography

The distribution, by area, of soils of the region is shown in Table 5-3 at the Order, Suborder, and Great Group levels. (This table is considered tentative and subject to change as more detailed surveys become available.) All 10 soil Orders are represented in the region; however, because of their limited extent, Histosols and Vertisols are not shown in Maps 6, 7, and 8. The majority of the soils are classified as Oxisols and Ultisols, which together account for 66% of the region. Following in extensiveness are the Entisols with about 19%, most of which are of alluvial origin found along the river network. The remaining orders cover relatively small areas, but they are locally important: Alfisols cover 6.7%; Inceptisols, 6.3%; and Spodosols, Mollisols, Aridisols, Vertisols, and Histosols, with less than 1% all together. Table 5-3 also shows that 48% of the region is included in five Great Groups: Haplorthox (18%), Tropudults (10%), Acrorthox (8%), Fluvaquents (6%), and Quartzipsamments (6%).

Table 5-3. Aereal extent of the Great Group soil classes in the central lowlands of tropical South America. (Tentative classification.)

Order	Suborder	Great Group	Area (million ha)	Percentage of total area
Oxisols	Orthox	Haplorthox	150.0	18.3
		Acrorthox	62.0	7.6
		Umbriorthox	4.0	0.5
		Eutrorthox	0.8	< 0.1
	Ustox	Haplustox	53.0	6.5
		Acrustox	32.0	3.9
		Eutrustox	24.0	3.0
	Aquox	Plinthaquox	1.0	0.1
		Total Oxisols	326.8	40.0
Ultisols	Udults	Tropudults	82.0	10.1
		Plinthudults	30.0	3.6
		Paleudults	29.0	3.5
		Rhodudults	4.0	0.5
	Aquults	Tropaquults	37.0	4.4
		Plinthaquults	15.0	1.8
		Paleuquults	0.3	< 0.1
		Albaquults	0.1	< 0.1
	Ustults	Haplustults	8.5	1.0
		Rhodustults	4.9	0.6
		Paleustults	1.6	0.2
		Total Ultisols	212.4	25.9
Entisols	Aque[illegible]	Fluvaquents	50.6	6.2
		Tropaquents	8.8	1.1
		Psammaquents	3.9	0.5
		Hydraquents	1.1	0.1
	Psamments	Quartzipsamments	52.0	6.4
		Ustipsamments	6.1	0.7
		Tropopsamments	2.2	0.3
	Fluvents	Tropofluvents	16.0	2.9
		Ustifluvents	0.7	< 0.1
		Xerofluvents	0.7	< 0.1
	Orthents	Troporthents	9.4	1.1
		Udorthents	3.3	0.4
		Ustorthents	1.1	0.1
		Total Entisols	155.9	20.0
Alfisols	Aqualfs	Tropaqualfs	19.1	2.3
		[illegible]aqualfs	< 0.1	< 0.1
	Udalfs	Tropudalfs	19.4	2.4
		Rhodudalfs	0.5	< 0.1
		Haplustalfs	6.6	0.8
	Ustalfs	Tropustalfs	6.2	0.8
		Rhodustalfs	2.7	0.3
		Paleustalfs	1.2	0.1
	Xeralfs	Haploxeralfs	0.5	< 0.1
		Total Alfisols	56.3	7.0
Inceptisols	Aquepts	Tropaquepts	19.1	2.3
		Sulfaquepts	3.0	0.4
		Humaquepts	1.0	0.1
		Haplaquepts	< 0.1	< 0.1
		Plinthaquepts	< 0.1	< 0.1
	Tropopepts	Eutropepts	12.5	1.5
		Dystropepts	7.7	0.9
		Ustropepts	6.6	0.8
	Andepts	Dystrandepts	1.1	0.1
		Hydrandepts	0.2	< 0.1
		Total Inceptisols	51.4	6.4
Spodosols	Aquods	Tropaquods	11.0	1.4
Mollisols	Aquolls	Haplaquolls	1.3	0.2
	Udolls	Argiudolls	< 0.1	< 0.1
		Total Mollisols	1.3	0.2
Aridisols	Orthids	Camborthids	1.2	0.1
Vertisols	Uderts	Chromuderts	0.5	0.1
Histosols	Hemists	Tropohemists	0.2	< 0.1
		TOTAL	817	101.5[a]

a. Numbers are rounded to the nearest decimal; amounts less than 0.1 were counted as 0.1.

Oxisols. Haplorthox are well-drained Oxisols with very low native fertility but fairly good soil structure. They are also known as Xanthic Ferralsols (FAO) and Latossolos (Brazilian system). Many of them have very high clay contens. Acrorthox are similar except for a lower clay cation-exchange capacity. Table 5-4 shows chemical data from two Oxisol profiles, one from the Cerrados of central Brazil and the other from Amazonia. They are deep, uniform, well-drained soils dominated by low-activity clays. Their structure is good, but they are very acid and low in bases and P. The Oxisols of the savannas may be high P fixers; those found in the forested regions are generally not high P fixers. Oxisols are common throughout the Amazon and the well-drained savanna regions (see Photo Plates).

Ultisols. Ultisols are fairly extensive in both well-drained and poorly drained positions. Tropudults, Paleudults, and Plinthudults are fairly well-drained, acid, infertile soils but with less desirable physical properties than the Oxisols because of a significant clay increase with depth. They are also known as Orthic Acrisols (FAO) and Podsolico Vermelho Amarelo (Red Yellow Podzolics) in the Brazilian classification system. The difference between these Great Groups—the depth to the "clay bulge" in the subsoil—is of little agronomic relevance. In Table 5-4, examples are given for a well-drained Paleudult and a poorly drained Plinthaquult found on the well- and poorly drained positions of the tropical rain forest, subregion A. The well-drained member is acid, infertile, and susceptible to compaction because of its low clay content. The poorly drained member shows high exchangeable Al contents in the subsoil, corresponding to a clayey mottled layer, a mixture of kaolinite and montmorillonite, which appears at first glance to be plinthite; however, analysis shows it is not (Sánchez and Buol, 1974). It is suspected that many of the soils classified as Plinthudults by various authors are either Paleudults or Hapludults. Some of these soils are devoted to shifting cultivation in the upper Amazon, but most are still under native vegetation because of their low productivity.

Alluvial soils. Soils along the flood plains of the rivers, although less extensive, are very important because this is where food crops can be expected to yield well without the need for soil amendments. They show little or no profile development and are classified as Entisols (Great Group, Fluvaquents), Inceptisols, and Mollisols. These soils are known in other classification systems as Alluvials, Hydromorphics, Low Humic Gleys, and Dystric or Eutric Gleysols. Periodic flooding is the main limiting factor.

An example of an Entisol is given in Table 5-4. However, from region to region there are often major differences in native fertility due to the source of sediments, a highly variable characteristic of *várzeas* and *barriales* soils. Consequently, it cannot be generalized that alluvial soils are always of high native fertility.

Sandy soils. Extensive areas of sandy soils, mainly Quartzipsamments, are found in the Espigão Mêstre and Parecis tablelands of eastern and western Brazil, respectively. The former region is desert in appearance; the latter is covered by grasslands affected by a strong dry season. There are considerable areas of other light-textured soils in the region, such as the Psamments in the vicinity of Três Lagoas, mainly eastward of the Paraná river.

Spodosols. A soil Order that attracts attention is the Spodosols, also known as Podzols, Ground Water Podzols, and Giant Tropical Podzols, including their deeper variants as Psamments. These soils are derived from coarse sandy materials and are found in clearly definable spots in parts of the Amazon away from the flood plains. Native forest vegetation is often different from that found on Oxisols and Ultisols. It is called *campinaranas* in Brazil. The Projeto Radambrasil recently identified large areas of Spodosols along the headwaters of the Rio Negro, which largely account for the color of this river; water passing through Spodosols characteristically carries suspended organic matter. Table 5-4 shows one example near the Ducke Forest near Manaus. Because of this extreme infertility and susceptibility to erosion, it would be better to leave the Spodosols in their natural state. Unfortunately, they have received more scientific attention than they deserve in terms of their areal extent (1.4% of the region). Therefore, the research on tropical Spodosols in the international literature (Klinge, 1971, 1975; Stark, 1978; Sombroek, 1966, 1979) should be kept in perspective; further, under no circumstances should results be extrapolated to the dominant Oxisols and Ultisols.

Well-drained fertile soils. Unfortunately only about 5.2% of the region has well-drained soils high in native fertility. These are classified mainly as Tropudalfs and Paleustalfs (Terra Roxa Estruturada), Eutropepts (Eutric Cambisols), Tropofluvents (well-drained Alluvials), Argiudolls (Chernozems), Eutrustox and Eutrorthox (Terra Roxa Legítima), and Chromuderts (Vertisols). Nevertheless, they represent a total of 42 million ha, and, where they occur, permanent agriculture has a better chance of success.

The Terra Roxa soils combine high native fertility with excellent physical properties; Table 5-4 shows an example of a Terra Roxa Estruturada near Altamira, Brazil. Many of the successful cacao plantations are located on such soils. Examples are found near Altamira, Porto Velho, and Rio Branco in Brazil, and in the "orient" (eastern region) of Ecuador associated with relatively recent volcanic deposits. Their relatively limited extent can be seen in Map 8, showing the Great Group soil classes.

Laterite or plinthite hazard. The area of soils with plinthite in the subsoil (Plinthaquox, Plinthaquults, Plinthudults) is limited. They total about 46 million ha, or 5.6% of the region. This point deserves emphasis, given the broad generalization that many tropical soils, if brought into production, will be irreversibly transformed into hardened plinthite or laterite. These three Great Groups are the only soils where this phenomenon can occur. However, as the soft plinthite is in the subsoil, the topsoil has to be first removed by erosion and the remaining soil dried out before irreversible hardening to laterite can take place. Since these soils occur mainly on flat and often poorly drained landscapes, erosion is not likely to be extensive.

It should be noted that many poorly drained subsoils of other soil Great Groups have mottled colors resembling phinthite, but are, in fact, mixtures of 1:1 and 2:1 clay minerals (Tyler et al., 1978). The subject of hardened plinthite is discussed in Chapter 6.

Table 5-4. Soil profile analyses of some typical soils found throughout the central lowlands of tropical South America.

Horizon depth (cm)	Clay (%)	Sand (%)	pH in H_2O	Organic C (%)	Exchangeable cations[a] (meq/100 g) Al	Ca	Mg	K	ECEC (meq/100 g)	Al Sat. (%)	P (ppm)
OXISOLS											
Typic Acrustox (Latosol Vermelho Amarelo). FCC: cdhakei. Experimental Station Brasilia, Brazil[b]											
0- 12	45	28	5.1	1.87	1.8	0.2		0.08	8.6	85	1
12- 30	44	26	5.0	1.40	1.4	0.2		0.05	6.6	82	1
30- 50	48	25	5.2	1.04	0.6	0.2		0.03	5.2	67	-
50- 85	48	24	4.9	0.77	0	0.2		0.02	3.4	0	-
85-125	50	22	5.3	0.50	0	0.2		0.01	1.9	0	-
125-160	50	22	5.3	0.44	0	0.3		0.02	1.4	0	-
160-200	48	22	5.9	0.49	0	0.2		0.01	1.2	0	-
200-220+	40	31	5.7	0.26	0	0.3		0.02	1.0	0	-
Haplic Acrorthox (Latosol Amarelo muito pesado). FCC: chaek. UEPAE-EMBRAPA, Experimental Station Manaus, Brazil[c]											
0- 8	76	15	4.6	2.9	1.1	1.70	0.30	0.19	3.29	33	-
8- 22	80	12	4.4	0.9	1.1	0.20		0.09	1.39	79	-
22- 50	84	8	4.3	0.7	1.2	0.20		0.07	1.47	82	-
50-125	88	7	4.6	0.3	1.0	0.20		0.04	1.24	81	-
125-265	89	5	4.9	0.2	0.2	0.20		0.11	0.51	39	-
Allic Haplorthox (Latosol Vermelho Amarelo Alico). FCC: ch. 66.8 km from Rio Branco toward Plácido de Castro, Edo. Acre, Brazil[d]											
0- 5	39	21	5.1	4.00	1.00	8.22	3.74	0.68	25.70	7	14
5- 20	43	22	5.0	1.21	1.60	1.10	1.02	0.17	10.24	41	4
20- 70	53	23	4.0	0.87	2.80	0.08	0.12	0.07	6.07	90	1
70-140	62	15	4.9	0.39	2.20	0.03	0.48	0.03	5.35	79	<1
140-170	63	13	5.4	0.27	1.40	0.05	0.20	0.03	3.78	81	<1
ULTISOLS											
Typic Paleudult. (Serie Yurimagua). FCC: Ihaek. Experimental Station Yurimaguas, Peru[e]											
0- 7	15	67	4.0	1.5	0.8	1.60	0.10	0.12	2.62	31	-
7- 48	23	57	3.5	0.5	3.2	1.60	0.10	0.08	4.98	64	-
48- 67	25	57	3.5	0.5	4.4	0.80	0.10	0.08	5.38	82	-
67-157+	29	57	3.5	0.4	5.3	0.60	0.10	0.08	6.08	87	-
Plinthaquult, Oxic, Allic. (Laterita hidromórfica Alica). FCC: Ihakg. Lat. 8°46'S, Long. 61°59'W. Municipio Porto Velho, Brazil[f]											
0- 40	28	42	3.8	2.90	5.20	0.15	0.04	0.07	17.62	4	2
40-100	30	52	4.0	2.21	5.20	0.16	0.03	0.07	14.97	95	3
100-130	6	90	4.5	0.16	2.20	0.11	0.01	0.03	3.47	93	1
130-160	20	64	4.5	0.19	5.60	0.11	0.01	0.04	6.47	96	1
160-200	21	60	4.6	0.18	6.60	0.13	0.01	0.05	7.49	97	1
ENTISOLS											
Quartipsamment, Ustoxic. (Areias Quartzosas). FCC: shke. 6.9 km from road S.J. Piauí - S. Méndez, Edo. Piauí, Brazil[g]											
0- 10	7	77	4.4	0.71	0.50	0.60	0.30	0.08	5.02	33	2
10- 19	6	94	4.4	0.34	0.60	0.15	0.05	0.05	2.90	59	3
19- 36	4	91	4.6	0.16	0.40	0.15	0.05	0.03	2.05	62	2
36- 31	5	95	4.8	0.18	0.40	0.15	0.05	0.03	1.72	62	2
81-115	11	89	4.9	0.12	0.50	0.10	0.10	0.03	1.56	67	2

Eutric Tropofluvent. (Solo Aluvial Eutrófico). FCC: I. Lat. 1°52'S, Long. 67°41'W. Municipio Japurá, Edo. Amazonas, Brazil[h]

0- 10	17	50	5.5	2.23	5	5.7	1.8	0.59	13.0	5	17
10- 80	12	72	5.1	0.66	32	1.7	0.7	0.11	5.7	32	14
80- 90	12	65	5.6	0.35	25	2.1	1.0	0.11	6.2	25	16
90-180	10	74	5.3	0.23	24	1.7	0.7	0.09	5.0	24	19

ALFISOLS

Tropudalf típico. (Terra Roxa Estruturada Eutrófica). FCC: c. Km 8 road to Panelas, Altamira, Edo. Pará, Brazil[i]

0- 8	40	44	7.0	2.51	0.01	25.24	2.28	0.28	29.16	3.4	8
8- 26	49	28	7.3	0.84	0.11	5.96	0.70	0.27	8.91	1.4	2
26- 60	50	24	6.9	0.53	0.01	3.22	0.65	0.10	5.55	0.23	2
60-100	56	23	6.4	0.26	0.11	2.47	0.43	0.09	5.34	0.32	3
100-130+	55	24	5.5	0.22	0.11	1.29	0.75	0.06	4.86	4.4	3

INCEPTISOLS

Udoxic Dystropept. FCC: cha. Transverse road - Florencia, Municipio Florencia, Caldas, Colombia[j]

0- 16	37	46.3	4.7	2.02	3.2	0.95	0.80	0.23	5.66	61	3.5
16- 85	52	29.8	4.7	0.51	6.7	0.22	0.43	0.03	7.74	90	0.9
85-173	49	29.6	4.9	0.22	6.3	0.10	0.47	0.08	7.19	90	0
173-208	28	40.9	4.9	0.15	6.1	0.10	0.41	0.13	7.68	90	0
208-228	20	56.2	4.9	0.08	5.3	0.20	0.56	0.11	7.71	85	0
228-247	28	33.1	4.9	0.09	8.1	0.16	0.63	0.17	9.60	89	0
247-350	21	38.5	4.9	0.07	6.1	0.16	0.53	0.21	7.55	87	0

SPODOSOLS

Arenic Tropaquod. (Podzol Alico). FCC: sgaek. km 4.5 of BR-174 SUFRAMA, Manaus, Brazil[k]

0- 3	2	89	3.8	6.3	5.4	0.30	0.16	5.86	92	
3- 25	2	95	4.4	0.5	0.7	0.10	0.04	0.84	83	
25- 50	2	94	5.0	0.1	0.1	0.10	0.02	0.12	83	
50- 90	1	98	5.1	0.0	-	0.10	0.01	0.11	-	
90-105	5	93	3.7	1.1	3.0	0.10	0.04	3.14	96	
105-125	9	91	4.7	2.2	2.9	0.10	0.03	3.03	96	
125-165	16	76	5.6	0.8	0.4	0.10	0.03	0.53	75	

a. Combined levels of exchangeable Ca and Mg are expressed in a single column.
b. Profile 3 of Min. of Agr. Tech. Bull. No. 8 (1979).
c. Profile SBCS-4 of Camargo and Rodrigues (1979).
d. Profile 89 of PROJ. RADAMBRASIL, Vol. 12, 1976c.
e. Profile Y-6 of Sánchez and Buol (1974).
f. Profile 24 of PROJ. RADAMBRASIL, Vol. 16, 1978a.
g. Profile 1 of PROJ. RADAMBRASIL, Vol. 1, 1973.
h. Profile 39 of PROJ. RADAMBRASIL, Vol. 14, 1977b.
i. Profile 8 of PROJ. RADAMBRASIL, Vol. 5, 1974b.
j. Profile of BENAVIDES, 1973.
k. Profile SBCS 2 of Camargo and Rodrigues (1979).

The citations for these references are found in the Bibliography of Main Soil Studies. Citations for (d) and (i) are in the References.

Table 5-5. Aereal extent (million ha) of Great Group soil classes of the central lowlands of tropical South America by climatic subregion (a to e)[a,b]

Order and Great Group	Total area	a = Tropical rain forest				b = Semi-evergreen seasonal forest				c = Isohyperthermic savanna			
		Flat, poorly drained	Well-drained (% slope)			Flat, poorly drained	Well-drained (% slope)			Flat, poorly drained	Well-drained (% slope)		
			<8	8-30	>30		<8	8-30	>30		<8	8-30	>30
OXISOLS													
Haplorthox	150.0	-	38.5	20.4	7.2	-	49.2	22.2	5.0	-	5.6	0.3	0.1
Acrorthox	62.0	-	2.2	5.4	1.1	-	35.3	13.8	4.1				
Umbriorthox	4.0					-	3.5	0.8	-				
Eutrorthox	0.8					-	0.8	<0.1	-				
Haplustox	53.0						<0.1	<0.1	<0.1		17.9	7.9	6.1
Acrustox	32.0										14.2	3.2	0.5
Eutrustox	24.0										7.1	1.4	0.1
Plinthaquox	1.0					0.9	-	-	-				
TOTAL	326.8		40.7	25.8	8.3	0.9	88.8	36.8	9.1		44.8	12.8	6.8
% of total area	100.0%		12.4%	7.9%	2.5%	0.3%	27.2%	11.3%	2.8%		13.7%	3.9%	2.1%
ULTISOLS													
Tropudults	82.0	-	8.5	3.3	0.3	-	47.1	16.9	4.1				
Plinthudults	30.0	9.6	19.3	0.3		-	0.3	-	-	0.6	0.9		
Paleudults	29.0	-	7.6	2.5	< 0.1	-	14.3	3.4	0.2				
Rhodudults	4.0						1.3	2.7	0.4				
Tropaquults	37.0	5.8	-	-	-	8.1				11.8			
Plinthaquults	15.0	9.8	-	-	-	0.6				4.8			
Paleaquults	0.3					0.3							
Albaquults	0.1												
Haplustults	8.5						<0.1	0.1	0.1	0.1	0.1	0.2	0.1
Rhodustults	4.9						1.9	-	<0.1		2.0	0.5	
Paleustults	1.6										0.8		
TOTAL	217.4	25.2	35.4	6.1	0.3	9.0	64.9	23.1	4.8	17.3	3.8	0.7	0.1
% of total area	100.0%	11.9%	16.7%	2.8%	0.1%	4.2%	30.6%	10.9%	2.2%	8.1%	1.8%	0.3%	<0.1%
ENTISOLS													
Fluvaquents	50.6	25.1				18.8	-			1.8			
Tropaquents	8.8	1.8				11.1	-			5.3			
Psammaquents	3.9	2.2				0.2	-			0.4			
Hydraquents	1.1												
Quartzipsamments	52.0					0.3	4.1	0.4	-	0.1	11.6	1.2	<0.1
Ustipsamments	6.1					-	0.7	0.3	0.1	0.5	1.3	0.1	
Tropopsamments	2.2					<0.1	0.1	-	-				
Tropofluvents	16.0	-	3.5	-		1.9	3.1	-	-		2.4	< 0.1	
Ustifluvents	0.7					-	-	-	-		0.2		
Xerofluvents	0.7												
Troporthents	9.4	-	<0.1	<0.1	0.1	-	0.9	4.0	2.3		0.8	0.5	0.5
Udorthents	3.3												
Ustorthents	1.1										<0.1	< 0.1	0.1
TOTAL	155.9	29.1	3.5	<0.1	0.1	32.3	8.[illegible]	4.7	[illegible]	8.1	16.5	1.9	0.6
% of total area	100.0%	18.7%	2.2%	<0.1%	<0.1%	20.[illegible]%	5.7%	3.0%	1.5%	5.2%	10.6%	1.2%	0.4%
ALFISOLS													
Tropaqualfs	19.1	1.3	-	-	-	1.6	-	-	-	3.8			
Natraqualfs	<0.1					<0.1	-	-	-				
Hapludalfs	19.4	0.1	10.3	6.5	1.1		1.1	0.3					
Rhodudalfs	0.5.												
Haplustalfs	6.6	-				-			-		0.7	0.7	0.3
Tropustalfs	6.2												
Rhodustalfs	2.7					-			-		-		
Paleustalfs	1.2										1.2	-	-
Haploxeralfs	0.5												
TOTAL	56.3	1.4	10.3	6.5	1.1	5.6	1.1	0.3		3.8	1.9	0.7	0.3
% of total area	100.0%	2.5%	18.3%	11.5%	0.2%	9.9%	1.9%	0.5%		6.7%	3.4%	1.2%	0.5%
INCEPTISOLS													
Tropaquepts	19.1	3.3	-	-	-	6.3	-	-	-	3.2			
Sulfaquepts	3.0					2.4	0.6	-	-				
Humaquepts	1.0									0.7			
Haplaquepts	<0.1					<0.1				0.1			
Plinthaquepts	<0.1									0.1			
Eutropepts	12.5	-	3.5	2.0	1.8	-	1.2	0.1	-		0.4	-	-
Dystropepts	7.7	-	0.9	0.1	0.1	-	0.7	0.8	0.3	-	-	0.4	1.8
Ustropepts	6.6									-	0.1	0.3	0.5
Dystrandepts	1.1	0.2	0.9	<0.1	<0.1		-	-	-	-			
Hydrandepts	0.2					0.5				0.5			
TOTAL	51.4	3.5	5.3	2.1	1.9	9.2	2.5	0.8	0.3	4.6	0.5	0.7	2.3
% of total area	100.0%	6.8%	10.3%	4.1%	3.7%	17.9%	4.9%	1.6%	0.6%	8.9%	1.0%	1.4%	4.5%
SPODOSOLS													
Tropaquods	11.0	8.5	-	-	-	2.5							
% of total area	100.0%	77.0%				23.0%							
MOLLISOLS													
Haplaquolls	1.3	0.8	-	-	-	0.5	-	-					
Arguidolls	<0.1					-	<0.1	<0.1	<0.1				
TOTAL	1.3	0.8				0.5							
% of total area	100.0%	61.5%				38.5%							
ARIDISOLS													
Camborthids	1.2												
% of total area	100.0%												
VERTISOLS													
Chromuderts	0.5		0.5										
% of total area	100.0%		100.0%										
HISTOSOLS													
Tropohemists	0.2												
% of total area	100.0%												

a. Climatic subregions f and o account for only 18.2 million ha.
b. Numbers are rounded to nearest decimal. Amounts less than 0.1 are not included in the summation.

