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 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 agro ecological 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 agro technology specific to, or advantagenous 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 l979 the survey was broadened to include the forested regions and to serve as 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, Peru, 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,LOO scale, is printed and enclosed in Volume 2 of this study, *The Land Systems Map and Its Legend.* The map is described and explained in Chapter 2.

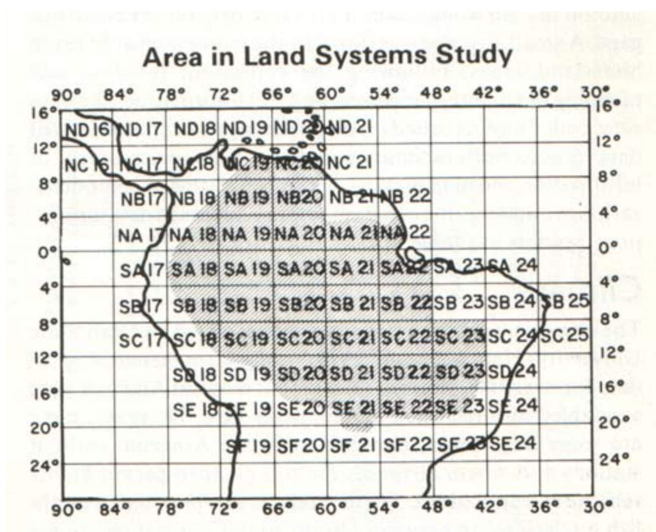

Fig. 1 Geographical extent of CIAT's land resource survey, later detailed on the Land Systems Map (Vol. 2). The letter-number codes refer to sheets of the International Chart of the World at the Millionth Scale.

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 I 000 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 database 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 too precipitation occurrence (DEP PREC) to determine the amount of rainfall that will be equaled 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 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 (1068) 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- X 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 capacitv (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

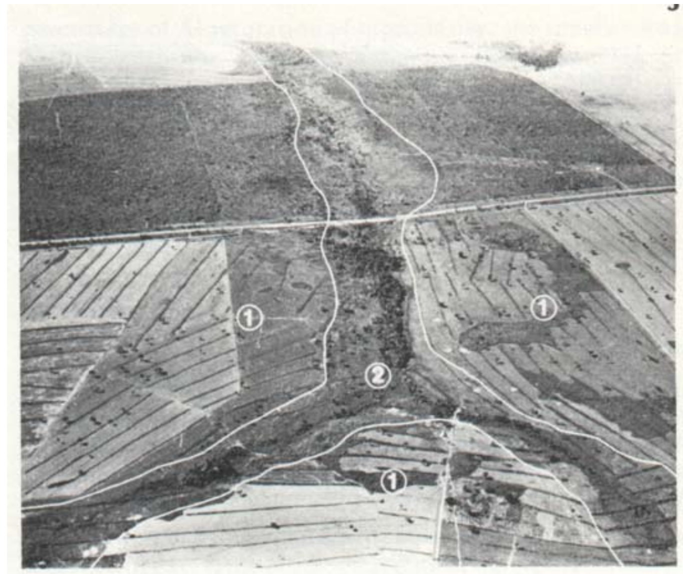

Fig. 2 Land system No. 46, subdivided into land facets 1 and 2.

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 database 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 I and 2 of Volume 3 in this study, *Computer Summary and Soil Profile*

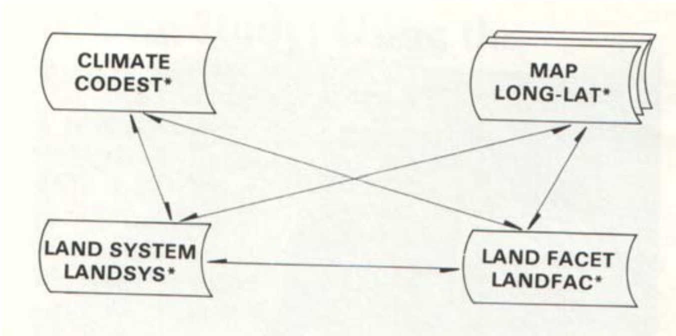

Fig. 3 Schematic of computer files on the data base concept used for the Land Systems Map. Asterisks indicate actual name used for the four cross-referenced files. Information maybe combined from two or more files as shown by the interconnecting lines.