d = Isothermic savanna				e = (Semi-)deciduous forest			
Flat, poorly drained	Well-drained (% slope)			Flat, poorly drained	Well-drained (% slope)		
	<8	8-30	>30		<8	8-30	>30
					<0.1	1.0	0.2
	6.6	5.7	5.0	-	1.7	1.0	0.5
	8.6	4.4	0.5				
	6.4	1.4	0.1	-	2.4	3.9	2.5
	21.6	11.5	5.6		4.1	5.9	3.2
	6.6%	3.5%	1.7%		1.2%	1.8%	0.9%
0.2				10.5			
					7.7	0.1	0.1
	0.8	0.1	-	-	0.2	< 0.1	-
				< 0.1	0.8	-	-
0.2	0.8	0.1		10.5	8.7	0.1	0.1
<0.1%	0.4%	<0.1%		4.9%	4.1%	< 0.1%	<0.1%
				2.3	-	-	-
				0.4	-	-	-
				1.0	-	-	-
	<0.1	0.2	0.4		28.3	2.4	1.9
					2.5	0.5	< 0.1
				1.2	2.6	< 0.1	-
	<0.1						
					0.7	< 0.1	0.1
					< 0.1	< 0.1	< 0.1
					1.0	0.2	0.4
	0.1	0.2	0.4	4.9	35.1	3.1	2.4
	<0.1%	0.1%	0.2%	3.1%	22.5%	2.0%	1.5%
1.2				6.6			
-	0.5		-				
				-	1.4	2.9	0.6
-	0.1	0.1	-	-	1.0	0.3	0.1
					0.5	-	-
1.2	0.6	0.1		6.6	2.9	3.2	0.7
2.1%	1.1%	0.2%		11.7%	5.1%	5.7%	1.2%
				2.3			
				0.2	< 0.1	< 0.1	
					0.3	0.4	0.4
-	0.2	0.2	0.2	-	0.2	0.9	0.7
					5.0	0.1	0.1
0.1							
0.1	0.2	0.2	0.2	2.5	5.5	1.4	1.2
0.2%	0.4%	0.4%	0.4%	4.9%	10.7%	2.7%	2.3%
				-	1.2	-	-
					100.0%		
				0.2			
				100.0%			

Soils in Relation to Climatic Subregions and Topographical Position

Table 5-5 provides distribution estimates of the Great Group classification according to climatic subregions and topographic subdivisions. It may be seen that the higher ratio of Ultisols to Oxisols in subregion A, tropical rain forest, as compared with subregion B, semi-evergreen seasonal forest, is associated with the poorly drained areas where wet Ultisols are abundant. On the well-drained lands in subregion A, the ratio of Ultisols is significantly lower: 0.54 compared with 0.69 in subregion B. Ultisols account for a much lower percentage of the soils in subregions C, D, and E.

There is a higher proportion of Haplorthox in subregion A, Acrorthox in subregion B, Haplustox in subregion C, and Acrustox in subregion D. Oxisols only account for a small proportion of the soils of subregion E. The high proportion of Acrorthox in subregion B indicates a greater extent of soils with very low cation-exchange capacity (less than 1.5 meq/100 g clay) than in subregion A. The relatively large extent of well-drained Inceptisols in subregion A is mainly associated with sediments derived from materials of volcanic origin from the Andes.

The Alfisols found in subregions A, B, C, and D are also associated with superior soil-parent materials, often basic, indicating the strong impress soil-parent materials have in forming soils even under vigorous weathering conditions. The best soils found throughout the region generally are the recent alluvials, Entisols; however, this is by no means always the case. Further, many alluvial soils are subject to periodic flooding.

Part 3 in the *Computer Summary and Soil Profile Descriptions of the Land Systems* (Volume 3) contains a series of soil profile descriptions from typical land facets described by many different authors. As such it provides readers, especially soil scientists, with a more detailed picture of the morphology and properties of some of the soils in the region and emphasizes the great diversity in soil properties and agricultural potentials.

Chapter 6. SOIL PHYSICAL AND CHEMICAL PROPERTIES

After the soils of the land facets were classified, they were described in terms of their physical and chemical properties. This chapter summarizes these properties.

Summary of the Soil Physical Properties of the Region

Soil physical properties were classified and coded in terms of slope, depth, initial infiltration rate, hydraulic conductivity, drainage, moisture-holding capacity, temperature regime, presence of expanding clays, and texture and presence of coarse materials. Details of their definitions are recorded in the glossary to Part 1 in Volume 3.

The classification of soils on the basis of physical properties is designed to evaluate their suitability for crop production from a physical standpoint: in the words of F. Hardy (student notes), to study the "root room" of a soil, or its physical characteristics as a growth environment for roots, tubers, and underground stems and tissues of all kinds, including nodules for symbiotic nitrogen fixation. The classification contains the factors necessary to apply the technique developed by Mansfield (1977) for assessing land capability for crops based on soil physical limitations. It also contains the information necessary to use the soil Fertility Capability Classification (FCC) method of Buol et al. (1975).

Although there are important physical limitations, such as poor drainage, in 21% of the region, severe erosion hazard in 8%, and varying degrees of drought stress all over, the physical properties of the soil in the Land Systems Map can be generally considered favorable.

Soil Texture

Map 12 (see Map Plates) is a computer-based map of soil texture to the 50 cm depth according to the FCC criteria. Table 6-1 shows the tabular data by climatic and topographic subdivision. The most extensive textures are loamy (L) (18–35% clay) and loamy over a clayey subsoil (LC). These L and LC classes together account for 55% of the soil. Uniformly clayey (C) profiles account for 26% of the area, the remainder being divided by shallow soils over rock and other textural combinations. Table 6-1 shows that there is a physical barrier to root development at 50 cm or less in 15.8 million ha (2% of the region). Sandy topsoil textures are also important.

Erosion Hazard

Table 6-1 also provides a synthesis of the slope classes of the region. Flat, poorly drained lands cover 21% of the region. Of the well-drained lands, about 61% have level to gentle slopes (0 to 8% slopes). Topography is rolling (8 to 30% slopes) in 14% of the region, and steep (more than 30% slopes) in the remaining 4%. The presence of a textural change within 50 cm of the soil surface, such as LC, SL, and SC, makes the soils susceptible to erosion, particularly on steep slopes. Table 6-1 also shows that 64.8 million ha (8% of the region) have soils with a sharp textural (SC, LC) change on slopes greater than 8%, or have shallow soils (LR and CR). The deep soils with textural changes, mostly classified as Ultisols or Alfisols, are generally quite susceptible to erosion unless protected by a plant canopy during periods of heavy rains.

Indiscriminant forest clearing, especially in hilly regions, often leads to serious soil erosion and also increases the rate of flow of water (along with topsoil) away from catchment areas. This, in turn, provokes flooding from rivers, often many miles downstream. It is a particularly serious problem in parts of the sub-Andean foothills where "colonization" is proceeding apace. For example, in Bolivia, the greater frequency and intensity of flooding in recent years, at Trinidad, a city located near the Mamoré river in the middle of the Mojos Pampas, can be associated with the uncontrolled and excessive forest clearing by settlers in the Chapare district, a major sub-Andean catchment region of that river (Cochrane, 1973). Such problems can only be avoided by ensuring that colonizers have as little access as possible into the sub-Andean foothills i.e., that major road systems are located well into the plains areas.

Soil Moisture Relationships

The definition of soil Great Groups and their extent (shown in Table 6-1) permits a calculation of the relative importance of soil-moisture regimes in the region, as defined in Soil Taxonomy (Soil Survey Staff, 1975). About 61% of the region has an udic or perudic soil-moisture regime, indicating that the subsoil is moist during 9 or more months per year. Approximately 21% of the area has an aquic regime, indicating the presence of waterlogged conditions in some parts of the solum during the year. The remaining 18% has an ustic regime, which indicates that the subsoil is dry for more than 90 but less than 180 consecutive days during the year.

The moisture situation is not as clear as these figures

Table 6-1. Aereal extent of FCC textural classes of the soils of the central lowlands of tropical South America by climatic subregions (a to e)[a].

FCC texture class	a = Tropical rain forest				b = Semi-evergreen seasonal forest				c = Isohyperthermic savanna				d = Isothermic savanna				e = (Semi-)deciduous forest			
	Flat, poorly drained	Well-drained (% slope)			Flat, poorly drained	Well-drained (% slope)			Flat, poorly drained	Well-drained (% slope)			Flat, poorly drained	Well-drained (% slope)			Flat, poorly drained	Well-drained (% slope)		
		<8	8-30	>30		<8	8-30	>30		<8	8-30	>30		<8	8-30	>30		<8	8-30	>30
L (loamy)	22.1	19.1	11.0	3.7	26.9	42.5	16.5	3.5	4.6	19.8	7.7	6.0	0.1	5.7	7.1	5.1	6.2	12.2	4.9	3.1
LC (loamy over clayey)	22.5	49.3	14.3	2.8	11.1	46.0	20.4	4.5	14.0	5.2	1.4	0.9	0.6	0.3	0.3	0.2	13.5	10.6	3.5	1.1
C (clayey)	7.1	23.0	13.3	3.8	14.8	60.6	25.4	6.3	8.0	20.7	4.8	1.1	0.2	15.8	4.5	0.3	1.7	2.2	0.5	0.2
S (sandy)	4.6	1.4	-	-	3.2	6.0	0.7	0.1	1.4	15.2	1.8	0.1	-	0.8	0.3	0.6	1.7	30.8	3.3	1.9
SL (sandy over loamy)	6.8	5.0	0.3	-	1.4	2.6	0.7	0.1	1.4	1.1	0.2	-	0.1	0.1	0.1	0.1	0.7	0.3	-	-
LR (loamy over rock)	-	0.5	1.2	1.8	0	0.8	3.8	2.2	0.1	0.4	0.2	0.3	-	0.2	0.2	0.2	-	0.1	0.2	0.4
LS (loamy over sandy)	0.8	0.4	0.3	0.1	0.3	0.5	0.1	-	0.1	1.8	0.8	0.3	-	-	0.3	0.1	0.1	-	-	-
SC (sandy over clayey)	-	-	-	-	0.8	0.1	0.1	-	4.4	-	-	-	-	-	-	-	-	0.1	0.1	0.1
CR (clayey over rock)	-	-	-	-	-	0.1	0.2	0.1	-	0.2	0.8	2.0	-	-	-	-	-	-	-	-
CL (clayey over loamy)	1.2	0.2	-	-	0.1	0.1	-	-	0.5	0.1	-	-	-	-	-	-	0.7	-	-	-

a. Subregions f and g not included due to the relatively small percentage of these soils in the area covered by this study.

suggest because subregion B, which covers a large expanse of the Amazon, includes both udic and ustic soil-moisture regimes in well-drained soils as presently defined (Ranzani, 1978) in detailed soil-water balance studies done near the edge of subregion E (Marabá, Pará), which are classified as well-drained soils in ustic suborders.

Cochrane et al. (1981) have compared the classification of the main soils in the region at the Great Group level with moisture-regime classes and total wet-season evapotranspiration regimes (WSPE) (Table 6-2). There is an approximate relationship, presumably because the definition of moisture regimes provides for a broad separation of the Great Groups. However, there is the implication that the definition of WSPE regimes, or an equivalent approximation of "usable energy" regimes as accorded by annual water balance patterns, could lead to an improved classification of soils in the tropics. The definitions of soil-moisture regimes according to Soil Taxonomy, incidentally, are currently undergoing review because of certain doubts as to the applicability of the present criteria to tropical circumstances (A. van Wambeke, pers. comm., 1980).

Classification considerations aside, it is relevant to point out that most soils in subregion B suffer from temporary moisture stresses during 3 to 4 months of the year; this affects plant growth. The clearly defined dry season in the savannas makes this situation more obvious, especially in the well-drained soils of subregion C and D. Even in the clearly udic soil-moisture regime of subregion A, temporary soil moisture stress occurs sporadically and severely affects crops like upland rice and corn (Bandy, 1977). Thus it appears that shallow-rooted annual plants growing on most well-drained soils in the region can suffer from lack of water during some part of the year.

Map 13 illustrates the soil moisture-holding capacities of soils throughout the region. More detailed or crop-specific studies must take such capacities into greater account.

Hardened Plinthite or Laterite

It is pertinent to note that the physical properties of most Amazon forest and many savanna soils are generally quite good. The dominance of coarse gravelly topsoils underlain by plinthite in much of West Africa's equivalent to subregion B poses major limitations to the development of permanent agriculture in that vast region (Lal et al., 1975). As noted in Chapter 5, this situation is virtually nonexistent in tropical South America. Hardened plinthite or laterite outcrops do occur, but in geomorphically predictable positions in the landscape, such as on edges of peneplains or plateaus that have been dissected by streams and rivers. These are common in the Guyanian and Brazilian shields, and in the Tertiary surfaces of the Amazon and Orinoco basins. Laterite outcrops occur in the high Llanos of eastern Colombia near Carimagua (see Photo Plate 44), an ICA (Instituto Colombiano Agropecuario) National Agricultural Research Center where ICA and CIAT work cooperatively in crop, pasture, and short-term research. These outcrops provide excellent low-cost road-building materials and, consequently, reduce the cost of opening up many hinterland areas. In fact, the lack of laterite in many areas is a definite constraint to road building and construction in general.

Soil Chemical Properties

Definition of Soil Chemical Properties

Soil chemical properties for both the topsoil (0–20 cm) and subsoil (21–50 cm) were coded and summarized as detailed in the glossary to Part 1 of Volume 3. Some aspects of this coding and definition merit additional comment.

pH (pH in water, 1:1 soil to water ratio). A pH less than 5.3 was considered a realistic level to separate soils with a potential Al toxicity problem. Above pH 5.4, Al is virtually insoluble and not found either in the exchange complex or in the soil solution; below about pH 5.3 the amount of Al in soil solution may be significant. Therefore, pH 5.3 gives a crude critical level for identifying those soils for which the equation developed by Cochrane et al. (1980) for estimating the liming requirements of acid mineral soils might profitably be used. The letter "h" was used to code soils with a pH less than 5.3; this is the same letter used by the FCC system (Buol et al, 1975), and the definition approximates the philosophy of the FCC definition of soil acidity.

Exchangeable Al (Al extracted by 1*N* KCl). The levels used are considered tentative and mainly applicable to soils with a low effective cation-exchange capacity.

Exchangeable Ca, Mg, Na (1*N* KCl extraction). This is a first attempt to equate soil-nutrient levels with crop needs in the sense:

A = adequate for most crops
M = inadequate for crops requiring high levels of the nutrient
B = inadequate for most crops except those tolerant to low levels of the nutrient.

Exchangeable K (1*N* NH_4Cl extraction). In practice, there does not appear to be much difference between the K levels extracted with NH_4Cl and NH_4OAc. The tentative classification of exchangeable K also qualifies the potash levels according to the FCC criteria. This stipulates as an alternative definition of low K that the soil has less than 10% weatherable minerals in the silt and sand fraction within 50 cm of the soil surface, or that K levels are less than 2% of the sum of the bases, if the sum of the bases is less than 10 meq/100 g soil.

Total exchangeable bases (TEB). This is the sum of the exhangeable Ca, Mg, K, and Na. In some acid mineral soils, Mn and even Fe levels obtained by extraction with 1*N* KCl may be high and contribute to the TEB. Zinc and Cu levels could also be included, but in practice are generally so low as to be insignificant.

Cation-exchange capacity (CEC). This refers to the effective cation-exchange capacity (ECEC) calculated by the sum of the TEB plus Al (1*N* KCl extraction). The level, less than 4 meq/100 g soil, would correspond approximately to less than 7 meq/100 g soil, if the CEC is determined by the sum of the cations at pH 7.0, and less than 10 when determined by the sum of the cations at pH 8.2 (Buol et al., 1975).

Table 6-2. Comparison (in percentage of total area) of the well-drained Great Group soil classes by WSPE[a] and moisture regime classes.

Great Group[b]	WSPE (mm) >1300	1061-1300	900-1060	<900	Wet months (no.)[c] >8	6-8	<6
Ustic							
AUSHA, AUSPA, AUSRH, OUSAC, OUSEU, OUSHA, UUSHA, UUSPA, UUSRH	0	2.3	20.1	5.4	0.6	21.6	5.5
Orthic							
OORAC, OOREU OORHA, OORUM	6.7	28.1	1.3	0	14.4	21.7	0
Udic							
AUDHA, UUDPA, UUDPL, UUDRH, UUDTR	15.6	20.4	0	0	17.9	18.2	0
TOTAL	22.3	50.8	21.4	5.4	32.9	61.5	5.5

a. WSPE = Wet-season potential evapotranspiration.
b. A = Alfisol; O = Oxisol; U = Ultisol; US = ustic; OR = orthic; UD = udic; HA = haplic; PA = paleic; RH = rhodic; AC = acric; EU = eutric; UM = umbric; PL = plinthic; TR = tropic.
c. Months with MAI (moisture availability index) > 0.33.

SOURCE: Cochrane et al., 1981.

Table 6-3. Comparison of P levels (ppm) by classification system.

	P code	Bray II	Truog	Olsen	"Available P"
A	alto, high	> 7	> 5	> 3	> 7
M	medium	3-7	2-5	1-3	3-7
B	bajo, low	< 3	< 2	< 1	< 3

The classification of TEB and CEC in terms of high, medium, and low clearly has no direct significance with respect to plant nutrient needs. Nevertheless, they are considered convenient groupings to help with the interpretation of the soil's ability to supply nutrients. When considered together with organic matter content and clay mineralogy, they provide an idea of the ability of a soil to retain nutrients and its state of leaching.

Organic matter (OM). The classification has been made to help with the overall interpretation of soil fertility. The percentage of OM is determined by multiplying the organic carbon by 1.7.

Phosphorus. The levels refer to P extracted by the Bray II method (Bray and Kurtz, 1945). In very approximate terms, Table 6-3 gives a comparison of P levels extracted by the Bray II method, the Truog method (Jackson, 1958), and the "available P" method of Vettori (1969).

The classifications are also used to equate soil levels with plant requirements.

Phosphorus fixation. Phosphorus fixation is difficult to quantify. The criterion of Buol et al. (1975) was used: soils with a clay content greater than 35% and a ratio of free Fe_2O_3 to percentage of clay greater than 0.15, or those with allophane-dominant clay mineralogy, are classified as potentially high-P fixers. In the absence of more specific information, these parameters give a tentative rating of potential P-fixation problems.

Manganese. The levels refer to Mn extracted with 1*N* KCl, defined as low, satisfactory, and toxic. The definition of Mn toxicity as greater than 35 ppm or greater than 1% saturation of ECEC is provisional, as plants vary widely in their ability to withstand high levels of Mn in the soil solution. Furthermore, Mn levels tend to build up, sometimes for relatively short periods, under reducing conditions (Collins and Buol, 1969).

Sulphur. The classifications low, satisfactory, high, and unknown have been made without attempting to define an extraction procedure or limits for soil S; it only reflects what is known about S deficiencies as recorded in the literature.

Zinc (1*N* KCl extraction). Only the classes low, satisfactory, and unknown have been used. These levels are based on relatively few studies with commercial crops; little is known concerning crop tolerance to different levels of Zn.

Iron (1*N* KCl extraction). The classes low, satisfactory, high, and unknown provide only a rough guide, as they do not take crop tolerance differences into account. At the high level, some crops, e.g. rice, may suffer from excess Fe (Howeler, 1973). Like Mn, soil Fe levels vary with the fluctuating oxidation and reduction conditions brought about by different soil-moisture levels. Temporary Fe deficiency sometimes occurs in sugarcane as plant roots grow through well-aerated, unsaturated topsoils (T.T. Cochrane, unpublished data). As the roots penetrate saturated subsoils, the Fe deficiency generally disappears.

Copper (1*N* KCl extract). Little is known about critical Cu levels. Generalized levels have been determined based on experiences from other tropical areas. There is evidence to suggest that they may be correlated with P levels in some acid mineral soils (T.T. Cochrane, unpublished data).

Boron (extraction by refluxing with 100°C water for 10 minutes). The classes used approximate critical levels for several crops including sugarcane.

Molybdenum (1*N* KCl extract). Little is known concerning soil Mo levels in the region. The classes used are based mainly on generalized criteria from other parts of the tropics.

Free carbonates. This characteristic refers to carbonates detected simply by dropping 30% HCl onto soil samples taken to a depth of 50 cm and observing CO_2 effervescence. The presence of calcium and magnesium carbonates detected in this way is also used as an FCC modifier: "b" = basic reaction.

Salinity. This is the salinity of the saturated extract at 24°C of a soil sample taken to a depth of 1 m. The levels are based on the general values developed by the U.S. Soil Salinity Laboratory Staff (1954) that purport to identify those soils with sufficient salinity to present problems for most crops. It should be noted, however, that some crops are susceptible to a significantly lower level of soil salinity. The 4 mmhos level approximates a 1:2.5 soil-to-water extract conductivity reading of 400 µmhos.