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 I 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

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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
  CD                        80
  TRF
  SESF
  SDSF
  CAAT
  OTHER

INDUCED VEGETATION (%)

  PASTURE                40   10
  CROPS                   5
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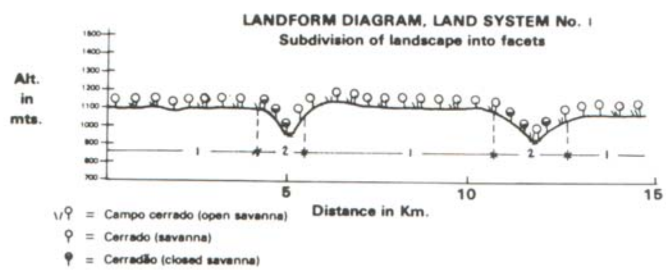


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                              FACETS
                            1    2    3
SOIL CLASSIFICATION
  ORDERS                  O      O
  SUBORDERS               OUS    OUS
  GREAT GROUPS            OUSAC  OUSAC
SOIL PHYSICAL PROPERTIES
  SLOPE                     B    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            SD   SD
  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 B  M B
  EXCHANGEABLE K           K K  K K
  EXCHANGEABLE NA          B B  B B
  TOTAL EXCH. BASES        B B  B B
  CATION EXCH. CAPAC.      E E  E E
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                                    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 PEREN-NIAL STREAMS, and DEPTH OF WELLS. These descriptors are explained in the glossary to Part I of the *Computer Summary.* The two dimensional landform diagrams in Figure 4 were 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: GEN-ERAL DESCRIPTION, PERCENTAGE OF L.S. (land system), TOPOGRAPHIC CLASS, ALTITUDE, ORI-GINAL VEGETATION CLASS %, INDUCED VEGE-TATION %, SOIL CLASSIFICATION, SOIL PHY-SICAL PROPERTIES, SOIL CHEMICAL PROPERTIES, ELEMENTS OF IMPORTANCE MAINLY TO ANIMAL NUTRITION, and FERTILITY CAPABILITY CLASS-IFICATION. These headings continue the descriptive data of the land system printouts of the study (Part I 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- X 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- X 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

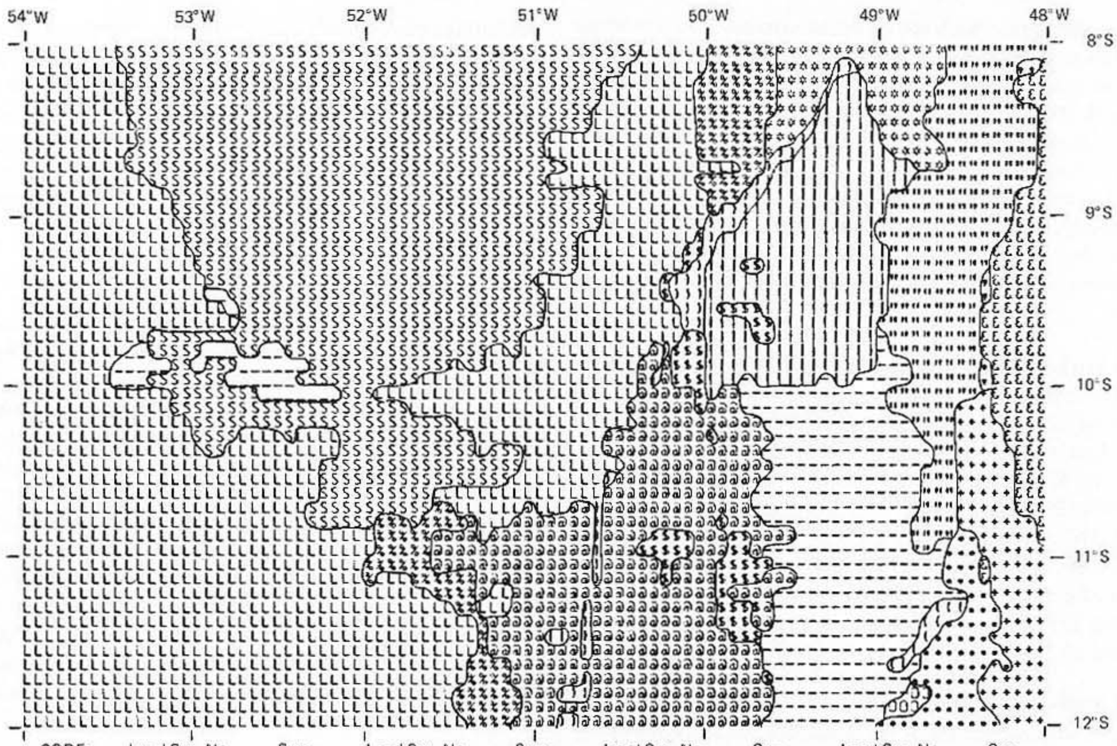
The computerized data base descriptors for the study are described in the glossary to coding in Part 1 of the *Computer Summary and Soil Profile Descriptions.* This section also details the criteria used to synthesize and code the data input and explains how agronomists without access to computers might 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 printouts 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.