Natric. Sodium levels were given separate mention to identify problem soils. Sodium affects clay dispersion and moisture availability. The levels refer to readings for soil samples taken to a depth of 50 cm and are those limits set by the U.S. Soil Salinity Laboratory (1954).

Cat clay. This identifies the presence of acid sulphate soils (Moorman, 1963). It is identified by the criterion of pH in 1:1 soil-to-water extracts less than 3.5 after drying or jarosite mottles with hues 2.5Y or yellower and chromas 6 or more within a depth of 60 cm. It is used with this definition as an FCC modifier: "c" = cat clay.

X-ray amorphous. Greater than 35% clay and pH greater than 10 in 1*N* NaF, or positive to field NaF test, or other indirect evidences of allophane in the clay fraction of the surface 20 cm of the soil. This criterion, the definition of the FCC modifier "x," purports to identify soils with allophane-dominated mineralogy; these often have high P-fixing capacity and low rates of mineralization.

Elements of importance mainly to animal nutrition. This evaluation is based purely on specific knowledge about deficiencies and toxicities occurring in a given area. For example, certain soil areas are associated with iodine deficiency in animals.

Examination of Soil Chemical Data

When examining soil chemical data, it is good practice to identify potential soil toxicity factors first, then examine potential deficiencies in the light of what is likely to occur, once corrective measures have been postulated to overcome the soil toxicity problem (see Appendix 2). Such an examination must be preconditioned by the appreciation of climatic and physical conditions.

Historically, Cochrane (1962) examined Ministry of Agriculture files dating to the late 1800s in the Caribbean Island of St. Vincent and found he was able to detect a hitherto unsuspected relationship between the fertilizer response of cotton varieties and their genetic adaptation to acid, infertile soils. For years it has been assumed that the "best" varieties were those that gave the greater responses to the higher fertilizer treatments.

Appendixes 3 and 4 provide agronomists faced with the task of investigating soil fertility problems for specific crops a more detailed guide as to what may be deduced from existing soil survey and fertility evaluation studies and how agronomic work might be speeded up to provide field-proven answers for farming practice. They use the Llanos Orientales of Colombia (the eastern lowland, well-drained plains) as a case study. Chapter 9 also discusses this topic.

Plant Tolerances to Toxicities and Deficiencies

Clearly, any interpretation of soil chemical data (and certain physical data) must take the tolerances of different crops and varieties or cultivars of those crops into account. It may be noted that several Brazilian wheat varieties have a much greater tolerance to soil Al than those developed in Canada.

Summary of Soil Chemical Properties of the Region

It was concluded that the physical properties of the soils of the central lowlands can generally be considered favorable. The opposite statement can be made as to their chemical properties. The vast majority of the region's soils are acid and infertile in their *undisturbed* state.

From the soil survey classification data, it was noted that only about 5% of the region has high base status soils with relatively high native fertility. The analytical data indicate that the main chemical soil constraints in the region are soil acidity (Al toxicity), P deficiency, low effective cation-exchange capacity, and widespread deficiencies of N, K, S, Ca, and Mg. Toxicities of Mn and Fe are present in some soils, as are deficiencies of these elements in others. Trace element deficiencies, including B, Zn, and Cu, are commonly seen (Cochrane and Sánchez, 1982), and Mo deficiency has been identified in the Brazilian Cerrados (CIAT, 1980a). Table 6-4 shows the extent of many of these fertility limitations in the region. Table 6-5 disaggregates the topsoil data according to climatic subregions and topographical positions. Table 6-6 interprets these data in terms of FCC units.

In examining these tables, however, it must be remembered that the figures are largely based on soil-survey information taken under natural vegetation conditions. As shown by Falesi (1976), in the semi-evergreen forest circumstance with a large biomass content, burning in situ can result in returning to the soil very large quantities of bases, including K and Ca, thus completely changing the chemical characteristics of the topsoil. The subsoil conditions may also be affected as nutrients leach from the topsoil.

Soil acidity. Tables 6-4 and 6-5 show that 75% of the region has soil pH values lower than 5.3, indicating not only an acid reaction but also the presence of potentially toxic levels of exchangeable Al for many crops. The proportion of acid soils is less in the flat, poorly drained topographies (52%). Map 14 is a computer printout composition map of topsoil (0–20) pH levels over the region. Soil acidity is indicated by the "h" modifier in Table 6-6.

Aluminum toxicity in plants is the main consequence of extreme soil acidity. Plant species and cultivars within a species differ in their tolerance to Al; this is expressed in terms of the percentage of Al saturation of their effective cation-exchange capacity (ECEC). Some plants sensitive to Al suffer at levels as low as 10% Al saturation. In general, however, when there is 70% Al saturation or more within the top 50 cm, the soil is considered Al toxic. Such soils have been assigned the "a" modifier of the FCC system. Table 6-6 shows that 358 million ha, or 44%, of the soils in the region are potentially Al toxic in their natural state. Map 15 is a computer printout composition map of topsoil (0–20 cm) Al saturation levels over the region.

Map 16 shows a computer map of the Al saturation levels in the subsoils (21–50 cm)of the region. It may be noted that there are significant changes in the distribution of the subsoil levels as compared with the topsoil levels. Table 6-5 shows that there is a considerable lowering of subsoil Al saturation levels in subregions C and D, the savanna regions.

Correcting Al toxicity. Al toxicity in soils may be corrected by liming, unfortunately the amounts of lime currently being used by farmers to overcome Al toxicity are usually far in excess of those really needed. Large, unneeded applications of lime have been made in southern Mato Grosso, Brazil, for instance (see Photo Plate 28). Recently, Cochrane et al. (1980) have published an improved liming equation that permits the calculation of the minimal lime requirement for a given acid, mineral soil that will enable the healthy growth of a crop with a known tolerance to Al toxicity. This equation has been recorded in Appendix 2 for the convenience of agronomists.

It might be noted that lime per se is not a scarce resource in the region; deposits abound along the eastern foothills of the Andes and the central plateau of Brazil. However, mining and transportation costs are major limiting factors especially for distant frontiers, and the estimation of minimal lime re-

Table 6-4. Summary of selected fertility parameters in the central lowlands of tropical South America.

Code[a]	Range	Topsoil (0-20 cm) Area (million ha)	Topsoil (0-20 cm) Percentage of total	Subsoil (21-50 cm) Area (million ha)	Subsoil (21-50 cm) Percentage of total
pH					
A	> 7.3	0.4	< 0.1	0.6	0.1
M	5.3-7.3	245.8	70.0	203.2	24.9
h	< 5.3	570.8	30.1	613.0	75.0
Organic Matter (%)					
A	> 4.5	145.0	17.8	4.1	0.5
M	1.5-4.5	614.4	75.2	90.5	11.1
B	< 1.5	57.6	7.0	722.4	88.4
Al saturation (%)					
B	0-10	221.5	27.1	243.6	29.8
M	10-40	95.5	11.7	91.3	11.2
H	40-70	141.4	17.3	100.0	12.3
a	>70 (toxic)	358.6	43.9	382.0	46.8
Exchangeable Ca (meq/100 g)					
A	> 4.0	163.7	20.0	68.1	8.3
M	0.4-4.0	338.3	41.4	184.6	22.6
B	< 0.4	315.0	38.6	564.3	69.1
Exchangeable Mg (meq/100 g)					
A	> 0.8	169.6	20.8	63.3	7.8
M	0.2-0.8	410.8	50.3	184.7	22.6
B	< 0.2	236.6	29.0	568.9	69.6
Exchangeable K (meq/100 g)					
A	> 0.3	97.4	12.0	6.3	0.7
M	0.15-0.3	240.8	29.5	105.6	12.9
k	< 0.15	477.1	58.4	705.1	86.3
ECEC[b] (meq/100 g)					
A	8	255.6	31.3	119.6	14.6
M	4-8	319.0	39.0	283.3	34.7
e	4	242.4	29.7	414.1	50.7
P[c] (ppm)					
A	7	97.1	11.9	28.4	3.5
M	3-7	341.5	41.8	89.1	10.9
B	3	378.3	46.3	699.4	85.6
P fixation					
i	> 35% clay and % free Fe_2O_3/% clay > 0.15	101.2	12.4		
O	low	715.7	87.6		
U	no estimate	< 0.1	< 0.1		

a. a = Al toxic, FCC modifier in topsoil; A and H = high; B = low; h = acid, FCC modifier in topsoil; i = FCC modifier for P fixation; k = K deficient, FCC modifier in topsoil; M = medium.
b. ECEC = effective cation-exchange capacity.
c. By Bray II.

quirements, along with the use of crop cultivars with a certain tolerance to high soil Al levels, are important agrotechnologies for the agricultural development of the region. Consequently, the estimation of a minimal "liming need" can lead to the more effective use of lime and considerable savings in food production.

Phosphorus deficiency. Table 6-4 indicates that 86% of the region's soils have topsoil available P levels lower than 7 ppm, according to the Bray II method. Map 17 (see also Chapter 7) shows the distribution of available P levels in the topsoils over the region, and Map 18 (see Chapter 7) shows the distribution of subsoil P levels. Since the generally recognized adequacy level of this method for annual crops in Oxisols and Ultisols of Brazil is 7 ppm P, it is safe to state that the vast majority of soils in the area are deficient in P for most annual crops. Fortunately, this widespread P deficiency is not accompanied by a widespread high P fixation capacity (see Map 19).

Tables 6-4 and 6-6 show that an estimated 100 million ha, just 12% of the region, have soils with a high P-fixation capacity, as defined by the "i" modifier of FCC. Only those topsoils with more than 35% clay contents and with a high proportion of iron oxides present are considered high P fixers (Sánchez and Uehara, 1980; Sánchez et al., 1980). This situation is largely limited to clayey Oxisols and Ultisols, and, among them, only those having the "Ci" notation in the FCC system. Phosphorus-sorption isotherms, conducted with soil samples of Ultisols from Peru and Brazil by North Carolina State University (1973) and Dynia et al. (1977), show that the fixation capacity is low. Figure 7-3 (Chapter 7) shows the distribution of soils with possible P-fixation problems over the region. Clearly, while P fixation is a possible major constraint of Oxisols in the Cerrados of Brazil and the Llanos of Colombia, it is not a widespread problem in the Amazon, although it is locally important. The use of species and cultivars tolerant to low P levels is a possible alternative to increasing P fertilization in P-deficient soils.

Because of its importance, recent advances in means and ways of correcting P deficiencies are specifically discussed in Chapter 7.

Low potassium reserves. Table 6-5 shows that about 58% of the region (477 million ha) has soils with low K availability. Table 6-6 indicates a lower figure, as soils with "g" (gley) or "d" (dry) modifiers are not taken into account. Although burning native forests increases available K levels, this effect tends to be short-lived, unless rapid recycling takes place. In savanna regions, seasonal burns do little to increase the invariably low levels of the soils. Consequently, this is an important economic constraint in the region. Map 20 illustrates levels of potash in the topsoil throughout the region.

Low calcium and magnesium levels. Table 6-5 shows that 39% of the region (315 million ha) has soils with low Ca levels and 29% (236 million ha) low Mg levels. Burning native forests increases both Ca and Mg levels. In savanna areas, however, Ca and Mg deficiencies must be corrected by fertilization; adding a modest dressing of dolomitic limestone may be a cost-effective means of overcoming these deficiencies. In fact, many soils low in Ca and Mg are potentially Al toxic; in such cases, the addition of dolomitic limestone will solve both the Al toxicity and the Ca- and Mg-deficiency problems. Map 21 illustrates Ca topsoil and Map 22 Ca subsoil levels throughout the region studied.

Low effective cation-exchange capacity. Low ECEC is an important soil constraint because of the susceptibility of K to leaching from the soil profile and the danger of creating serious nutrient imbalances among cations such as K, Ca, and Mg. Tables 6-4 and 6-5 show that approximately 242 million ha (30% of the region) have this condition in the topsoil, and 414 million ha (50%) have it in the subsoil. Low ECEC is more prevalent in subregions B and C and occurs mainly in Oxisols, sandy-textured Ultisols, and all Spodosols. Rapid leaching losses and serious K-Mg imbalances have been recorded in Ultisols in Peru (Villachica, 1978; Villachica and Sánchez, 1980).

Sulphur deficiency. McClung (1959) found severe sulphur deficiencies in a greenhouse trial with soils from the state of Goiás, Brazil, in soils described as Humic Latosols (Acrustox) and in a sandy Terra Roxa Mixturada (Rhodustalf) in São Paulo. The common occurrence of S deficiency in the soils of Central Brazil has been confirmed by several consequent studies, including the recent greenhouse trials on the Oxisols of Planaltina reported by CIAT (1980a). Although few field-trial results seem to have been recorded, S deficiency is probably a major constraint in many savanna soils where sulphur is lost through burning. Sulphur deficiencies have also been reported by Wang et al. (1976) in rice in *várzeas* (flood plains) along the Jari river in eastern Amazonia.

Deficiencies of other nutrients. The region is a heaven for scientists interested in nutrient deficiencies. In the Ultisols of Yurimaguas, for example, deficiencies of all essential nutrient elements except for Fe and Cl have been recorded in annual crops (Villachica and Sánchez, 1980). In addition to N, P, and K deficiencies, the most widespread ones seem to be Mg, S, and Zn. The limited data base for these parameters impedes a geographic appraisal of where specific deficiencies occur and their relationship to soil properties.

Constraints occurring together. Table 6-6 shows how several of these constraints occur together on the same land units, as defined by the various FCC modifier combinations. Only about 42 million ha (5% of the area) showed no major fertility limitations. The rest showed various combinations of Al toxicity (a), acid but not Al toxic (h), low ECEC (e), low K reserves (k), high P fixation (i), poor drainage (g), and dry season drought stress (d). The most frequent combinations involved Al toxicity, low K reserve, low ECEC, and high P fixation. Clearly the FCC system does not take low or insufficiency levels of phosphorus into account, only potential P fixation. Low levels of P are virtually universal in the Oxisols and Ultisols of the region.

Because of the basic importance of P for crop production throughout the region, recent advances and means or ways of correcting these deficiencies are described in Chapter 7.

Table 6-5. Aereal extent (million ha) of some topsoil (0-20 cm) and subsoil (20-50 cm) chemical properties within the topographic subdivisions of the climatic subregions of central lowland tropical South America.

Parameter and range*	a = Tropical rain forest: Flat, poorly drained	Well-drained (% slope) <8	8-30	>30	b = Semi-evergreen seasonal forest: Flat, poorly drained	Well-drained (% slope) <8	8-30	>30	c = Isohyperthermic savanna: Flat, poorly drained	Well-drained (% slope) <8	8-30	>30	d = Isothermic savanna: Flat, poorly drained	Well-drained (% slope) <8	8-30	>30	e = (Semi-)deciduous forest: Flat, poorly drained	Well-drained (% slope) <8	8-30	>30
pH																				
Topsoil																				
A >7.3	0.:	-	-	-	0.1	-	-	-	-	-	-	-	-	-	-	-	<0.1	-	-	-
M 5.3-7.3	30.0	15.9	6.0	1.3	30.0	15.9	6.0	1.3	10.1	18.5	6.7	4.?	0.6	2.0	1.7	0.9	17.8	46.3	7.2	3.8
h <5.3	28.5	143.3	61.8	15.6	28.5	143.3	61.8	15.6	24.6	46.0	10.9	6.0	0.3	20.8	11.1	5.5	6.5	9.8	6.0	3.7
Subsoil																				
A >7.3	-	-	-	-	<0.1	1.0	-	-	-	-	-	-	-	-	-	-	<0.1	<0.1	-	-
M 5.3-7.3	28.8	13.1	3.0	0.5	31.9	17.6	4.6	1.0	11.5	8.6	2.3	2.0	0.8	0.4	1.0	0.8	10.1	38.7	5.7	3.0
h >5.3	36.2	85.8	37.4	11.6	26.5	141.5	63.2	15.9	23.2	55.9	15.3	8.7	0.1	22.4	11.7	5.6	14.2	17.4	7.6	4.5
% Organic Matter																				
Topsoil																				
A >4.5	27.3	13.9	4.0	13.6	22.8	18.3	3.9	0.3	19.1	12.2	4.9	4.5	0.9	0.4	0.9	0.3	2.5	2.7	0.9	0.8
M 1.5-4.5	33.3	83.9	35.2	9.1	31.0	124.1	53.1	1.2	15.4	44.0	11.7	2.6	1.0	22.4	11.9	6.1	21.5	53.4	11.9	6.7
b <1.5	4.5	1.1	1.2	1.7	4.8	16.8	10.8	15.3	0.3	8.3	1.0	3.5	-	-	-	-	0.4	0.2	0.4	-
Subsoil																				
A >4.5	<0.1	0.1	-	-	0.3	0.1	-	-	<0.1	-	-	-	-	-	-	-	-	-	-	-
M 1.5-4.5	21.8	5.4	4.7	1.2	10.2	14.4	4.4	0.6	10.0	4.8	<0.1	<0.1	0.1	-	-	-	0.3	0.7	0.1	-
B <1.5	42.8	83.4	35.6	10.9	45.6	144.2	63.4	16.2	24.5	59.7	17.6	10.7	0.8	22.9	12.8	6.4	24.1	55.7	13.2	7.5
% Al Saturation																				
Topsoil																				
a >70	24.7	70.2	23.8	6.0	14.3	94.0	42.8	10.?	3.8	20.1	6.2	5.0	0.3	14.8	6.9	2.6	0.4	4.4	4.2	2.7
H 40-70	7.6	8.9	9.6	4.6	3.3	36.8	13.4	3.4	7.6	10.1	4.1	2.6	0.1	2.6	3.6	2.8	7.1	5.5	1.8	1.2
M 10-40	5.9	2.1	0.3	0.2	14.0	14.2	6.6	2.4	13.4	19.9	2.1	0.5	0.1	4.1	1.2	0.3	2.2	0.5	0.4	0.5
B <10	26.8	17.7	6.8	1.2	26.8	14.2	6.0	0.8	9.9	14.4	5.3	2.6	0.4	1.2	1.1	0.8	14.8	46.0	6.8	3.1
Subsoil																				
a >70	25.9	73.4	23.4	6.0	20.1	115.0	42.8	9.2	3.7	17.6	3.1	3.9	0.1	4.4	1.4	0.2	8.7	10.9	4.7	2.9
H 40-70	11.1	5.6	7.7	2.1	3.6	17.1	8.0	1.3	-9.4	10.6	3.5	1.0	-	3.4	3.5	1.3	4.0	2.8	1.2	1.0
M 10-40	0.6	6.5	6.3	3.4	6.4	11.6	8.8	3.5	5.8	13.5	3.0	1.0	0.1	10.4	4.3	1.3	0.3	1.3	1.3	0.2
B <10	27.6	13.4	3.1	0.6	28.5	16.5	8.2	2.8	15.7	21.8	8.0	4.8	0.8	4.7	3.6	3.6	11.5	41.2	7.0	3.4
Exchangeable K (meq/100 g)																				
Topsoil																				
A > 0.3	22.5	7.2	1.7	1.8	25.3	12.8	5.9	0.9	5.8	2.8	0.1	0.1	-	-	-	-	0.5	2.0	0.9	0.8
M 0.15-0.3	18.9	29.6	11.5	3.3	11.1	46.4	19.3	5.1	17.2	17.5	7.0	5.9	0.6	0.5	2.0	0.5	10.0	11.4	3.6	1.5
k < 0.15	23.6	62.1	27.2	7.0	22.1	100.1	42.6	10.8	11.7	43.8	10.5	4.7	0.3	18.1	10.8	5.8	13.4	43.0	8.7	5.2
Subsoil																				
A > 0.3	0.7	<0.1	-	-	1.1	1.0	-	-	<0.1	-	-	-	-	-	-	-	<0.1	1.9	-	-
M 0.15-0.3	13.3	3.8	1.7	1.8	14.8	9.9	5.3	1.0	10.9	8.4	3.1	2.2	0.4	0.9	0.7	0.2	6.2	4.7	2.9	0.7
k < 0.15	51.0	94.9	38.6	10.3	42.6	148.2	62.5	15.8	23.3	5.6	14.5	8.5	0.5	21.9	12.1	6.2	17.8	49.8	10.4	0.7

Exchangeable Ca (meq/100 g)																					
Topsoil																					
A	> 4.0	27.1	19.9	8.2	2.8	23.8	20.4	8.9	3.0	12.4	6.0	32.5	1.9	0.1	6.9	0.5	0.1	3.9	5.4	3.7	1.5
M	0.4-4.0	26.8	61.3	16.3	4.4	20.2	48.8	23.6	5.1	12.3	17.0	4.6	6.2	0.5	6.1	3.2	1.2	17.8	47.7	7.9	5.3
B	< 0.4	11.2	27.7	16.9	4.9	14.6	90.0	35.3	7.8	10.0	41.5	9.7	2.7	0.3	16.0	9.0	5.1	2.7	3.2	1.7	0.7
Subsoil																					
A	> 4.0	7.5	12.5	6.5	1.2	12.8	6.2	1.2	0.1	6.5	9.6	-	-	0.1	-	-	-	1.8	2.2	0.9	0.8
M	0.4-4.0	36.7	23.4	4.1	1.7	23.5	15.9	9.2	1.5	11.3	10.4	4.5	2.8	0.6	1.0	0.7	0.2	9.6	9.8	4.2	0.9
B	< 0.4	20.9	63.0	29.9	9.1	22.2	137.0	57.4	15.3	16.9	53.5	13.1	8.0	0.3	21.9	12.8	6.2	13.1	44.4	8.1	
Exchangeable Mg (meq/100 g)																					
Topsoil																					
A	> 0.8	23.0	15.7	7.7	2.8	28.6	25.4	10.8	3.4	11.2	6.9	3.3	1.9	0.1	0.8	0.5	0.1	3.8	5.5	3.7	1.5
M	0-2-0.8	29.8	48.5	11.9	4.2	17.8	83.8	31.0	7.1	15.3	25.3	8.2	4.2	0.5	16.6	9.7	5.1	17.9	47.4	8.2	5.8
B	< 0.2	12.3	34.7	20.7	5.1	12.1	50.1	26.0	6.4	8.2	29.2	6.2	4.7	0.3	5.5	2.6	1.2	2.7	3.5	1.4	0.3
Subsoil																					
A	> 0.8	5.0	11.3	6.4	1.2	15.6	6.1	1.0	0.1	7.9	1.0	< 0.1	< 0.1	-	-	-	-	1.7	2.2	0.9	0.8
M	0.2-0.8	24.3	17.4	3.4	1.8	24.[illegible]	33.7	14.7	3.7	9.1	10.2	4.3	2.6	0.7	1.4	1.0	0.3	7.6	4.3	3.4	0.9
B	< 0.2	35.7	70.2	30.7	9.1	18.9	119.5	52.0	13.0	17.6	53.2	13.3	8.1	0.3	21.5	11.8	6.1	15.1	49.8	9.0	3.8
Effective cation exchange capacity (meq/100 g)																					
Topsoil																					
A	> 8	44.0	34.5	8.0	1.3	36.2	5.0	1.6	4.3	16.2	7.4	3.2	2.0	0.2	0.8	0.5	< 0.1	5.2	[illegible]	0.4	1.5
M	4-8	14.8	53.4	27.2	9.9	18.4	62.9	33.4	10.6	9.1	16.1	4.2	4.7	0.4	5.6	3.1	1.2	17.6	16.6	2.1	1.6
e	< 4	5.8	10.9	5.2	0.8	3.9	46.5	18.2	1.9	10.3	40.9	10.1	4.1	0.3	16.4	9.1	5.1	1.6	34.1	7.4	4.4
Subsoil																					
A	> 8	16.7	18.4	0.7	1.3	25.1	20.8	5.9	< 0.6	10.3	1.3	-	-	0.1	-	-	-	< 0.1	0.2	0.8	0.9
M	4-8	43.3	41.6	8.6	3.2	22.1	66.8	31.6	9.1	8.2	8.4	4.6	4.4	0.7	1.4	1.0	0.3	8.0	6.1	3.3	5.9
e	< 4	5.1	38.9	24.4	7.6	11.3	71.5	30.3	7.3	16.0	54.7	13.0	6.3	0.1	21.5	11.8	6.1	15.9	48.3	9.0	0.7

a. a = Al toxic, FCC modifier in topsoil; A and H = high; B = low; h = acid, FCC modifier in topsoil; i = FCC modifier for P fixation; k = K deficient, FCC modifier in topsoil; M = medium.

Table 6-6. Aereal extent (million ha) of Fertility Capability Classification modifier combinations of the soils of central lowland of tropical South America.

FCC modifier combination[a]	Area	FCC modifier combination[a]	Area
a	63.1	gb	0.7
ae	10.3	gdsn	<0.1
ai	2.0	ga	19.3
ak	145.6	gai	0.5
ake	44.5	gak	13.7
akei	14.8	gake	3.6
aki	16.2	gh	17.6
		ghi	0.2
d	43.3	ghk	16.4
da	1.7	ghke	12.1
dae	0.6	gi	0.6
daei	2.3	gk	11.5
daek	1.0	gke	0.4
daeki	0.3	gkei	1.2
dai	3.1	gs	0.1
dak	1.8		
dake	28.7	h	23.7
dakei	28.5	hc	3.0
daki	1.4	he	2.0
db	0.4	hei	4.3
dei	2.1	hi	1.1
dg	1.1	hix	0.2
dh	6.4	hk	22.0
dhe	0.1	hke	3.4
dhi	3.3	hkei	8.1
dhh	5.4	hki	1.5
dhke	30.8		
dhkei	1.31	i	0.1
di	3.7	ix	1.1
dk	12.6		
dke	39.5	k	6.2
e	<0.1		
g	79.75	Without modifiers	42.4
gak	2.6		
gake	2.1	TOTAL	816.9

a. a = Al toxic, c = cat clay, d = dry, e = low cation exchange capacity (CEC), g = gley, h = acid, i = P fixation, k = K deficient, n = natric, s = salinity, x = X-ray amorphous.

Table 6-7. Average chemical composition of the topsoil (0-20 cm) of an Oxisol under semi-evergreen seasonal forest and ***Panicum maximum*** pastures of different ages in the proximity of Paragominas, Pará, Brazil.

Vegetation type	Clay (%)	OM (%)	N (%)	pH in H_2O	Exchangeable cations (meq/100 g) Ca+Mg	Al	Available elements (ppm) K	P	Al saturation (%)
Forest	65	2.79	0.16	4.4	1.47	1.8	23	1	53
Pasture (age in no. of years)									
1	50	2.04	0.09	6.5	7.53	0.0	31	10	0
3	60	3.09	0.18	6.9	7.80	0.0	78	11	0
4	55	2.20	0.11	5.4	3.02	0.2	62	2	6
5	50	1.90	0.10	5.7	2.81	0.2	66	3	6
6	51	1.90	0.09	6.0	3.84	0.0	74	7	0
7	48	1.77	0.08	5.7	2.61	0.0	47	1	0
8	52	1.69	0.08	5.4	2.10	0.0	39	1	0
9	50	2.34	0.11	5.9	4.10	0.1	70	2	2
11	45	3.37	0.15	6.0	4.10	0.0	86	1	0
13	62	2.80	0.20	5.6	4.80	0.0	54	1	0

SOURCE: Serrão et al. (1979).

Chapter 7. PHOSPHORUS LIMITATIONS AND MANAGEMENT CONSIDERATIONS

by
L. A. León and L. L. Hammond[a]

Phosphorus is undoubtedly one of the most severely limiting elements in the acid, infertile soils of tropical Latin America, as shown by Maps 17 and 18 (see Map Plates). Total P ranges from only about 200 to 600 ppm and available P (Bray II) from 1 to 7 ppm. It is obvious that, to efficiently increase crop production, phosphate fertilizer must be added to these soils and plant species that are efficient P users must be selected. Because of the acid reaction of most soils in the region (pH 4.0–5.5), some soils, especially in the central savanna area, are high in free Fe and Al oxides and hydroxides which tend to rapidly fix large amounts of P (Map 19). This is especially so when it is applied in soluble forms such as monoammonium phosphate (MAP), diammonium phosphate (DAP), single superphosphate (SSP), or triple superphosphate (TSP) (Fenster and León, 1979).

To develop a sound, economic P-management strategy for pastures and crops grown on the acid, infertile soils of tropical Latin America, several strategies might be taken into consideration. These include but are not necessarily limited to: (1) use of cheaper, less-soluble forms of P such as phosphate rock (PR) or partially acidulated PR; (2) use of soil amendments to enhance the availability of soil-applied P; (3) determining optimal placement and rates of P fertilizer to increase its efficiency, both initially and residually; and (4) selection of plant species that will tolerate relatively low levels of available soil P.

Cheaper, Less Soluble Sources of P

The use of phosphate rock (PR) as a P source for crop production appears both economically and agronomically attractive for much of the region. Not only is the unit cost of the P much lower—one-third to one-fifth that of TSP or SSP (IFDC, 1979)—but also the residual value of the product is likely to be equal to or greater than that of the more soluble P carriers. Since continuous dissolution of PR can occur in acid soils, it is likely that release of available P will be more in unison with the requirements of growing forages which are predominant in much of the region.

Due to the high requirement for P, and especially following the sharp increase in phosphate rock prices during 1974–1975, there have been intensified exploration efforts that have identified new phosphate resources. The most significant of these developments has occurred in Brazil where about 1×10^6 tons/year are now being produced from igneous deposits at Jacupiranga, Araxa, Tapira, and Catalão (G. H. McClellan, IFDC, pers. comm., 1979). There are over 20 major deposits located in tropical Latin America (Figure 7-1).

The International Fertilizer Development Center (IFDC) has developed a research program on phosphates, which is strongly oriented toward identifying methods for using these resources. Much of the agronomic research on phosphates in Latin America has been conducted in cooperation with CIAT (Centro Internacional de Agricultura Tropical) in Cali, Colombia. The aim has been to select adapt, or develop technology that is the most cost effective for meeting the needs of agriculture with the resources (raw materials, energy, infrastructure, etc.) at hand. This approach involves developing or identifying phosphate fertilizers that are well suited to tropical and subtropical soils in agronomic, technical, and economic aspects. Application or adaptation of conventional technology may or may not be the best choice.

Direct application of finely divided phosphate rock may be one of the cheapest ways to supply P to crops in many acid soil areas in the tropics and subtropics. The degree to which direct application will be effective is determined by a number of interrelated factors. These include, but are not limited to: (a) the reactivity, or potential, of the rock source as determined by the chemical composition of the apatite; (b) the physical properties of the rock; (c) the properties of the soil (acidity, available P, exchangeable Ca in the soil, and P-sorption capacity); (d) the type of crop and cropping system; (e) the method of application; and (f) the time of reaction (Parish et al., 1980).

Chemical Reactivity of Phosphate Rocks

Many Oxisols and Ultisols possess properties conductive to the dissolution of directly applied ground phosphate rock. They are acid; some of them possess high P-sorption capacity; and they generally exhibit only low concentrations of P in the soil solution and exchangeable Ca in the soil. Still, the effectiveness of each potential rock source for direct application will be determined by the chemical reactivity of the phosphate rock. It has been shown that the reactivity depends on the degree of carbonate substitution for phosphate in the apatite structure (Lehr and McClellan, 1972); several solubility tests are suitable for estimating reactivity. These include extraction with neutral ammonium citrate, 2% citric acid, 2%

a. Soil Chemist, of the IFDC CIAT Phosphorus Project and Soil Scientist of the IFDC, respectively.

Fig. 7-1 Locations of 20 phosphate deposits in Latin America.

formic acid, and acid ammonium citrate at pH 3 (Chien and Hammond, 1978). Based on these measurements, it has been possible to categorize phosphate rocks into relative rankings of high, medium, or low potential for direct application. Based on agronomic evaluation of phosphate rock from 18 separate deposits around the world, it can be generalized that rocks with citrate-soluble P greater than 17% of the total P can be ranked as having a high potential for direct application. Those with 12–17% citrate-soluble P would be considered in the medium range, while rocks with less than 12% of the total P being citrate soluble would be expected to perform relatively poorly when compared to the initial crop response possible with water-soluble P fertilizers or the highly reactive phosphate rocks.

Figure 7-2 illustrates these differences with results from a short-term greenhouse experiment with P supplied by a number of rocks from South America. While some rocks performed nearly as well as TSP, a large range in effectiveness can be observed. Depending on soil properties, crop type, and management, finely ground rock with high, medium, and low citrate solubilities generally has effectiveness ranges of 80–100, 50–80, and 30–60%, respectively, when compared to the initial crop responses to TSP. Recent studies on residual value of phosphate sources show that, even for the low-reactivity rocks in some soil-crop combinations, the initial differences between sources diminish with time. Table 7-1, in fact, shows that there has been significant response to P but no difference between sources in total yield of *Brachiaria decumbens* following 4 years of production, despite the fact that yields during the first cutting followed the levels predicted by citrate solubility. Research has also shown that dustiness, one of the main objectionable properties of phosphate rock, can be eliminated without loss of effectiveness when granulated or "minigranulated," as it is called, to a size range of 50 to 150 mesh (Tyler screens). These minigranules are consistently equal to or nearly as effective as powdered rock. In contrast, conventional granulation (6- to 16-mesh [Tyler] granules) substantially reduces the agronomic effectiveness of the rock.

Partial Acidulation of Phosphate Rock

In some situations there is a need for a phosphate fertilizer intermediate in water solubility between directly applied, finely ground rock and conventional, fully acidulated fertilize. . This need is most apparent where the reactivity of available phosphate rock is too low to provide the P requirements of plants for rapid establishment or for crops with a short growing season. Partially acidulated phosphate rock (PAPR) is an alternative that may fill this gap and can be especially important to some developing countries, which have rock deposits but only a limited availability of acid for production of conventional fertilizers.

In recent studies it has been observed that phosphoric acid (H_3PO_4) is highly effective in increasing the initial P availability of low-reactivity phosphate rocks, using only 10–20% of the amount necessary to make triple superphosphate (Hammond et al., 1980). With the Pesca PR from Colombia, for example, 20% acidulation with H_3PO_4 was observed to be 79–90% as effective as TSP in a greenhouse experiment, whereas the unacidulated rock was only 10% as effective. Using sulphuric acid, 40–50% of the H_2SO_4 required to make single superphosphate may be required to be equally as effective as the material treated with 10–20% H_3PO_4. It is promising, therefore, that fertilizer prepared with less than the conventional quantities of acid can be a highly effective means of supplying P. The use of indigenous phosphate rock as a direct application material, or when processed by both conventional and nonconventional technologies, is being studied. Only careful agronomic, industrial, and economic evaluations will give the correct routes for utilization of these phosphate rock deposits; but the potential saving in terms of foreign exchange for many developing countries is such that these studies are a much needed activity.

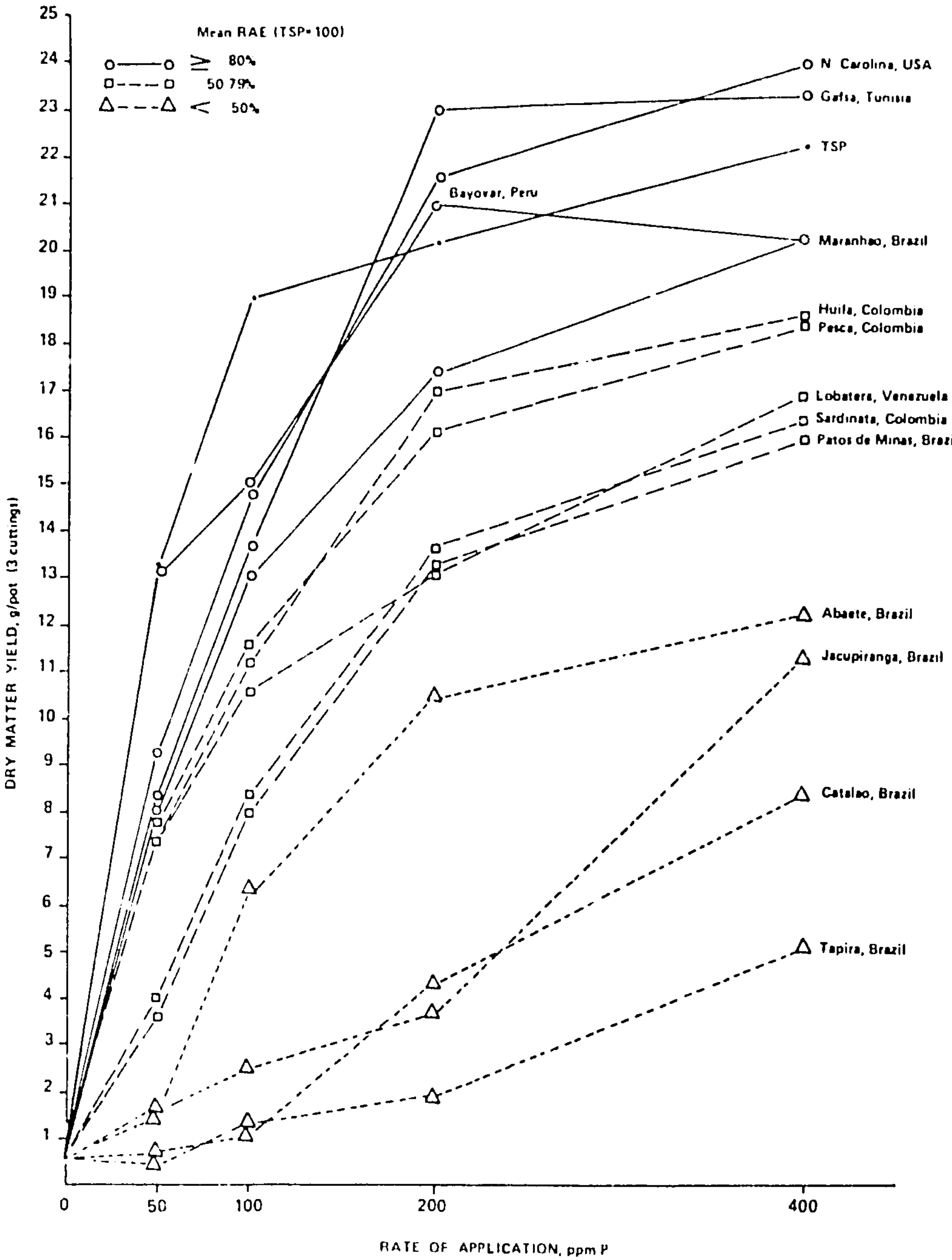


Fig. 7-2 Greenhouse comparisons of various phosphate rocks using *Panicum maximum* as the test crop. Source: Adapted from CIAT Annual Report (1979).

Table 7-1. Effect of phosphorus sources and levels (% of TSP residual) on relative yield of *Brachiaria decumbens* grown in the field on a Carimagua Oxisol Colombia (sum of 14 cuttings).

Phosphorus source	P_2O_5 added[a]			
	25 kg/ha	50 kg/ha	100 kg/ha	400 kg/ha
Triple superphosphate (TSP)				
Annual	(33.6)	(35.9)	(37.4)	(45.2)
Residual[b]	100	100	100	100
	(22.0)	(30.6)	(32.4)	(38.1)
Phosphate rock (PR)				
Fosbayovar	119	80	102	109
Florida	122	94	100	105
Gafsa	109	103	104	104
Huila	95	113	98	110
Pesca	111	81	111	116
Tennessee	104	76	95	108
Check (14.4)				

a. Figures in parentheses are dry matter yield (t/ha).
b. TSP residual considered as 100% at each P_2O_5 rate.

Table 7-2. Decrease in P fixation due to lime and silicate applications sufficient to neutralize exchangeable Al in a clayey Oxisol from Brazil with an original pH of 4.6, 1.45 meq Al/100 g soil and 80% Al saturation.

Amendment applied	P fixed (ppm) to give			Decrease (%) in P fixed		
	.03	.10	.20	.03	.10	.20
	(ppm P in solution)			(ppm P in solution)		
None	230	325	415	-	-	-
Lime (1.5 t/ha)	135	275	370	41	15	11
Calcium silicate (1.8 t/ha)	125	265	355	46	18	14

SOURCE: Adapted by Sánchez (1977) from Smyth (1976).

Soil Amendments to Enhance the Availability of Soil-Applied P

One of the problems encountered with some of the P-deficient, acid, infertile soils of tropical Latin America is their high P-fixation capacity (see Map 19). To decrease this fixation capacity, soil amendments, such as lime or Ca silicates, are sometimes applied. It is important here to note that the concept of adding lime to increase production through utilization of the native P in the soil is probably erroneous in the acid, P-deficient soils of tropical Latin America since the total amount of P in these soils is so low. The concept of adding lime to increase or maintain the availability of applied P, however, has merit.

For example, a greenhouse experiment was conducted using a Carimagua Oxisol, in which varying rates of P were applied with combinations of Ca silicate, lime, and Mg oxide (CIAT, 1977). In all cases, the addition of one or more of the amendments significantly increased the yield of *Stylosanthes guianensis* (two cuttings) over that of TSP applied alone. The highest yield was obtained with TSP plus additions of Mg oxide and Ca silicate.

The main problem encountered with many of the P-amendment experiments is determining if the lime or Ca silicate is enhancing the availability of the applied P or whether there is an additional lime and/or nutrient response. On these acid soils, Ca and Mg deficiencies are common, so the additions of amendments may very well be responses to these cations. Research by Smyth (1976) in Brazil would indicate, however, that there is definitely an amendment effect of decreasing P fixation from both the lime and Ca silicate (Table 7-2).

Placement and Rate of P Fertilizers

Placement of phosphorus. In tropical Latin America, P fertilization of pastures has generally followed the classical approach of broadcasting and incorporating basic slag or superphosphate during establishment, followed by periodic top-dressing. Recently, however, some research has been conducted to ascertain the effect of P placement on establishment of pasture and annual crops (León and Fenster, 1979).

Preliminary results from a continuing experiment at the Quilichao experiment station near Cali, Colombia (Fenster and León, 1979) indicate that broadcasting P is superior to banding in growing *Panicum maximum* and *Andropogon gayanus* pastures (Figure 7-3). Nevertheless, in this same experiment, broadcast plus band application of P gave the highest yields. This would suggest that banding is important in establishing these pastures, but broadcast treatments are necessary for maintenance.

It is also probable in very low P-supplying soils, that when only banded P is applied, root growth is restricted to the band area; thus the plants are susceptible to drought, even during short periods when it does not rain. Short periods of drought are common in many Oxisols and Ultisols because of their low water-holding capacity.

In another experiment initiated by León and Fenster (1979) with *Brachiaria decumbens* at Quilichao, the highest yields were realized with 100 kg P_2O_5/ha of TSP broadcast and incorporated. In this case, broadcast and incorporation of the TSP was superior to other methods of application. When a basal treatment of 100 kg P_2O_5/ha as phosphate rock was broadcast and incorporated, however, there was no difference in yield due to method of application of TSP. Nevertheless, yield increases due to P levels were evident. For the establishment of *Brachiaria decumbens*, it apparently is not necessary to apply more than 50 kg P_2O_5/ha as TSP. Long-term experiments by Yost et al. (NCSU, 1973, 1974, 1975) with corn at the Cerrado Center Station near Planaltina in Central Brazil indicate that a combination of broadcast plus band-placed P is the most promising strategy.

Rates of phosphorus. Several experiments have been conducted with a number of crops to determine the P rates necessary to maximize production, but only one is discussed in this section.

Hammond and León (CIAT, 1977) established an experiment on a Carimagua Oxisol in Colombia (land system No. 201) with *Brachiaria decumbens* using rates of 25, 50, 100, and 400 kg P_2O_5/ha as TSP. Figure 7-4 shows the response of this grass to different levels of phosphorus. This experiment is showing good residual effect of the soluble phosphorus applied initially. Fertilization after the first year, with the same P levels as a maintenance application, would appear reasonable only for the 25 kg P_2O_5/ha treatment, where the yield increase was more than 4 ton/ha. It is not considered necessary to use annual applications of 50 kg P_2O_5/ha or more, because yield increases due to these treatments are only of the order of 2 ton/ha.

Although the P-fixation capacity of these Oxisols is appreciable, it is not as high, for example, as in the case of the Andepts and some Oxisols from Brazil. This in part explains why the forage grasses yielded so well at lower P rates than did forage yields from experiments carried out in the Cerrado Center, Brazil (Fenster and León, 1979).

There is a good initial plant response to soluble forms of added phosphorus in many Oxisols. The residual effect, however, depends upon both the mineralogical and chemical characteristics of a soil as well as the test crop itself.

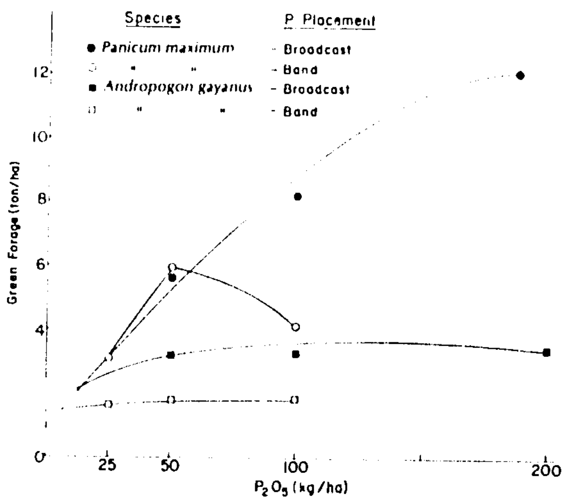


Fig. 7-3 Effect of rates and method of application of phosphorus (TSP) on two grasses grown on a CIAT-Quilichao Ultisol. Source: Unpublished data by Sánchez et al. (1978).

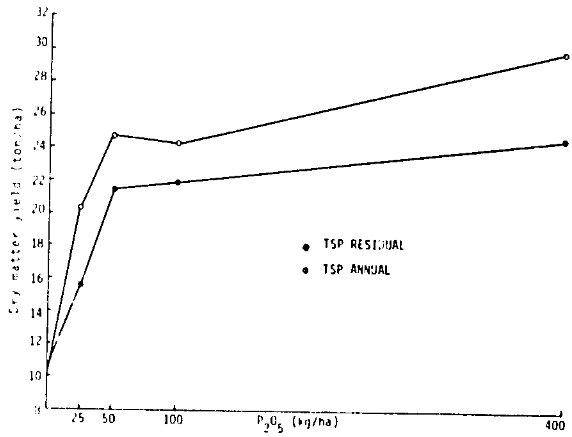


Fig. 7-4 Phosphorus response of ***Brachiaria decumbens*** grown on a Carimagua Oxisol (sum of eight harvests). In the annual treatment, P was reapplied 1 year after planting.

Selection of Plant Species Tolerant to Relatively Low Levels of Soil P

According to several researchers (Ozanne et al., 1969; IRRI, 1972; Salinas and Sánchez, 1976; CIAT, 1978a, 1980a), species or varieties that are tolerant to low levels of P produce maximum yields at lower levels of applied P than do the sensitive species or varieties.

Salinas and Sánchez (1976) present a literature review on differences among species and varieties in relation to low levels of available P in the soil. There is evidence of appreciable difference among species with respect to the external and internal critical levels of P. The most tolerant annual crops and tropical pastures to low levels of P are rice, cassava, sweet potatoes, corn, *Stylosanthes hamilis*, *Stylosanthes guianensis*, *Stylosantaes capitata*, *Centrosema pubescens*, and *Andropogon gayanus*. Four mechanisms are cited by Salinas and Sánchez to explain these differences: root extension, root exudation, influence of mycorrhiza fungi, and the differences in P absorption and translocation rates in relation to growth rates.

There is some limited evidence suggesting that tolerance to high Al saturation and low P may occur together in some species in acid soils. A faster translocation rate of P in the roots to the top and Ca translocation seem to be the main factors accounting for these differences.

Conclusion

Increase in food production due to correction of P deficiency in the acid tropical soils of Latin America can be achieved through a number of approaches. The chemistry of fertilizer reactions in these soils is not unique and, therefore, conventional fertilization practices can be expected to be satisfactory from an agronomic point of view. In the region described in this book, however, major limitations to standard approaches are frequently encountered due to the scarcity or high cost of soluble phosphate fertilizers. In those conditions, significant yield increases can be achieved with substantially reduced cost through the use of low-cost fertilizer sources, such as finely ground phosphate rock; the use of adequate placement and rates of P fertilizers together; and, where practical, the selection of plant species tolerant to low P levels.

While it is generally accepted that P is the most limiting plant nutrient in the region, full benefit from investment in phosphate fertilizer, regardless of source, can only be sustained with a complete fertilizer management strategy. Once the rate of plant growth is increased by relieving the phosphorus limitation, the increased uptake of N, K, Ca, Mg, S, and micronutrients must also be compensated.

Chapter 8. LEACHING LOSSES AND IMPROVEMENT OF SAVANNA AND FOREST SOILS

Perhaps as much as 75% of the central lowland region of tropical America has soils that may be described as leached acid soils or run a severe risk of further chemical degradation if used unwisely. These include a large percentage of the Oxisols, Ultisols, and Spodosols and some Alfisols and Inceptisols. Land clearing practices, cropping patterns, and soil amendments and fertilizers may degrade, maintain, or even improve soil fertility. Consequently, this chapter considers some of the underlying principles that are emerging concerning the management of the fertility of these soils, especially as they relate to the comparison of savanna and forest conditions.

Propensity of Soils to Leach

Leaching in soils is sometimes referred to as "chemical erosion." It may be defined as the movement of nutrients in soil solution away from the rhizosphere, the region of soil in which plant roots are found. To fully appreciate the susceptibility of a soil to leach if used for a specific purpose, the interactions of climate, vegetation, soil biotic factors, and mineralogical status must be considered.

While climate, vegetation, and soil biotic factors are universally accepted as variables, it is not so well recognized that the soil mineralogical status is also a variable. The clay fractions of many soils have both positively and negatively charged surfaces; these charges, measured in terms of their effective cation-exchange capacities, are pH-dependent.

Variable Charge Soils

As shown by Cochrane et al. (1981), many of the soils of the region classify as variable charged (Map 23). A proportion of these soils may in fact have a subsoil horizon that is negatively charged according to the delta pH test, pH H_2O - pH KCl. (If negative, soils are negatively charged; if positive, soils are positively charged.) It is assumed that such horizons have a greater capacity to retain anions than cations. Fortunately, as shown by Map 24, the comparative extension of these soils is not great. Nevertheless, they serve to emphasize that the charge characteristics of many soils of the region are a variable. This picture contrasts with many temperate regions of the world where soil parent materials are often relatively young and the principle clay minerals are the 2:1 types. These have virtually a permanent negative charge, or at least one which is not greatly affected by variations in pH, ionic strenght, or the dielectric constant of the soil solution.

The variable-charge exchange-capacity of many tropical soils has been studied by many authors including van Raij and Peech (1972), Gillman (1974), Keng and Uehara (1974), El-Swaify and Sayeth (1975), Gallez et al. (1976), Gillman and Bell (1976), Morais et al. (1976), and Cochrane and Sousa (1984) for Brazilian soils. The latter workers have developed a simple methodology for measuring cation- and anion-exchange capacities and both exchangeable cations and anions in acid mineral soils that provides a new approach for approximating soil surface variable-charge exchange-capacity analyses to field conditions. Tropical soils have by and large been formed from old weathered materials and are usually rich in residual materials, principally kaolinitic type clays and iron and aluminium oxides. As emphasized by Gillman (1979) the surface charge of their clays are dependent on pH, ionic strength, dielectric constant, and even the counterion valency of the soil solution.

Leaching anions. Because of the variable-charge exchange-capacity nature of many of the soils in the region, they have both a cation-exchange capacity and an anion-exchange capacity; the former is responsible for retaining nutrient bases, principally Ca^{++}, Mg^{++}, K^{+}, Na^{+}, Mn^{++}, Al^{+++}, and the latter anions including NO_3^-, $SO_4^{=}$, HCO_3^-, and Cl^-. In the soil solutions, the main anions are NO_3^- and $SO_4^{=}$, with lesser amounts of Cl^- and HCO_3^-, although the amounts of free bicarbonate lons that can exist in acidic solutions, except just on the acid side of neutrality, are extremely small (Nye and Greenland, 1965).

If nitrates, sulphates, or chlorides are added to the soil solution, some will be absorbed, depending on the anion capacity of a soil. However, most will remain in the soil solution where they must always be balanced by cations. The main cations that balance these anions in soil solution are Ca^{++}, Mg^{++}, K^{+}, and H_3O^{+}, with Al^{+++} becoming important in soils with pH lower than 5.3. Conversely, if cations are added to the soil, some will be absorbed on the soil surfaces, but the remainder will stay in solution, where they must be balanced by anions. In other words, for any soil, the total concentration of cations in the soil solution depends on the total concentration of anions, and vice-versa; they must balance.

Changing charge characteristics. To complicate matters, the addition of significant quantities of nutrient cations and anions, and particularly soil amendments such as lime, can produce a change in the charge characteristics of many of these soils; this will modify the ability of a soil to restrain the loss of nutrients through leaching. Unfortunately, studies of the effect of soil amendments on the surface charge of the soils are still virtually at the "identification of a potential problem" stage, and much work needs to be done before the full implications of the phenomenon can be translated into practical farming terms.

Organic Matter

Other ways exist to modify the cation-exchange capacity of a soil; the incorporation of organic matter is an example. There are many practical farming experiences of successful soil management through draconian measures involving the incorporation of organic matter, but there are examples of successful management with minimal input, such as the use of single superphosphate in Planaltina, Brazil. What is evident is that it is difficult to get something for nothing, and that it is easy to lose inputs if too much of the wrong type is applied.

Soil-Water Percolation

Leaching cannot occur unless water percolates through soil. The amount of percolation will depend on the physical properties of soil that enable them to hold and otherwise restrain water movements away from them, the climatic water balance, and the type of vegetative covering and its stage of growth.

Soil moisture-holding capacities vary considerably. Although clay soils generally hold more moisture than sandy soils, many clayey Oxisols have soil moisture-holding capacities approaching those of light-textured soils. In fact, the low moisture-holding capacities of Oxisols in the isothermic savannas of Central Brazil exaggerate the impact of the so-called *veranicos*, or Indian summers, the irregular periods of drought occurring during the wet season.

Climatic water-balance patterns, as already emphasized in Chapter 3, vary from ecosystem to ecosystem; clearly in the context of percolation, these must be qualified by the soil moisture-holding capacities.

The type of vegetation or crop covering, its stage of growth, and the rate at which it transpires (or, to put it crudely, how it pumps water out of a soil) will have a significant effect on the rate of soil-moisture percolation. Transpiration will obviously proceed apace during periods of high potential evapotranspiration, and vice-versa, always providing that soil moisture is not limiting. The "root-room" of a soil, or the suitability of the soil for root development in both a physical and chemical sense, will affect percolation and consequently leaching losses, particularly if roots can penetrate deeply. A good vegetative cover is obviously a prerequisite to ameliorate water percolation and consequent loss of nutrients.

Nitrogen Flushes and Leaching

Nitrogen flushes were first described by Hardy (1946). These occur in tropical soils with a marked dry season. They often follow a pattern of gradual nitrate build-up in the dry season, a rapid but short-lived increase at the start of the wet season, and a rapid tapering off as the dry season progresses. Flushes are most marked in ustic moisture conditions.

It is probable that the rapid build-up of microbial activity, particularly nitrifying bacteria at the start of the wet season, is associated with N mineralization (Birch, 1958); this proceeds faster at the lower C:N ratios resulting from a dry-season period. More recently, Semb and Robinson (1969) have proven that nitrification can take place at the very low soil-moisture tensions (below 15 bars) found in subsoils during the dry season.

Wild (1972) showed that nitrates move upward from the subsoil to the topsoil during the dry season. Conversely, Semb and Robinson (1969) found NO_3^- movements to the subsoil after the initial "flush" at the start of the wet season; as the excess of nitrates must be balanced by nutrient cations, the phenomenon could result in considerable soil leaching (losses of cations as well as valuable N), unless plant roots can absorb soil moisture and so avoid a permanent loss of nutrients from the plant rhizosphere. Interestingly, Kinjo and Pratt (1971) indicate that nitrate leaching may be reduced if the subsoil has a degree of anion-exchange capacity.

Leaching Trends in Savannas and Forests

Although few studies have been recorded in tropical America, there is evidence that nitrates will move with percolating soil moisture, beyond the main actively growing rhizosphere, soon after the start of the wet season, in savanna conditions (J. Salinas, CIAT, pers. comm.). It is probable that this phenomenon aggravates the very leached, acid condition very commonly found in these regions. The nitrates and accompanying cations percolate down the soil profile faster than the main body of roots grows, or faster than those which survive the dry season can absorb soil moisture. Once grass roots are well established, losses are considerably reduced; however, by that time the main effect of the "flush" of nitrates is over.

In contrast to savannas, Nye and Greenland (1960) report that there are many studies on forest soils which indicate a minimum of leaching beyond the rhizosphere. The reasons for this are threefold. First, the main body of tree roots does not die back in the dry season, as is common with grasses; therefore, they afford a more efficient mechanism to absorb percolating water. Second, much moisture, at least that from light rainfalls, is held on the leaves of trees and absorbed directly, or is absorbed by the leaf litter; consequently, the amount of water physically entering the soil is reduced. Third, with the exception of a proportion of the semi-evergreen seasonal forests, the dry season is generally not so severe under forest as under savanna conditions, and thus there is a lesser build-up of nitrates in the topsoil. It is evident, therefore, that forest vegetation provides a very efficient system of nutrient re-cycling, which largely avoids a net leaching of plant nutrients.

It should also be noted that not only are forests much more effective in recycling nutrients than savannas, but also they provide a much greater storehouse for nutrients. In a certain sense, they may be described as being able to "leach" soils: they have a maximum ability to withdraw nutrients from a soil and use them to produce biomass. Recycling nutrients via leaf fall and tree aging and decay is probably only a casual phenomenon. Consequently, under their native vegetation, many forest soils are as chemically poor as their savanna counterparts derived from similar parent materials.

Comparative figures of nutrients stored in forests versus savanna vegetation are not available for the region, but data from the African continent (Vine, 1968) would indicate that forests may store up to 10 times the amounts of nutrients stored by savannas. This, however, varies between forests and according to the arboreal content of savannas; Vine records figures to show that savannas with a high arboreal content have a greater reservoir of plant nutrients than do the open grassland types.

Fertility Improvement in Savannas and Forests

It is good sense to ensure that nutrients stored in biomass are returned to soils by burning and producing ash, if lands are to be cleared of their original vegetation and used for agriculture. This simple stratagem has been used by tropical bush farmers for thousands of years. This is particularly important in the case of forests, but may also be of significance in savannas with a considerable arboreal biomass content, such as the Cerradão.

Nevertheless, for most savannas, which do not have a significant biomass, improvement of their soils, if these are weathered and leached, must largely rely on correcting toxicity problems and fertilization. Care must be taken in fertilization and the application of amendments to avoid significant losses of the original costly inputs. Further, excess liming has often been responsible for inducing nutrient deficiencies, especially of Zn (Spain, 1976).

The "nitrogen flush" effect is particularly severe in savanna regions; fertilization and soil-amendment practices such as liming are best designed to take this phenomenon into account. Crops and pastures should be selected and managed, insofar as it is possible, to help avoid excess nitrate leaching at the start of the dry season. Nitrogen fertilizer treatments for many crops may best be delayed until after the effect of the initial nitrogen flush has passed. Conversely, in liming practices to ameliorate high soil Al levels for those crops sensitive to Al or to overcome Mn toxicity problems, advantage may be taken of the nitrogen flush to help with the incorporation of Ca deeper into the soil profile. In such cases, lime should be incorporated at the start of the wet season or, if feasible, before the start of the wet season. Work to improve management practices through a better understanding of the nitrogen flush and anion leaching generally could lead to higher, more stable production in the savannas.

In contrast with many savanna soils, weathered, leached forest soils can usually be significantly improved by the incorporation of nutrients stored in their biomass through burning. Experiences in the clearing of forests has been detailed in Cochrane and Sánchez (1982). One of the most spectacular demonstrations of the effect of burning after cutting in situ has been recorded by Falesi (1976). Table 8-1 records data from Falesi's work (Serrão et al., 1978) in which semi-evergreen seasonal forest growing on an Oxisol near Paragominas, along the Belém-Brasilia highway, was cut, burned, and transformed into pasture. The marked improvement in topsoil chemical properties is evident; burning and the incorporation of ash completely changed nutrient properties.

What is of even more interest is that these changes persist for many years under grass cultivation, with the exception of P levels. Probably soil N is largely tied up by the grass, and little leaching takes place. The climatic regime in this circumstance would also help avoid the excessive nitrogen-flush effect of the savannas.

Not all results related to burning forests and the subsequent management of improved soil fertility are as promising as those indicated from Falesi's work, as demonstrated by Cochrane and Sánchez (1982). It is probable that tropical rain forests present a more difficult situation, partly due to the problems of burning these forests in their more humid climate. Nor is it implied that cutting and burning even semi-evergreen seasonal forests will solve soil fertility problems for all crops. As indicated by Morán (1977), cutting and burning forests growing on soils with a higher fertility status due to better parent materials, specifically the Alfisols of Altamira along the transamazonic highway of Brazil, results in much better crops than cutting and burning forests on intrinsically less fertile lands. The fundamental fertility of a soil will have a very significant effect on crop production, and the selection of superior soils in both savanna and forest circumstances will facilitate farming success.

Table 8-1. Average chemical composition of the topsoil (0-20 cm) of an Oxisol under semi-evergreen seasonal forest and *Panicum maximum* pastures of different ages in the proximity of Paragominas, Pará, Brazil.

Topsoil	Clay	OM	N	pH (H_2O)	Exchangeable $Ca^{++}+Mg^{++}$	Al^{+++}	Available K	P	Al Sat.
		(%)			(meq/100 g)		(ppm)		(%)
Forest	65	2.79	0.16	4.4	1.47	1.8	23	1	53
1 year pasture	50	2.04	0.09	6.5	7.53	0.0	31	10	0
3 years pasture	60	3.09	0.18	6.9	7.80	0.0	78	11	0
4 years pasture	55	2.20	0.11	5.4	3.02	0.2	62	2	6
5 years pasture	50	1.90	0.10	5.7	2.81	0.2	66	3	6
6 years pasture	51	1.90	0.09	6.0	3.84	0.0	74	7	0
7 years pasture	48	1.77	0.08	5.7	2.61	0.0	47	1	0
8 years pasture	52	1.69	0.08	5.4	2.10	0.0	39	1	0
9 years pasture	50	2.34	0.11	5.9	4.10	0.1	70	2	2
11 years pasture	45	3.37	0.15	6.0	4.10	0.0	86	1	0
13 years pasture	62	2.80	0.20	5.6	4.80	0.0	54	1	0

Source: Serrão et al, 1978.

Chapter 9. ADAPTING SEED-BASED AGROTECHNOLOGY TO LOCAL CONDITIONS: SOME GUIDELINES

Agronomists and farmers everywhere are keenly aware of the need for new crop varieties and cultivars to improve production. However, they are often faced with the problem of judging the suitability of a variety, which has proven superior elsewhere, for a local climate and soil condition. The Land Systems Map and data base provide a convenient geographical orientation of climate, landscape, and soil parameters for this purpose. Because the majority of agronomists live in rural areas without access to computer facilities, the data base, using summarized formats, has been published as Volume 3, the *Computer Summary and Soil Profile Descriptions of the Land Systems*. Part 1 summarizes the landscape and soil features of all the land systems mapped, as detailed below. Part 2 is a selection of meteorological data sets taken from the Hancock et al. (1979) collection, which may be used to help approximate climatic conditions in any given land system. Part 3 records a range of typical soil profiles to provide an in-depth guide to help with the visualization and interpretation of soil properties.

This chapter explains how these data may be used for local agricultural planning.

Transferring Technology Based on Land Systems

The comparison of land systems is a useful starting point for the transfer of seed-based agrotechnology throughout the region. Their environmental descriptors also provide a basis for the more selective introduction of promising cultivars from other parts of the tropical world, with known climate and soil conditions. Unfortunately, the presence of biotic factors, including pests and diseases, against which an otherwise promising cultivar may have little or no resistance, is not always known; such may exclude the use of those cultivars in a given land system or even more an entire continent, as is the case of cassava varieties with no resistance to African mosaic disease.

Within certain limits, it may be possible to develop agr 'omic practices for local climate-soil environment to take advantage of promising cultivars adapted to apparently different environments elsewhere. Climates must be considered in relation to the type of crop being grown. For perennial crops, the annual climatic patterns should coincide. On the other hand, for short-term annual crops, the seasonal and monthly characteristics are paramount. Consequently, annual crops are often grown successfully in regions with very different overall climatic patterns. What is important is to try to match the water-balance, energy regimes, day lengths, and so on, to ensure that the local climatic conditions during the life cycle of the promising cultivars are compatible with those in which they were originally developed.

Of the nonbiotic factors affecting the successful introduction of promising cultivars, perhaps the most tricky to assess is the ability of local soils to meet their nutrient needs without the use of uneconomic applications of soil amendments. This is particularly true in the underdeveloped, acid-infertile soil circumstances, where the specific traits desired in a cultivar may be tolerance to excessive aluminium (see Appendix 2) and low phosphate availability.

Enhancing Soil Fertility Information

It might be emphasized that although much information can be deduced from small-scale maps, including the land systems maps, these maps are scale limited; consequently, in the absence of detailed soil studies, it will often be necessary for agronomists to enhance the soil information for any particular area of interest.

The careful evaluation of soil survey data can help the agronomist "zone-in" on what are likely to be probable soil nutrient problems. Visual crop deficiency symptoms seen in any area also help. In fact, the presence or absence of the minor and trace element constraints recorded in the land-systems printouts in Volume 3 were often confirmed by observing visual symptoms on crops. In his study of the tropical lowlands of Bolivia, Cochrane (1973) paid particular attention to the identification of visual deficiency symptoms on Dwarf Cavendish bananas (see Photo Plate 32).

For many undeveloped areas, especially where soil fertility has been little affected by the incorporation of soil amendments, the value of a soil survey can be enormously enhanced, with a minimum of effort, if a number of soil profiles, or even topsoil samples, can be described and sampled. This will permit the statistical comparison of soil nutrient levels over a given soil unit. Cochrane (1969) has shown that 12 to 18 topsoil samples, spaced over a relatively constant soil unit, will provide an adequate population in a statistical sense, to calculate means, standard deviations, and correlations between soil chemical properties; these are meaningful for helping to understand soil fertility. By this procedure, outlined in Appendix 3, unnecessarily repetitive soil sampling is avoided, and soil analytical time can be profitably spent in carrying out as complete a set of analyses as possible.

Most routine soil survey sample analyses are restricted to describing the more "permanent" soil properties. The case of total mineral analyses occasionally excepted, they rarely provide complete major, minor, and trace element analyses as now commonly carried out for soil fertility investigations. In fact, the lack of minor and trace element analytical data throughout the region surveyed was particularly disappointing. Part of the reason for this is historical. In the past, minor and especially trace element analyses were difficult and costly. The advent of atomic absorption spectrometry in the 1960s changed this situation. Unfortunately, old habits die hard.

The methodology developed was tested in the context of the present work on land system No. 201, in which the ICA (Instituto Colombiano Agropecuario)-CIAT Carimagua agricultural station is located, and results are recorded in Appendix 3. The results of identifying soil toxicity problems, probable nutrient deficiency problems, and possible nutrient problems compare well with the actual findings from CIAT's experimental work over the past 12 years. The approach advocates a breakaway from normal dogma concerning the collection of soil samples for fertility analysis, which involve making artificial composite samples from 12 to 20 subsamples.

Field Trials

Although soil information can be considerably enhanced by a relatively minor amount of work, field trials must still be carried out to quantify the nutrient needs of promising crop cultivars. Unfortunately, in many lesser developed circumstances, progress is often slow and recommendations incomplete.

In supplying fertilizer recommendations for the new generations of crop and pasture plant cultivars with a degree of tolerance to soil toxicities and low nutrient levels, it is necessary to use proven, comprehensive, but time-saving methods to establish recommendations. In many tropical lands, in addition to soil toxicities and major nutrient deficiencies, limiting factors may include minor or trace-element deficiencies or imbalances; consequently, the methodology adopted must provide a means of identifying these problems as quickly as possible. In this respect, Cochrane (1979) has shown that within a time span of less than 2 years, he was able to identify both minor and trace elements in field-proven conditions in Santa Cruz, Bolivia.

This methodology, which involves the monitoring of field trials through comparative tissue analyses, has been recorded in Appendix 4. The philosophy of the approach aims at starting field trials as soon as possible and maximizing information by subjecting tissue analysis data taken on a plot by plot basis, at a predetermined stage of crop growth to the same statistical analysis as yield data.

Summary

The land-systems data base provides a geographical and technical base to guide the successful transfer of seed-based agrotechnology both throughout the region and from other parts of the tropics. Nevertheless, technologies developed elsewhere must be proven in the local circumstance. The technique suggested for enhancing the soil fertility information to help with the selection of treatments in field trials and the comparative tissue analysis methodology suggested for maximizing information from such trials are both particularly relevant to tropical areas with limited research facilities.

The use of the land-system data base and complementary agronomic techniques should lead to the selection of high-yielding crop varieties with farm-effective fertilizer recommendations for a given ecosystem, more speedily and much more cheaply than has been the norm in the past. It should also contribute to the more successful conservation and use of the soil resources in tropical South America.

Epilogue.
DEVELOPING LAND SYSTEMS MAPS FOR OTHER AREAS

This work demonstrates the feasibility of undertaking a comprehensive assessment of tropical land resources on a continental basis, given the support of national scientists, in a short period of time. The computerized land-systems approach facilitates the synthesis and management of information now available in various forms in many organizations throughout the world. It permits a thorough analysis of climate, landscape, and soil factors, and provides a rapid means of quantifying these environmental constraints for specifying the desirable germplasm traits for pasture and crop cultivars. It provides a geographical base for the transfer of successful seed-based agrotechnologies from one location to another, and brings to light general research needs.

It complements work being carried out by national programs and help they are receiving from international projects, including the FAO land resource studies; activities in the International Soils Museum, Wageningen; the U.S. AID-funded Soil Management Support Services and IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) programs based at the University of Hawaii and the University of Puerto Rico; and the tropical soils research program at North Carolina State University.

The land-systems data base is already being put to good use in developing and transferring new pasture-plant and food-crop cultivars over tropical America, and is proving a novel way to investigate basic climate/landscape/vegetation/soil relationships per se. However, experience shows that crop cultivars often do just as well in continents away from their centers of development, always providing climate and soil circumstances are comparable (Purseglove, 1974). It is interesting to reflect, therefore, that tremendous mutual benefits lie in store for all countries if similar surveys and analyses could be extended throughout the tropics in general.

With a tropic-wide land-systems base, crop varieties and agrotechnologies successfully developed in one tropical ecosystem could then be transferred to other environmentally compatible areas with a much greater degree of potential success than is currently possible. This is not to suggest that production difficulties will not arise. Every continent has specific biological problems (pests, diseases, weeds, and soil microorganisms) that could affect the successful transfer of technologies. Nevertheless, considerable time and effort will be saved by ensuring compatible matches between seed-based agrotechnologies and climate-soil environments, rather than using the "hit or miss" methods still largely in vogue today.

There would be many additional benefits arising from such a global information system. Not the least would be the progressive build-up of information on cultivars well-adapted to the many climate-soil environments of the tropics, enhancing the ability of nations to better plan and manage production problems in environmentally, socially, or economically fragile regions. In short, a tropic-wide land-systems data base would be an invaluable resource for individual nations now striving to meet the escalating need for food in an ever-changing world.

APPENDIX 1. APPROXIMATE EQUIVALENCE BETWEEN SOIL TAXONOMY GREAT GROUPS, THE FAO SOIL MAP LEGEND, AND THE BRAZILIAN SOIL CLASSIFICATION SYSTEM

Sources:
The numbers in parentheses refer to the following citations:

1. FAO-Unesco. 1974. Soil map of the world. 1:5,000,000. Volume1. Legend. Unesco, Paris. p. 14–20.
2. Camargo, M.N., et al. 1975. Mapa esquemático dos solos das regiões norte, meio-norte e centro-oeste do Brasil. Bol. Tec. 17. Centro de Pesquisas Pedológicas, EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária), Rio de Janeiro, Brasil. p. 86—88.
3. Sánchez, P.A. (ed.) 1976. Properties and management of soils in the tropics. Wiley, New York. p. 52–86.

U.S. Soil Taxonomy	FAO Legend	Brazilian Classification
Alfisols	Luvisols (3)	Terra Roxa Estruturada (3)
	Eutric Nitosols (3)	Podzólico Vermelho Amarelo Equivalente Eutrófico (3)
Aqualfs	Gleyic Luvisols (1)	
Albaqualfs	Eutric Planosols (1, 2)	Planosols (1)
	Orthic Solonetz (1)	Solos Hidromórficos Cinzentos Eutróficos (2)
Duraqualfs		
Fragiaqualfs		
Glossaqualfs	Gleyic Podzoluvisols (1)	
Natraqualfs	Gleyic Solonetz (1, 2)	Solonetz Solodizado (2)
	Solodic Planosols (2)	Planosols (2)
	Eutric Planosols (2)	
Ochraqualfs		
Plinthaqualfs		
Tropaqualfs	Eutric Gleysols (2)	Solos Gley Pouco Húmicos. Eutróficos (2)
	Eutric Planosols (2)	Solos Hidromórficos Cinzentos Eutróficos (2)
Umbraqualfs		
Boralfs		
Cryoboralfs		
Eutroboralfs	Albic Luvisols (1)	
Fragiboralfs		
Glossoboralfs	Eutric Podzoluvisols (1)	
Natriboralfs		
Paleoboralfs		

U.S. Soil Taxonomy	FAO Legend	Brazilian Classification
Udalfs		
Agrudalfs		
Ferrudalfs		
Fragiudalfs		
Fraglossudalfs		
Glossudalfs	Eutric Podzoluvisols (1)	
Hapludalfs	Orthic Luvisols (1)	
Natrudalfs		
Paleudalfs	Eutric Nitosols (1, 2)	Terra Roxa Estruturada medium to high base status (1)
	Ferric Luvisols (2)	Laterítico Bruno Avermelhado Eutrófico (2)
		Podzólico Vermelho Amarelo Equivalente Eutrófico (2)
Rhodudalfs	Eutric Nitosols (1)	
Tropudalfs	Eutric Nitosols (1)	Terra Roxa Estruturada medium to high base status (1)
	Ferric Luvisols (2)	Laterítico Bruno Avermelhado Eutrófico (2)
		Podzólico Vermelho Amarelo Equivalente Eutrófico (2)
Ustalfs		
Durustalfs		
Haplustalfs	Calcic Luvisols (1)	Podzólico Vermelho Amarelo Equivalente Eutrófico (2)
	Ferric Luvisols (2)	
Natrustalfs	Gleyic Solonetz (1, 2)	Solonetz Solidizado (2)
	Solodic Planosols (2)	Planosols (2)
	Eutric Planosols (2)	
Paleustalfs	Eutric Planosols (1)	Planosols (1)
	Eutric (Rhodic) Nitrosols (2)	Laterítico Bruno Avermelhado Eutrófico (2)
	Ferric Luvisols (2)	Podzólico Vermelho Amarelo Equivalente Eutrófico (2)
Plinthustalfs	Plinthic Luvisols (1, 2)	Laterita Hidromórfica Eutrófica (2)
Rhodustalfs	Luvic Yermosols (1)	Terra Roxa Estruturada medium to high base status (1)
	Ferric Luvisols (2)	Podzólico Vermelho Amarelo Equivalente Eutrófico (2)
		Solos Brunos não Cálcicos (2)
Xeralfs		
Durixeralfs		
Haploxeralfs	Chromic Luvisols (1)	
	Orthic Luvisols (1)	
Natrixeralfs	Orthic Solonetz (1)	
Palexeralfs	Eutric Planosol (1)	Planosol (1)
Plinthoxeralfs	Plinthic Luvisols (1)	
Rhodoxeralfs	Chromic Luvisols (1)	
Aridisols	Typic Yermosols (1)	Soils with Natric B horizon (3)
Argids	Luvic Yermosols (1)	
Durargids	Luvic Xerosols (1)	
Haplargids	Luvic Xerosols (1)	
Nadurargids	Orthic Solonetz (1)	
Natrargids	Orthic Solonetz (1)	
Paleargids	Eutric Planosols (1)	Planosol (1)

U.S. Soil Taxonomy	FAO Legend	Brazilian Classification
Orthids		
Calciorthids	Calcic Xerols (1)	
	Calcic Yermosols (1)	
	Gypsic Xerosols (1)	
Camborthids	Haplic Xerosols (1)	
	Haplic Yermosols (1)	
Durorthids	Haplic Xerosols (1)	
	Haplic Yermosols (1)	
Gypsiorthids	Gypsic Yermosols (1)	
Paleorthids		
Salorthids	Orthic Solonchaks (1)	
Entisols		Regosols (3)
Aquents		
Cryaquents		
Fluvaquents		
Haplaquents	Eu-Dystric Gleysols (1)	
Hydraquents		
Psammaquents	Eu-Dystric Gleysols (1)	
Sulfaquents		
Tropaquents	Eu-Dystric Gleysols (1)	Solos Gley Pouco Húmicos Distróficos y Eutróficos (2)
Arents		
Arents		
Fluvents	Fluvisols (1)	
Cryofluvents		
Torrifluvents		
Tropofluvents	Eu-Dystric Fluvisols (1)	Solos Aluviais Eutróficos y Distróficos (2)
	Dystric Cambisols (1)	
	Gleyic Cambisols (1)	
Udifluvents		
Ustifluvents		
Xerofluvents		
Orthents	Regosols (1)	
Cryorthents	Gelic Regosols (1)	
Torriorthents		
Troporthents		
Udorthents		
Ustorthents		
Xerorthents		
Psamments	Regosols (1)	Red and Yellow Sands (3)
	Arenosols (1)	
	Ferralic Arenosols (3)	
Cryopsamments	Gelic Regosols (1)	
Quartzipsamments	Albic Arenosols (1)	Red and Yellow Sands (1)
	Ferralic Arenosols (2)	Areias Quartzosas Vermelhas Amarelas (2)
Torripsamments	Albic Arenosols (1, 2)	Areias Cinzentas com fragipan (2)
Udipsamments	Albic Arenosols (1)	
Ustipsamments		
Xeropsamments		
Histosols	Histosols (1)	Solos Orgânicos (2)
Inceptisols	Cambisols (3)	Soils with incipient B horizon (3)
Andepts	Andosols (1)	

U.S. Soil Taxonomy	FAO Legend	Brazilian Classification
Cryandepts		
Durandepts		
Dystrandepts	Ochric Andosols (1)	
	Humic Andosols (1)	
Eutrandepts	Mollic Andosols (1)	
Hydrandepts	Humic Andosols (1)	
Placandepts		
Vitrandepts	Vitric Andosols (1)	
Aquepts		
Andaquepts	Eu-Dystric Gleysols (1)	
Cryaquepts	Gelic Gleysols (1)	
Fragiaquepts	Eu-Dystric Gleysols (1)	
Halaquepts	Gleyic Solonchak (2)	Solos Salinos Costeiros Indiscriminados (2)
Haplaquepts	Eu-Dystric Gleysols (1)	
Humaquepts	Humic Gleysols (1)	
Placaquepts		
Plinthaquepts	Plinthic Gleysols (1, 2)	Laterita Hidromórfica Distrófica (2)
	Plinthic Acrisols (2)	
	Plinthic Ferralsols	
Sulfaquepts		
Tropaquepts	Eu-Dystric Gleysols (1, 2)	Solos Gley Húmicos Distróficos
	Humic Gleysols (2)	Solos Gley Pouco Húmicos Distróficos (2)
Ochrepts		
Cryochrepts	Gelic Cambisols (1)	
Durochrepts		
Dystrochrepts	Dystric Cambisols (1)	
Eutrochrepts	Eutric Cambisols (1)	
	Calcic Cambisols (1)	
Fragiochrepts		
Ustochrepts	Calcic Cambisols (1)	
	Eutric Cambisols (1)	
Xerochrepts	Eutric Cambisols (1)	
	Calcic Cambisols (1)	
	Chromic Cambisols (1)	
Plaggepts		
Plaggepts		
Tropepts		
(Oxic Tropepts)	Ferralic Cambisols (1)	
Dystropepts	Dystric Cambisols (1)	
Eutropepts	Eutric Cambisols (1)	
Humitropepts	Humic Cambisols (1)	
Somoritropepts		
Ustropepts		
Umbrepts		
Cryumbrepts		
Fragiumbrepts		
Haplumbrepts	Humic Cambisols (1)	
	Rankers (1)	
Xerumbrepts		
Mollisols		
Albolls		
Argialbolls	Mollic Planosols (1)	
Natralbolls	Mollic Solonetz (1)	

U.S. Soil Taxonomy	FAO Legend	Brazilian Classification
Aquolls		
Argiaquolls	Gleyic Phaeozems (1)	Solos Gley Húmicos Eutróficos (2)
	Mollic Gleysols (1, 2)	
Calciaquolls		
Cryaquolls		
Duraquolls		
Haplaquolls	Mollic Gleysols (1, 2)	Solos Gley Húmicos Eutróficos (2)
Natraquolls		
Borolls		
Argiborolls	Orthic Greyzems (1)	
	Luvic Chernozems (1)	
Calciborolls	Calcic Chernozems (1)	
Cryoborolls		
Haploborolls	Haplic Chermozems (1)	
Natriborolls	Mollic Solonetz (1)	
Peleborolls		
Vermiborolls	Haplic Chernozems (1)	
Rendolls		
Rendolls	Rendzinas (1)	
Udolls		
Argiudolls	Luvic Phaeozems (1, 2)	Brunizem Avermelhado (2)
Hapludolls	Haplic Phaeozems (1)	
	Eutric Fluvisols (1)	Solos Aluviais Eutróficos (2)
Paleudolls	Luvic Phaeozems (1, 2)	Brunizem Avermelhado (2)
Vermudolls	Calcic Phaeozems (1)	
Ustolls		
Argiustolls	Luvic Phaeozems (1)	
	Luvic Kastanozems (1)	Brunizem Avermelhado (2)
Calciustolls	Calcic Kastanozems (2)	
Durustolls		
Haplustolls	Haplic Kastanozems (1)	
Natrustolls	Mollic Solonetz (1)	
Paleustolls	Luvic Phaeozems (1, 2)	Brunizem Avermelhado (2)
Vermustolls		
Xerolls		
Argixerolls		
Calcixerolls		
Durixerolls		
Haploxerolls		
Natrixerolls	Mollic Solonetz (1)	
Palexerolls		
Oxisols		
Aquox		
Gibbsiaquox		
Ochraquox	Dystric Gleysols (2)	Solos Gley Pouco Húmicos Distróficos y Eutróficos (2)
Plinthaquox	Plinthic Ferralsols (1, 2)	Laterita Hidromórfica Distrófica (2)
	Plinthic Gleysols (1, 2)	
	Plinthic Acrisols (2)	
Umbraquox	Humic Gleysols (2)	Solos Gley Húmicos Distróficos (2)
Humox		
Acrohumox		
Gibbsihumox		

U.S. Soil Taxonomy	FAO Legend	Brazilian Classification
Haplohumox		
Sombrihumox		
Orthox	Orthic, Acrix y Xantic Ferralsols (3)	
Acrorthox	Acric Ferralsols (1, 2)	Latosol Vermelho Amarelo Distrófico (2)
	Orthic Ferralsols (1, 2)	Latosol Vermelho Escuro Distrófico (2)
	Rhodic Ferralsols (1, 2)	(Rhodic Ferralsol=) Latosol Roxo (1)
	Humic Ferralsols (2)	
Eutrorthox	Orthic Ferralsols (1)	Latosol Roxo Eutrófico (2)
	Rhodic Ferralsols (1, 2, 3)	Latosol Vermelho Escuro Eutrófico (2)
		Latosol Roxo ou Terra Roxa Legítima (Dusky Red Latosol) (3)
Gibbsiorthox		
Haplorthox	Acric Ferralsols (1)	Latosol Amarelo Distrófico (2)
	Orthic Ferralsols (1)	Latosol Roxo Distrófico (2)
	Rhodic Ferralsols (1, 2)	Latosol Vermelho Amarelo Distrófico (2)
	Xantic Ferralsols (1, 2)	Latosol Vermelho Escuro Distrófico (2)
	Humic Ferralsols (2)	(Xantic F=) Pale Yellow Latosol (1)
		(Rhodic F=) Latosol Roxo (1)
Sombriorthox		
Umbriorthox	Xantic Ferralsols (1)	
	Humic Ferralsols (1)	
Torrox	Rhodic Ferralsols (1)	Latosol Vermelho Amarelo Eutrófico y Distrófico (2)
	Acric Ferralsols (1, 2)	Red Yellow Latosol (1)
	Orthic Ferralsols (1, 2)	
	Humic Ferralsols (2)	
Ustox	Orthic Ferralsols (3)	Latosol Amarelo (3)
	Acric Ferralsols (3)	Latosol Vermelho Amarelo (3)
	Xantic Ferralsols (3)	Latosol Vermelho Escuro (3)
Acrustox	Orthic Ferralsols (1)	Latosol Vermelho Amarelo Distrófico (2)
	Acric Ferralsols (1, 2)	Latosol Vermelho Escuro Distrófico (2)
	Rhodic Ferralsols (2)	
	Humic Ferralsols (2)	
Eutrustox	Orthic Ferralsols (1, 2)	Latosol Roxo Eutrófico (2)
	Rhodic Ferralsols (1, 2, 3)	Latosol Vermelho Amarelo Eutrófico (2)
		Latosol Vermelho Escuro Eutrófico (2)
		Latosol Roxo ou Terra Roxa Legitima (Dusky Red Latosol) (3)
Sombriustox		
Haplustox	Orthic Ferralsols (1)	Latosol Roxo Distrófico (2)
	Acric Ferralsols (1, 2)	Latosol Vermelho Amarelo Distrófico (2)
	Rhodic Ferralsols (2)	Latosol Vermelho Escuro Distrófico (2)
	Humic Ferralsols (2)	

U.S. Soil Taxonomy	FAO Legend	Brazilian Classification
Spodosols	Podzols (1)	Podzols (3)
Aquods	Gleyic Podzols (1)	
Cryaquods		
Duraquods		
Fragiaquods		
Haplaquods		
Placaquods		
Sideraquods		
Tropaquods	Gleyic Podzols (2)	Podzol Hidromórfico (2)
Ferrods		
Ferrods	Ferric Podzols (1)	
Humods		
Cryohumods	Humic Podzols (1)	
Fragihumods		
Haplohumods		
Placohumods	Placic Podzols (1)	
Tropohumods		
Ultisols	Acrisols (3)	Podzólico Vermelho Amarelo (Red Yellow Podzolic) (3)
	Dystric Nitosols (3)	
Aquults	Gleyic Acrisols (1)	
Albaquults	Dystric Planosols (1, 2)	Planosols (1) Solos Hidromórficos Cinzentos Distróficos (2)
Fragiaquults		
Ochraquults		
Paleaquults		
Plinthaquults	Plinthic Acrisols (1, 2) Plinthic Gleysols (1, 2) Plinthic Ferralsols (1, 2)	Laterita Hidromórfica Distrófica (2)
Tropaquults	Dystric Planosols (2)	Solos Hidromórficos Cinzentos Distróficos (2)
	Dystric Gleysols (2)	Solos Gley Pouco Húmicos Distróficos (2)
Umbraquults	Humic Gleysols (2)	Solos Gley Húmicos
Humults		
Haplohumults		
Plaehumults	Humic Nitosols (1)	
Plinthohumults		
Sombrihumults		
Tropohumults	Humic Nitosols (1)	
Udults		
Fragiudults		
Hapludults	Orthic Acrisols (1, 2)	Red Yellow Podzolic Soils, low base status (1)
	Ferric Acrisols (2)	Podzólico Vermelho Amarelo (2)
Paleudults	Dystric (Rhodic) Nitosols (1, 2)	Podzólico Vermelho Amarelo (2)
	Humic (Rhodic Nitosols) (1, 2)	Laterítico Bruno Avermelhado Distrófico
	Ferric Acrisols (2) Orthic Acrisols (2)	
Plinthudults	Plinthic Ferralsols (2)	Laterita Hidromórfica Distrófica (2)
	Plinthic Acrisols (1, 2)	Podzólico Vermelho Amarelo Plíntico (2)

U.S. Soil Taxonomy	FAO Legend	Brazilian Classification
Rhodoudults	Dystric Nitosols (1)	Podzólico Vermelho Amarelo (2)
	Ferric Acrisols (2)	
	Orthic Acrisols (2)	
	Dystric (Rhodic) Nitosols (1)	
Tropoudults	Humic (Rhodic) Nitosols (2)	Terra Roxa Estruturada low base status (1)
	Ferric Acrisols (2)	Podzólico Vermelho Amarelo (2)
	Orthic Acrisols (2)	Laterítico Bruno Avermelhado Distrófico (2)
Ustults		
Haplustults	Ferric Acrisols (2)	Red Yollow Podzolic Soils low base status
	Orthic Acrisols (1, 2)	Podzólico Vermelho Amarolo (2)
Paleustults	Orthic Acrisols (1)	Podzólico Vermelho Amarelo (2)
	Ferric Acrisols (1, 2)	
Plinthustults	Plinthic-Acrisols (1, 2)	Laterita Hidromórfica Distrófica (2)
	Plinthic Ferralsols (2)	Podzólico Vermelho Amarelo Plíntico (2)
Rhodoustults	Dystric Nitosols (1)	Terra Roxa Estruturada low base status (1)
	Orthic Acrisols (1)	Podzólico Vermelho Amarelo (2)
	Ferric Acrisols (2)	
Xerults		
Haploxerults	Orthic Acrisols (1)	Red Yellow Podzolic Soils low base status (1)
Palexerults	Ferric Acrisols	Terra Roxa estruturada low base status (1)
	Dystric Nitosols (1)	
Vertisols	Vertisols	Solos Grumossolicos (2)

Appendix 2. RECENT METHODOLOGY FOR CORRECTING AL TOXICITY

Since the mid-1960s, the preferred method of making liming recommendations to correct Al toxicity in acid mineral soils has been to base them on the equation:

meq Ca/100 g soil = 1.5 meq exch. Al/100 g soil,

as recorded by Mohr (1960), Cate (1965), and Kamprath (1970), rather than on liming to a given pH. Nevertheless, Evans and Kamprath (1970), Kamprath (1971), and subsequent workers including Spain (1976), have indicated that, for many crops, the equation usually grossly overestimates liming requirements, partly because of varying degrees of plant tolerance to Al.

In recent years, Spain (1976), Rhue and Grogan (1977), and Salinas (1978) have shown that consistent differences in Al tolerance are found among plant species and cultivars within species. It is evident, therefore, that crop tolerance to Al should be taken into account in estimating the amounts of lime needed to correct Al toxicity. Another problem with the above equation is that it is based solely on the amount of exchangeable Al in the soil; it does not take the levels of exchangeable Ca, Mg, and K already in the soil into account. The level of these exchangeable cations is important in determining liming requirements.

An Improved Liming Equation

In 1980, Cochrane et al. published the following equation for liming acid mineral soils to compensate crop aluminium tolerance and take the levels of exchangeable Ca and Mg in the soil into account:

$$\text{Lime required } (CaCO_3 \text{ equiv. tons/ha}) = 1.8\,[Al - RAS\,(Al + Ca + Mg)/100] \qquad [1]$$

in which:

Al = meq Al/100 g soil, 1N KCl extract
Ca = meq Ca/100 g soil, 1N KCl extract
Mg = meq Mg/100 g soil, 1N KCl extract
RAS = required % Al saturation of the effective cation exchange capacity.

In this equation, the lime requirement estimated by the formula is multiplied by 1-1.3 if it exceeds the value of the meq Al/100 g soil, 1N KCl extract.

It is noted that:

1. In order to calculate the minimal liming requirement of a soil for a given crop, the RAS will be the same as the percentage of Al saturation at which the crop tolerates soil Al;
2. This formula assumes that the apparent specific gravity of the soil is about 1.2. For a soil with a known apparent specific gravity, a correction may be made by dividing the estimated lime requirement by 1.2 and multiplying by the known specific gravity.

Virtually no exchangeable Al or soil solution Al is found in mineral soils (containing less than 7% organic matter) with a pH higher than 5.4, as noted by McCart and Kamprath (1965) and Pratt and Alvahydo (1966). Therefore, the term "acid mineral" soil is used in the context of a soil having a pH less than 5.5 and an organic matter content less than 7%.

In acid mineral soils, soil solution Al and percentage Al saturation are related, as shown by Evans and Kamprath (1970) and Breenes and Pearson (1973). Furthermore, Nye et al. (1961) have shown that the amount of Al in soil solution is low until an Al saturation of about 60% is reached.

Several investigators, including Evans and Kamprath (1970), Abruña et al. (1975), and Sartain and Kamprath (1975), have shown a close relationship between Al saturation and plant response. Evans and Kamprath (1970) noted that maize tolerated up to 70% Al saturation compared with 30% for soya bean. Upland rice, cassava, cowpea, groundnut, and many pasture species are tolerant to quite high rates of Al saturation, as shown by Spain (1976). Recently, Salinas (1978) has identified varietal tolerances to Al toxicity in wheat, maize, sorghum, rice, and beans as part of a low-input strategy to manage Brazilian Oxisols.

These concepts were integrated to formulate the equation for liming mineral acid soils. This equation estimates minimal liming needs at different levels of Al saturation. It is clear that lime should only be applied to soils with pH values lower than 5.5, and that it should reduce Al saturation to a level commensurate with the tolerance of the crop to Al. The equations were derived in the following way.

Assuming that all the Al is in the exchangeable form, the following relationship would express the basic liming concept:

$$Al_F = Ca_X \qquad [2]$$

where:

Al_F = meq of Al/100 g soil replaced by liming in the exchange complex, and
Ca_X = meq of Ca/100 g soil added to the exchange complex.

Likewise, in order to calculate the amount of Ca that should be added to the exchange complex to reduce the Al saturation to a given level, the equation:

$$(Al - Al_F)/(Al - Al_F + Ca + Ca_X + Mg) = RAS/100 \qquad [3]$$

could be used in which:

Al = meq of Al/100 g soil in the original exchange complex;
Al_r = meq of Al/100 g soil replaced by liming;
Ca = meq of Ca/100 g soil in the original exchange complex;
Ca_v = meq of Ca/100 g soil added to the exchange complex;
Mg = meq of Mg/100 g soil in the original exchange complex; and
RAS = required percentage Al saturation.

By using equation [2], each occurrence of Al_r in equation [3] can be replaced by Ca_v. Then, solving the resulting equation for Ca_v, gives:

$$Ca_v = Al - RAS(Al + Ca + Mg)/100 \quad [4]$$

Since not all the Al replaced by liming is exchangeable, as emphasized by Kamprath (1970), the right side of the equation should be multiplied by a factor of 1.5 when moderate levels of Al saturation are required, and by a factor of 2 when very low levels are needed. Equation [4] then becomes:

$$\frac{\text{meq Ca/100 g soil}}{\text{required for liming}} = 1.5\,[Al - RAS(Al + Ca + Mg)/100] \quad [5]$$

where the factor 1.5 is replaced by 2 when the estimated liming requirement using the factor 1.5 is greater than the chemical lime equivalent of the exchangeable Al. This criterion follows from the calculated data. It is clear that the highest lime requirement estimated by the equation is twice the chemical lime equivalent of the exchangeable Al.

Equation [5] was used for estimating field lime requirement, as given by equation [1]. It assumes that a soil has an apparent specific gravity of 1.2; that 1 hectare of soil to the 20-cm depth would weigh 2.4 million kg.

Testing the Equation

Cochrane et al. (1980) tested the equation using data from other authors' field and incubation studies over a variety of soils ranging from North Carolina state in the United States to São Paulo state in southern Brazil. This included Kamprath's (1970) incubation data for four North Carolina Ultisols; L.A. Leon's (CIAT, pers. comm.) incubation data from Colombian Oxisols and Ultisols; field data from a Central Brazilian Acrustox (Salinas, 1978); data from field trials on an Acrustox from São Paulo (van Raij et al., 1977); and data from further field trials on a Central Brazilian Acrustox (González-Erico, 1976). It gave a very good estimation of the field-proven lime rates needed to reduce the percentage of Al saturation to a required value.

Soil Analysis for the Equation

The use of the equation requires no soil analysis beyond the 1N KCl extraction of Al, Ca, and Mg. There is ample literature on crop tolerance to Al, in terms of percentage of Al saturation, to use as a preliminary guide to make reasonable RAS (required Al saturation in percent) estimates. Additional information is accumulating rapidly. Interestingly, where specific liming trials have been carried out, the equation may be used in a converse sense to estimate the tolerance of a particular crop accession or cultivar.

Summary

The equation synthesizes what has been established to date concerning the problem of Al toxicity in soils to permit a realistic prediction of minimal lime requirements. Inherent to its development was the organization of current knowledge concerning soil Al. The equation should only be used for establishing liming requirements to solve Al toxicity problems. This emphasis is required because liming is also used to reduce excessive amounts of soil Mn, to supply trace elements found as impurities in liming materials, and to make a trace element like Mo more available. (It might be noted that in liming to correct Mn toxicities, soils should be properly drained as a prerequisite for overcoming such problems.)

Appendix 3.
A STATISTICAL PROCEDURE FOR ENHANCING SOIL SURVEYS FOR SOIL FERTILITY INVESTIGATIONS

Agronomists requiring more information for designing field fertilizer trials are faced with the problem of how much to sample, and even how to go about soil sampling. In soil survey, particularly, precision is generally, but often erroneously, associated with sample density; much sampling and many analyses are demanded for surveys with large mapping scales.

The approach advocated by Cochrane (1969) for enhancing soil surveys for fertility investigations is to examine and sample 12 to 18 soil profiles or topsoil samples over a relatively constant soil unit. Once these samples have been analyzed chemically (and this analysis should be as complete as possible), the chemical analytical data might be analyzed statistically to establish means, standard deviations, and a correlation matrix. This can then be scrutinized and interpreted to help understand soil fertility problems according to the following procedure to identify probable toxicity and nutrient problems, always bea[illegible] in mind the crop and its genetic make-up in terms of nutrient tolerances and demands:

I. Methodic scrutiny of the statistical data.
   A. Inspect means, maximums, minimums, and standard deviations to:
      1. Identify probable and possible toxicity problems (Al, Mn, Fe) from the soil analytical figures.
      2. Identify probable and possible deficiency problems in the same way.
      3. Note circumstances that could give correlations with little implication insofar as soil properties are concerned, including those populations with small standard deviations compared with their means (perhaps those with a standard deviation less than 20% of the mean).
   B. Inspect the correlation matrix for possible meaningful correlations, in the sense of A-3 above, and list both positive and negative correlations in order of significance. It has been well known for many years that relationships exist between the availability of certain major and minor nutrients. The presence of strong correlations within this sample may indicate that the relationships in question may apply to the specific soil under study.

II. Interpretation.
   A. In the event of a probable toxicity problem:
      1. a. For Al, calculate liming needs according to the equation of Cochrane et al. (1980).
         b. For Mn, "guesstimate" liming needs.
         c. For Fe toxicity, ensure that the soil is well drained.
      2. Then reconsider the implication of these treatments on the deficiencies and their correlations. There is a possible implication that a positive correlation between two elements will mean that raising one will increase the availability of the other if it is not in short supply, or cause more serious deficiency if it is in short supply. For a negative correlation, the reverse situation would apply.
   B. In the event of probable deficiency problems:
      1. Consider first the implication of any actions that will probably be taken to solve a toxicity problem, if such exists.
      2. Starting with the most serious problem, estimate a fertilizer application for adequate correction. If this probable deficiency is correlated with another, consider possible effects of the correction.
      3. Continue this process for other deficiencies, in descending order of apparent importance.

The procedure was applied to land system No. 201, land facet No. 1, the principle soils (Haplustox) of CIAT's Carimagua station located in the eastern plains of Colombia; the correlation matrix of the soil analytical data has been recorded in the tables in this Appendix. The procedure was also followed experimentally for a limited number of other soils, including soils from central Brazil and northern Bolivia. In short, while the methodology is still in an experimental stage, it indicated the presence of:

1. Toxicity problems for Al and Fe (the latter if soils used were under wet conditions).
2. Probable nutrient problems for P, K, Ca, and Mg.
3. Possible nutrient problems for Mn, Zn, and B.

Recommendations from the Statistical Procedure

K deficiency. The addition of K might aggravate the Mg deficiency problem. Therefore [illegible] and Mg should be added together.

Possible Mn, Zn, and B deficiencies. The correlations of these elements with others are not as highly significant as others and could probably be field tested without too much problem. For example, the negative correlation between Zn and pH (in H_2O) is probably only significant if major changes take place in pH. Although S levels appear moderate, availability could be questioned. The positive correlation between P and Cu levels should be borne in mind. In this respect, the type of P fertilizer to be applied must be considered in the light of its ability to supply other nutrients (such as S and Ca in the case of single superphosphate), apart from the effect of the fertilizer components on leaching.

Thus, it is clear that fertilizer trials should be designed to take liming, P, K, and Mg treatments into account and, if possible, Mn, Zn, B, and possibly S and even Cu. The soils should be well drained and not used for wetland crops to avoid Fe toxicity problems.

Discussion

The recommendations from the statistical procedure compare well with actual findings from CIAT's experimental work over the past 12 years: Al toxicity and low levels of P and bases (K, Ca, and Mg) were found to be the major limiting factors for many arable crops (Spain, 1976). Fe toxicity was reported for flooded rice (Howeler, 1973). Ngongi et al. (1977) found K and S deficiency problems in cassava. Howeler et al. (1977) also describe lime by Zn, Mn, B, and Cu interactions in cassava; further, they found that high liming rates reduced yields by inducing Zn deficiency and possibly Mn and B deficiencies. Much costly experimental work went into establishing these and similar results (reported in CIAT's annual reports); had the statistical sampling procedure discussed in this Appendix been incorporated into the initial soil survey study of the region, the soil fertility specialists would have saved both time and costs. There is clearly a critical need to improve the role soil surveys play in providing a basis for soil fertility investigations, especially when carried out on undeveloped lands.

Table A3-1. Soil analytical data o' samples of 18 profiles throughout land facet No. 1. Land System 201: horizon A.

Sample no.	pH H_2O	pH KCl	OM	P	Al	Ca	Mg	K	Na	CEC	% Al S	B	Zn	Mn	Cu	Fe	S	Mo
1	4.8	3.9	1.7	1.5	1.4	0.09	0.02	0.05	0.03	1.59	90	0.26	0.40	1.8	0.36	24.4	5.0	1.04
2	4.7	3.7	5.3	1.7	3.8	0.07	0.01	0.01	0.03	3.92	98	0.32	0.55	2.3	0.53	15.4	4.5	1.31
3	4.6	3.6	4.2	1.6	3.8	0.15	0.02	0.10	0.03	4.10	93	0.30	0.55	4.0	0.53	23.4	4.5	1.23
4	4.6	3.7	3.8	1.5	2.8	0.10	0.02	0.10	0.04	3.06	93	0.35	0.60	2.1	0.36	38.4	6.0	1.18
5	4.4	3.6	4.3	2.1	3.6	0.12	0.02	0.14	0.04	3.92	93	0.26	0.70	3.3	0.71	58.4	7.0	1.24
6	4.4	3.7	3.8	1.0	3.1	0.08	0.01	0.07	0.03	3.29	95	0.30	0.55	1.9	0.53	40.0	3.5	1.01
7	4.5	3.7	4.5	1.8	3.0	0.11	0.02	0.11	0.03	3.27	93	0.24	0.50	5.9	0.53	16.8	3.0	1.04
8	4.3	3.6	3.6	1.2	3.7	0.11	0.02	0.09	0.03	3.95	94	0.26	0.55	3.9	0.71	39.0	5.0	1.17
9	4.5	3.6	3.6	1.5	2.6	0.12	0.02	0.07	0.03	2.84	93	0.23	0.60	2.8	0.53	44.0	6.0	1.36
10	4.6	3.7	3.5	1.5	2.3	0.14	0.02	0.07	0.03	2.56	91	0.28	0.60	2.6	0.35	50.4	6.0	1.27
11	4.7	3.8	3.4	4.8	2.0	0.18	0.02	0.11	0.05	2.36	87	0.23	0.60	2.2	4.94	60.0	8.0	0.99
12	4.5	3.8	3.9	1.4	2.5	0.08	0.02	0.07	0.03	2.70	94	0.24	0.75	1.9	0.36	51.6	8.0	1.20
13	4.8	3.7	3.3	1.2	2.9	0.08	0.01	0.06	0.07	3.12	95	0.25	0.50	2.4	0.71	24.4	5.0	1.01
14	4.8	3.6	2.8	1.7	2.5	0.09	0.01	0.05	0.03	2.68	94	0.30	0.50	3.6	0.53	39.0	7.0	1.31
15	4.6	3.9	4.8	1.0	2.6	0.09	0.02	0.10	0.03	2.84	93	0.17	0.50	2.8	0.71	41.2	4.5	1.36
16	4.4	3.8	4.1	1.1	2.9	0.09	0.03	0.10	0.03	3.15	93	0.23	0.45	2.6	0.90	66.8	4.5	1.36
17	4.7	3.7	3.5	1.7	2.7	0.08	0.01	0.08	0.03	2.90	94	0.22	0.45	2.8	0.53	26.8	6.0	1.29
18	4.7	3.7	3.9	1.1	2.8	0.07	0.01	0.06	0.04	2.98	95	0.28	0.40	1.5	0.53	49.6	5.0	1.40

Table A3-2. Preliminary description of analytical results from Table A3-1.

Variable	No. of samples	Mean	S.D.	Preliminary description
pH H_2O	18	4.58888889	0.15296631	L
pH KCl	18	3.71111111	0.09633818	L
OM	18	3.77777778	0.77955912	M
P	18	1.63333333	0.84575062	VL
Al	18	2.83333333	0.62778790	H
Ca	18	0.10277778	0.02986352	VL
Mg	18	0.01722222	0.00574513	VL
K	18	0.08000000	0.02970443	VL
Na	18	0.03500000	0.01043185	L
CEC	18	3.06833333	0.63078149	VL
% Al S	18	93.22222222	2.28950433	T
B	18	0.26222222	0.04236474	L
Zn	18	0.54166667	0.09275204	VL
Mn	18	2.80000000	1.05160941	VL
Cu	18	0.79722222	1.04454778	M
Fe	18	39.42222222	15.12222967	T
S	18	5.47222222	1.39823652	M
Mo	18	1.20944444	0.13798859	M

a. T = toxic (Fe under poorly drained conditions), VL = very low, L = low, M = moderate, H · high.

Table A3-3. Correlation coefficients of analytical data in Table A3-1 (prob >IRI under HO:RHO = 0; N = 18).

pH H_2O

pH H_2O	K	CEC	Mg	Al	Zn	OM	Fe	Na	Mn	pH KCl	P	S	Cu	Ca	B	% Al S	Mo
1.00000	-0.51784	-0.50621	-0.50573	-0.47983	-0.42151	-0.39190	-0.39049	-0.36863	-0.28889	-0.24837	-0.21219	-0.17724	-0.12865	-0.12162	0.11296	-0.09331	-0.05605
0.0000	0.0277	0.0321	0.0323	0.0439	0.0815	0.1077	0.1091	0.1322	0.2450	0.3203	0.3979	0.4817	0.6109	0.6307	0.6554	0.7127	0.8252

pH KCl

pH KCl	CEC	Al	B	Mn	% Al S	Mg	Zn	pH H_2O	Cu	Ca	Mo	OM	Fe	P	K	S	Na
1.00000	-0.63468	-0.62896	-0.45320	-0.42386	-0.35855	0.27161	-0.25235	0.24837	0.21836	-0.17493	-0.16766	-0.12967	-0.10884	0.06738	-0.06167	-0.04124	0.00000
0.0000	0.0047	0.0052	0.0589	0.0796	0.1440	0.2756	0.3124	0.3203	0.3840	0.4875	0.5061	0.6081	0.6673	0.7905	0.8079	0.8709	1.0000

OM

OM	Al	CIC	% Al S	pH H_2O	MO	S	Zn	Mn	K	Na	pH KCl	P	Cu	Ca	Mg	B	Fe
1.00000	0.69754	0.69746	0.48412	-0.39190	0.35423	-0.29741	0.27389	0.24755	0.18036	-0.14467	-0.12967	-0.10141	-0.07283	-0.07047	-0.05108	-0.03048	-0.02620
0.0000	0.0013	0.0013	0.0418	0.1077	0.1492	0.2307	0.2114	0.3220	0.4739	0.5668	0.6081	0.6889	0.7740	0.7811	0.8405	0.9044	0.9116

P

P	Cu	Ca	% Al S	S	MO	Na	K	Zn	Al	Fe	pH H_2O	CEC	Mg	OM	B	pH KCl	Mn
1.0000	0.91160	0.70180	-0.66023	0.53307	-0.37181	0.29336	0.29268	0.26245	-0.25703	0.23322	-0.21219	-0.20299	0.10492	-0.10141	-0.09905	-0.06738	0.02381
0.0000	0.0001	0.0012	0.0029	0.0227	0.1287	0.2374	0.2385	0.2927	0.3032	0.3517	0.3979	0.4192	0.6786	0.6889	0.6958	0.7905	0.9253

Al

Al	CEC	OM	% Al S	pH KCl	pH H_2O	Mn	S	B	Cu	P	Zn	Fe	MO	K	Mg	Ca	Na
1.0000	0.99585	0.69754	0.64936	-0.62896	-0.47983	0.39115	-0.34735	0.30669	-0.26771	-0.25703	0.21215	-0.20332	0.20258	0.13564	-0.11960	-0.07739	-0.06287
0.0000	0.0001	0.0013	0.0035	0.0052	0.0439	0.1085	0.1579	0.2158	0.2828	0.3032	0.3980	0.4184	0.4201	0.5915	0.6364	0.7602	0.8043

Ca

Ca	% Al S	P	Cu	K	Mg	Zn	S	Mn	Fe	MO	pH KCl	pH H_2O	Na	Al	OM	B	CEC
1.00000	-0.74945	0.70180	0.62916	0.53712	0.45904	0.35925	0.31892	0.29595	0.27365	-0.24370	-0.17493	-0.12162	0.08497	-0.07739	-0.07047	-0.07026	0.00120
0.0000	0.0003	0.0012	0.0052	0.0215	0.0553	0.1431	0.1971	0.2331	0.2719	0.3298	0.4875	0.6307	0.7375	0.7602	0.7811	0.7818	0.9962

Mg

Mg	K	% Al S	pH H_2O	Fe	Ca	B	pH KCl	Na	Zn	Mn	Cu	Al	P	CEC	S	MO	OM
1.00000	0.58597	-0.53168	-0.50573	0.46522	0.45904	-0.31150	0.27161	-0.24537	0.22998	0.20446	0.14959	-0.11960	0.10492	-0.06466	0.06306	0.05730	0.05108
0.0000	0.0106	0.0232	0.0323	0.0517	0.0553	0.2083	0.2756	0.3264	0.3586	0.4157	0.5535	0.6364	0.6786	0.7988	0.8037	0.8213	0.8405

K

K	Mg	Ca	pH H_2O	% Al S	Fe	Mn	B	Zn	Cu	P	CEC	OM	Al	Mo	S	Na	pH KCl
1.00000	0.58597	0.53712	-0.51784	-0.47572	0.42874	0.40863	-0.32721	0.29891	0.29859	0.29268	0.21411	0.18036	0.13564	-0.13203	0.11330	0.07593	-0.06167
0.0000	0.0106	0.0215	0.0277	0.0460	0.0758	0.0922	0.1850	0.2282	0.2238	0.2385	0.3936	0.4739	0.5915	0.6015	0.6544	0.7646	0.8079

Na

Na	Mo	Cu	pH H_2O	P	Mg	Mn	S	OM	% Al S	Ca	K	Al	CEC	Fe	Zn	B	pH KCl
1.00000	-0.42703	0.38571	0.36863	0.29336	-0.24537	-0.23057	0.19156	-0.14467	-0.09852	0.08497	0.07593	-0.06287	-0.04067	0.03431	0.01520	-0.01331	0.00000
0.0000	0.0772	0.1139	0.1322	0.2374	0.3264	0.3573	0.4464	0.5668	0.6973	0.7375	0.7646	0.8043	0.8727	0.8925	0.9523	0.9582	1.0000

Continued

Table A3-3 Continued.

CEC

CEC	Al	OM	pH KCl	% Al S	pH H_2O	Mn	S	B	Zn	Cu	K	P	Mo	Fe	Mg	Na	Ca
1.00000	0.99585	0.69746	-0.63468	0.58192	-0.50621	0.42060	-0.32152	0.28345	0.24457	-0.21485	0.21411	-0.20299	0.17732	-0.16440	-0.06466	-0.04067	0.00120
0.0000	0.0001	0.0013	0.0047	0.0113	0.0321	0.0822	0.1932	0.2544	0.3280	0.3919	0.3936	0.4192	0.4815	0.5145	0.7988	0.8727	0.9962

% Al S

% Al S	Ca	P	Al	Cu	CEC	Mg	OM	K	S	Fe	pH KCl	Mo	B	Na	pH H_2O	Zn	Mn
1.00000	-0.74945	-0.66023	0.64936	-0.64663	0.58192	-0.53168	0.48412	-0.47572	-0.39302	-0.39126	-0.35855	0.35791	0.30997	-0.09852	-0.09331	-0.07387	0.00733
0.0000	0.0003	0.0029	0.0035	0.0037	0.0113	0.0232	0.0418	0.0460	0.1066	0.1084	0.1440	0.1448	0.2106	0.6973	0.7127	0.7708	0.9770

B

B	pH KCl	K	Mg	% Al S	Al	CEC	Cu	Fe	Mn	pH H_2O	Zn	P	Mo	Ca	S	OM	Na
1.00000	-0.45320	-0.32721	-0.31150	0.30997	0.30669	0.28345	-0.24936	-0.24028	-0.12543	0.11296	0.10230	-0.09905	-0.08430	-0.07026	-0.05848	-0.03048	-0.01331
0.0000	0.0589	0.1850	0.2083	0.2106	0.2158	0.2544	0.3183	0.3389	0.6199	0.6545	0.6863	0.6958	0.7395	0.7818	0.8177	0.9044	0.9582

Zn

Zn	S	pH H_2O	Ca	Fe	K	OM	P	pH KCl	CEC	Mg	Al	Cu	B	Mo	% Al S	Na	Mn
1.00000	0.56508	-0.42151	0.35925	0.33984	0.29891	0.27389	0.26245	-0.25235	0.24457	0.22998	0.21215	0.12543	0.10230	-0.09001	-0.07387	0.01520	0.00603
0.0000	0.0145	0.0815	0.1431	0.1677	0.2282	0.2714	0.2927	0.3124	0.3280	0.3586	0.3980	0.6200	0.6863	0.7225	0.7708	0.9523	0.9811

Mn

Mn	pH KCl	CEC	K	Al	Fe	S	Ca	pH H_2O	OM	Na	Mg	B	Cu	Mo	P	% Al S	Zn
1.00000	-0.42386	0.42060	0.40863	0.39115	-0.33897	-0.31604	0.29595	-0.28889	0.24755	-0.23057	0.20446	-0.12543	-0.10849	-0.08067	0.02381	0.00733	0.00603
0.0000	0.0796	0.0822	0.0922	0.1085	0.1588	0.2014	0.2331	0.24[illegible]	0.3220	0.3573	0.4157	0.6199	0.6683	0.7503	0.9253	0.9770	0.9811

Cu

Cu	P	% Al S	Ca	S	Na	Fe	Mo	K	Al	B	pH KCl	CEC	Mg	pH H_2O	Zn	Mn	OM
1.00000	0.91160	-0.64663	0.62916	0.41015	0.38571	0.37432	-0.36646	0.29859	-0.26771	-0.24936	0.21836	-0.21485	0.14959	0.12865	0.12543	-0.10849	-0.07283
0.0000	0.0001	0.0037	0.0052	0.0909	0.1139	0.1259	0.1347	0.2288	0.2828	0.3183	0.3840	0.3919	0.5535	0.6109	0.6200	0.6683	0.7740

Fe

Fe	S	Mg	K	% Al S	pH H_2O	Cu	Zn	Mn	Ca	Mo	B	P	Al	CEC	pH KCl	Na	OM
1.00000	0.52054	0.46522	0.42874	-0.39126	-0.39049	0.37432	0.33984	-0.33897	0.27365	0.25749	-0.24028	0.23322	-0.20332	-0.16440	0.10884	0.03431	-0.02820
0.0000	0.0268	0.0517	0.0758	0.1084	0.1091	0.1259	0.1677	0.1698	0.2719	0.3023	0.3369	0.3517	0.4184	0.5145	0.6673	0.8925	0.9116

S

S	Zn	P	Fe	Cu	% Al S	Al	CEC	Ca	Mn	OM	Na	pH H_2O	K	Mo	Mg	B	pH KCl
1.00000	0.56508	0.53307	0.52054	0.41015	-0.39302	-0.34735	-0.32152	0.31892	-0.31604	-0.29741	0.19156	0.17724	0.11330	0.08071	0.06306	-0.05848	-0.04124
0.0000	0.0145	0.0227	0.0268	0.0909	0.1066	0.1579	0.1932	0.1971	0.2014	0.2307	0.4464	0.4817	0.6544	0.7502	0.8037	0.8177	0.8709

Mo

Mo	Na	P	Cu	% Al S	OM	Fe	Ca	Al	CEC	pH KCl	K	Zn	B	S	Mn	Mg	pH H_2O
1.00000	-0.42703	-0.37181	-0.36646	0.35791	0.35423	0.25749	-0.24370	0.20258	0.17732	-0.16766	-0.13203	-0.09001	-0.08430	0.08071	-0.08067	0.05730	-0.05605
0.0000	0.0772	0.1287	0.1347	0.1448	0.1492	0.3023	0.3298	0.4201	0.4815	0.5061	0.6015	0.7225	0.7395	0.7502	0.7503	0.8213	0.8252

Table A3-4. Soil analytical data of samples of 18 profiles throughout land facet No. 1. Land System No. 201: horizon B.

Sample No.	pH H_2O	pH KCl	OM	P	Al	Ca	Mg	K	Na	CEC	% Al S	B	Zn	Mn	Cu	Fe
1	5.0	4.0	0.7	0.6	0.9	0.09	0.01	0.05	0.03	1.08	86	0.15	0.40	1.6	0.18	6.3
2	4.9	4.0	1.4	0.3	1.4	0.08	0.01	0.05	0.03	1.57	91	0.17	0.70	1.6	0.36	9.6
3	5.1	4.0	1.1	0.3	1.7	0.07	0.01	0.05	0.03	1.86	93	0.16	0.40	1.7	0.18	10.4
4	5.0	4.0	1.0	0.4	1.5	0.07	0.01	0.04	0.03	1.65	93	0.10	0.45	1.3	0.18	17.6
5	4.8	3.8	1.3	0.4	2.3	0.09	0.01	0.06	0.03	2.49	93	0.17	0.35	1.6	0.36	12.8
6	4.9	3.9	1.3	0.4	1.7	0.08	0.01	0.04	0.03	1.86	93	0.18	0.40	2.3	0.18	16.6
7	4.7	3.9	2.1	0.4	2.2	0.06	0.01	0.05	0.03	2.35	95	0.13	0.35	3.9	0.36	6.4
8	5.0	4.0	0.9	0.3	1.6	0.08	0.03	0.05	0.03	1.77	92	0.16	0.25	2.9	0.53	10.6
9	4.9	4.0	0.9	0.4	1.2	0.14	0.01	0.04	0.03	1.44	85	0.25	0.35	2.1	0.18	13.3
10	5.3	4.2	0.5	0.3	0.6	0.09	0.01	0.04	0.03	0.77	81	0.13	0.25	1.5	0.18	8.0
11	4.9	4.0	1.0	0.5	1.2	0.06	0.01	0.04	0.03	1.34	92	0.10	0.25	1.5	0.18	22.6
12	4.8	4.0	1.1	0.4	1.2	0.07	0.01	0.03	0.02	1.33	92	0.15	0.35	1.8	0.18	14.4
13	4.9	3.9	0.7	0.3	1.5	0.07	0.01	0.04	0.17	1.79	93	0.22	0.25	2.1	0.18	6.4
14	4.6	3.9	0.9	0.5	1.7	0.06	0.01	0.04	0.03	1.84	94	0.14	0.25	2.0	0.18	4.6
15	5.0	4.1	1.5	0.4	1.2	0.07	0.01	0.07	0.03	1.38	89	0.14	0.40	2.6	0.36	6.8
16	5.1	4.0	1.5	0.3	1.4	0.06	0.01	0.05	0.07	1.59	92	0.12	0.25	2.2	0.36	6.8
17	4.9	4.0	1.1	0.4	1.6	0.06	0.01	0.04	0.03	1.74	94	0.14	0.35	1.5	0.36	8.0
18	5.0	4.1	1.1	0.3	1.1	0.05	0.01	0.04	0.03	1.23	92	0.10	0.35	1.4	0.53	5.2

Table A3-5. Preliminary description of analytical results from Table A3-4.

Variable	No. of samples	Mean	S.D.	Preliminary description
pH H_2O	18	4.93333333	0.15718105	L
pH KCl	18	3.98888889	0.09002541	L
OM	18	1.11666667	0.36822308	M
P	18	0.38333333	0.08574929	VL
Al	18	1.44444444	0.41476035	M
Ca	18	0.07500000	0.02007339	VL
Mg	18	0.01111111	0.00471405	VL
K	18	0.04555556	0.00921777	VL
Na	18	0.03944444	0.03403670	L
CEC	18	1.61555556	0.41599240	VL
% Al S	18	91.11111111	3.62813984	T
B	18	0.15055556	0.03932851	L
Zn	18	0.35277778	0.10910360	VL
Mn	18	1.97777778	0.64767054	VL
Cu	18	0.27888889	0.12447012	VL
Fe	18	10.38333333	4.92917485	H

a. T = toxic (Fe under poorly drained conditions), VL = very low, L = low, M = moderate, H = high.

Table A3-6. Correlation coefficients of analytical data in Table A3-4 (prob > |R| under HO:RHO = 0; N = 18).

pH H_2O

pH H_2O	pH KCl	Al	CEC	% Al S	P	OM	Mn	B	P	Na	Fe	Cu	K	Mg	Zn	Ca
1.00000	0.73441	-0.61056	-0.59766	-0.59483	-0.43644	-0.36588	-0.31588	-0.16494	-0.25400	-0.23250	-0.14361	0.09857	-0.06301	0.03080	0.00333	0.00000
0.0000	0.0005	0.0071	0.0088	0.0092	0.0702	0.1354	0.2016	0.5131	0.3091	0.3532	0.5697	0.6972	0.8038	0.9034	0.9895	1.0000

pH KCl

pH KCl	CEC	Al	pH H_2O	% Al S	B	OM	Mn	Ca	K	Mg	Zn	Na	Cu	Fe
1.00000	-0.85430	-0.83671	0.73441	-0.64434	-0.34705	-0.31349	-0.25670	0.13051	0.10827	0.10585	-0.04002	0.03665	0.03207	-0.02050
0.0000	0.0001	0.0001	0.0005	0.0039	0.1582	0.2052	0.3038	0.6057	0.6689	0.6759	0.8747	0.8852	0.8995	0.9357

OM

OM	Mn	Al	CEC	% Al S	K	Cu	pH H_2O	Ca	Zn	pH KCl	Na	B	Mg	P	Fe
1.00000	0.59854	0.59186	0.56656	0.51369	0.43904	0.40343	-0.36588	-0.31435	0.31358	-0.31349	-0.20104	-0.18753	-0.14685	-0.10246	-0.07503
0.0000	0.0087	0.0097	0.0142	0.0292	0.0683	0.0969	0.1354	0.2039	0.2051	0.2052	0.4238	0.4562	0.5609	0.6858	0.7673

P

P	pH H_2O	Cu	Na	pH KCl	Mg	Fe	B	OM	Ca	Mn	CEC	Zn	% Al S	Al	K
1.00000	-0.43644	-0.42070	-0.30568	-0.25400	-0.24254	0.20806	-0.11919	-0.10246	0.08544	-0.08120	-0.06486	-0.05764	-0.05042	-0.04411	-0.02481
0.0000	0.0702	0.0821	0.2174	0.3091	0.3322	0.4074	0.6376	0.6858	0.7361	0.7487	0.7982	0.8203	0.8425	0.8620	0.9222

Al

Al	CEC	pH KCl	% Al S	pH H_2O	OM	Mn	K	Cu	Ca	B	Mg	Zn	P	Na	Fe
1.00000	0.99537	-0.83671	0.76661	-0.61056	0.59186	0.43309	0.27011	0.21864	-0.18370	0.12822	0.09360	0.05561	-0.04411	0.03519	0.03318
0.0000	0.0001	0.0001	0.0002	0.0071	0.0097	0.0726	0.2784	0.3834	0.4656	0.6121	0.7118	0.8265	0.8620	0.8898	0.8960

Ca

Ca	B	% AL S	OM	Cu	Fe	Al	CEC	pH H_2O	Zn	Na	P	Mg	Mn	K	pH KCl
1.00000	0.72649	-0.64615	-0.31435	-0.29194	0.19530	-0.18370	-0.13384	0.13051	0.12758	-0.10762	0.08544	0.06216	-0.03620	0.03179	0.00000
0.0000	0.0006	0.0038	0.2039	0.2398	0.4374	0.4656	0.5965	0.6057	0.6139	0.6708	0.7361	0.8064	0.8866	0.9003	1.0000

Mg

Mg	Cu	Mn	P	Zn	OM	K	pH H_2O	Al	CEC	Na	Ca	% AL S	B	pH KCl	Fe
1.00000	0.50349	0.35536	-0.24254	-0.23510	-0.14685	0.12033	0.10585	0.09360	0.09266	-0.06925	0.06216	0.06114	0.05993	0.03080	0.01097
0.0000	0.0332	0.1479	0.3322	0.3477	0.5609	0.6344	0.6759	0.7118	0.7146	0.7848	0.8064	0.8095	0.8133	0.9034	0.9655

K

K	OM	Cu	Mn	CEC	Fe	Al	Zn	Mg	pH H_2O	Na	pH KCl	Ca	P	% Al S	B
1.00000	0.43904	0.41073	0.32734	0.28448	-0.28007	0.27011	0.21771	0.12033	0.10627	-0.08333	-0.06301	0.03179	-0.02481	-0.01954	-0.00901
0.0000	0.0683	0.0904	0.1848	0.2526	0.2603	0.2784	0.3855	0.6344	0.6689	0.7424	0.8038	0.9003	0.9222	0.9386	0.9717

Na

Na	B	P	Zn	Fe	pH KCl	OM	% Al S	Cu	CEC	Ca	K	Mn	Mg	pH H_2O	Al
1.00000	0.37377	-0.30568	-0.29261	0.25986	-0.23250	-0.20104	0.13867	-0.13345	0.10908	-0.10762	-0.08333	0.07412	-0.06925	0.03665	0.03519
0.0000	0.1265	0.2174	0.2387	0.2977	0.3532	0.4238	0.5832	0.5976	0.6666	0.6708	0.7424	0.7701	0.7848	0.8852	0.8898

CEC

CEC	Al	pH KCl	% Al S	pH H_2O	OM	Mn	K	B	Cu	Ca	Na	Mg	P	Zn	Fe
1.00000	0.99537	-0.85430	0.73930	-0.59766	0.56656	0.44391	0.28448	0.20043	0.19985	-0.13384	0.10908	0.09265	-0.06486	0.04241	0.01672
0.0000	0.0001	0.0001	0.0005	0.0088	0.0142	0.0650	0.2526	0.4252	0.4266	0.5965	0.6666	0.7146	0.7982	0.8673	0.9475

% Al S

% Al S	Al	CEC	Ca	pH KCl	pH H_2O	OM	Cu	Mn	B	Na	Fe	Mg	P	Zn	K
1.00000	0.76661	0.73930	-0.64615	-0.64434	-0.59483	0.51369	0.25299	0.22891	-0.19834	0.13867	0.07379	0.06114	-0.05042	0.03633	-0.01954
0.0000	0.0002	0.0005	0.0038	0.0039	0.0092	0.0292	0.3111	0.3609	0.4301	0.5832	0.7711	0.8095	0.8425	0.8862	0.9386

B

B	Ca	Na	pH KCl	Cu	CEC	% Al S	OM	pH H_2O	Mn	Al	P	Zn	Mg	Fe	K
1.00000	0.72649	0.37377	-0.34705	-0.24500	0.20043	-0.19834	-0.18753	-0.16494	0.16442	0.12822	-0.11919	0.08873	0.05993	-0.03818	-0.00901
0.0000	0.0006	0.1265	0.1582	0.3271	0.4252	0.4301	0.4562	0.5131	0.5143	0.6121	0.6376	0.7263	0.8133	0.8804	0.9717

Zn

Zn	OM	Na	Mg	K	Mn	Ca	B	Fe	Cu	P	Al	CEC	pH H_2O	% Al S	pH KCl
1.00000	0.31358	-0.29261	-0.23510	0.21771	-0.16221	0.12758	0.08873	0.07994	0.06088	-0.05764	0.05561	0.04241	-0.04002	0.03633	0.00333
0.0000	0.2051	0.2387	0.3477	0.3855	0.4693	0.6139	0.7263	0.7525	0.8103	0.8203	0.8265	0.8673	0.8747	0.8862	0.9895

Mn

Mn	OM	CEC	Al	Mg	K	pH H_2O	Cu	Fe	pH KCl	% Al S	Zn	B	P	Na	Ca
1.00000	0.59854	0.44391	0.43309	0.35536	0.32734	-0.31588	0.28936	-0.26121	-0.25670	0.22891	-0.18221	0.16448	-0.08120	0.07412	-0.03620
0.0000	0.0087	0.0650	0.0726	0.1479	0.1848	0.2016	0.2442	0.2951	0.3038	0.3609	0.4693	0.5143	0.7487	0.7701	0.8856

Cu

Cu	Mg	P	K	OM	Fe	Ca	Mn	% Al S	B	Al	CEC	Na	pH KCl	Zn	pH H_2O
1.00000	0.50349	-0.42070	0.41073	0.40343	-0.37203	-0.29194	0.28936	0.25299	-0.24500	0.21864	0.19985	-0.13345	0.09857	0.06088	0.03207
0.0000	0.0332	0.0821	0.0904	0.0969	0.1284	0.2398	0.2442	0.3111	0.3271	0.3834	0.4266	0.5976	0.6972	0.8103	0.8995

Fe

Fe	Cu	K	Mn	Na	P	Ca	pH KCl	Zn	OM	% Al S	B	Al	pH H_2O	CEC	Mg
1.00000	-0.37203	-0.28067	-0.26121	-0.25986	0.20806	0.19530	-0.14361	0.07994	-0.07503	0.07379	-0.03818	0.03318	-0.02050	0.01672	0.01097
0.0000	0.1284	0.2603	0.2951	0.2977	0.4074	0.4374	0.5697	0.7525	0.7673	0.7711	0.8804	0.8960	0.9357	0.9475	0.9655

Appendix 4. COMPARATIVE TISSUE ANALYSIS FOR ACCELERATING FIELD TRIALS

The philosophy of this approach is to start field trials as soon as possible and to maximize information that can be obtained through careful monitoring using *comparative* tissue analysis.

Selection of Treatments for Field Trials

If sufficient soil analytical information from soil surveys is lacking, the technique described in Appendix 3 can fill a void in helping to determine nutrient factors that should be examined in a field trial. This approach advocates a breakaway from normal dogma concerning the collection of soil samples for fertility analysis, which usually recommends the making of an artificial composite sample from 12 to 20 subsamples in the field. Such a technique is useful for monitoring fertility characteristics of individual plots in a field trial, but is not so useful for obtaining a preliminary judgment to select treatments.

Once the treatments are chosen, field trials should be kept as simple as possible; replicated plot designs are often adequate. However, the size and number of plots are important considerations. Plots should be large enough to facilitate "splitting" of treatments. Additionally, nontreated plots should be laid down alongside the trial for further work, wherever possible.

Monitoring

Once the treatments and design of a trial are chosen, a program for monitoring the trial through soil and, especially, tissue analysis on a plot by plot basis is essential. Composite samples for both soils and tissue samples should be used to fairly represent the plot by plot treatments. Tissue analysis should be as complete as possible. Most laboratories, even in lesser developed countries, have a capacity or could easily extend their capacity to do this work. Consequently, the fertility specialist has a reading on all elements necessary for plant nutrition.

Treating Tissue Analytical Data as Yield Data

By taking plot by plot composite tissue samples, Cochrane (1979a) has shown that the need for a prior knowledge concerning tissue analytical figures is obviated. He illustrated that the analytical data for the samples can be treated and analyzed statistically in the same way as yield data, to determine any significant differences. This is a considerable break from existing practices, which center around the time-consuming and costly procedures previously advocated for establishing "critical" levels for tissue analytical data. Obviously, the use of tissue analyses will be enhanced if previous work is available to obtain an idea as to possible deficiency levels.

Cochrane has emphasized that in order to take meaningful tissue samples, the trial must be monitored for *meteorological conditions*, especially moisture stress. Tissue samples are thus best collected after a suitable period of nonclimatic-induced conditions.

In the case of the plot by plot composite soil samples, these should be taken to reflect changes in soil brought about by fertilizer treatments. It is not sufficient to take "before" and "after" samples; they should be taken to fairly monitor the effect of fertilizer on soil conditions such as pH and, ideally, the transport of nutrients down the soil profile. Certainly both "topsoil" (perhaps 0–20 cm) and subsoil (21–50 cm) samples should be taken.

Implementing the Results of Monitoring

Once the trial has been laid down and monitoring has started, any results of the monitoring that suggest the need for further in-field trial treatments should be implemented as soon as possible. Comparative tissue monitoring ensures that appropriate action can be taken timely enough to investigate problems not obvious from the original soil analytical data. For example, Table A4-1, adapted from one of Cochrane's trial results, shows how the Mn concentrations in the leaves of sugarcane altered with increasing applications of $(NH_4)_2SO_4$. This was detected soon after the trial started and led to the speedy laying down of a supplementary trial to confirm that Mn was indeed deficient. In another trial reported in the same paper (Cochrane, 1979a), the levels of Zn looked suspiciously low; again, speedy action by splitting the trial for Zn led to the finding that Zn was, in fact, deficient. The net result of this work was that fertility problems were identified and fertilizer practices formulated with a minimum of delay.

Summary

Appendix 3 describes ways and means for enhancing the soil fertility information in soil surveys with relatively little effort. Appendix 4 was prepared to emphasize that there are proven innovations for speeding the process of making field-tested, farm fertilizer recommendations. The use of tissue analyses to complement fertilizer trials on a plot by plot basis is independent of a prior knowledge of nutrient content and would have wide applicability.

Table A4-1. Effect of increasing rates of NH_4SO_4 on yield of cane and sugar and concentration of mineral constituents of the leaf on a dry matter basis.

N rate (kg/ha)	Wt. of cane per plot (kg)	Wt. of sugar per plot (kg)	Mineral concentrations in leaf N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Mn (%)
0	393	30	1.14	0.16	1.00	0.18	0.10	0.10	23.8
22	453	34	1.17	0.[illegible]	0.97	0.20	0.09	0.11	26.3
44	506	38	1.26	0.16	1.14	0.20	0.12	0.12	26.3
66	532	40	1.13	0.13	1.00	0.20	0.11	0.13	28.3
88	611	49	1.38	0.14	1.01	0.19	0.12	0.13	36.3
110	701	50	1.39	0.16	1.15	0.16	0.12	0.11	41.3
LSD (P = 0.05)	36	4.14	0.11	-	-	-	-	-	6.8

SOURCE: Cochrane (1979a).

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