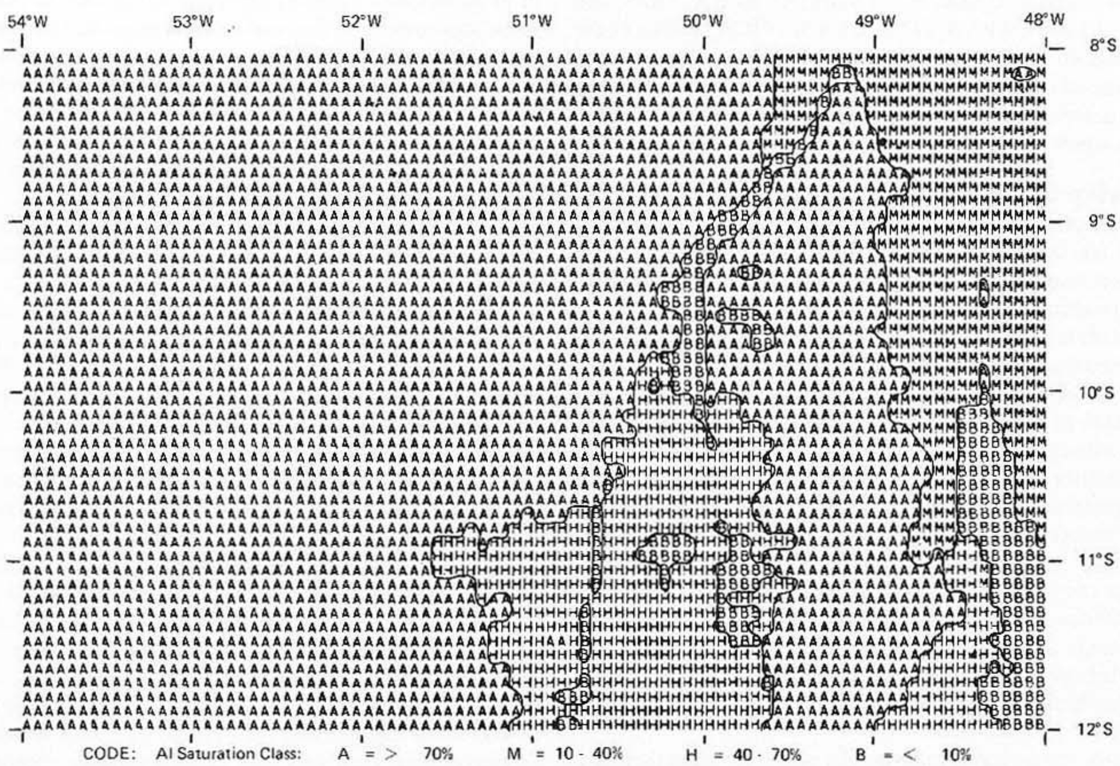
The criteria used to describe the data summarized in the *Computer Summary* are explained more fully in the text. Additionally, use is made of the thematic and single-factor map-making capabilities of the map file to help illustrate overall constraints and advantages to developing germ-plasm based agrotechnology 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 database summaries and other pertinent information as appendices. Part I 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.



CODE: Land Sys. No.	Sym.	Land Sys. No.	Sym.	Land Sys. No.	Sym.	Land Sys. No.	Sym.
17	+	23	@	27	"	35	)
19	-	24	I	28	%	38	L
20	.	25	$	29	£	40	S
21	0	26	*	34	(	111	—
						112	,

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



CODE: Al Saturation Class: A = > 70% M = 10 - 40% H = 40 - 70% B = < 10%

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

Part 3 records a range of typical soil profiles to provide a better guide of soil characteristics. Guidelines for agronomists who wish to use the database 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.

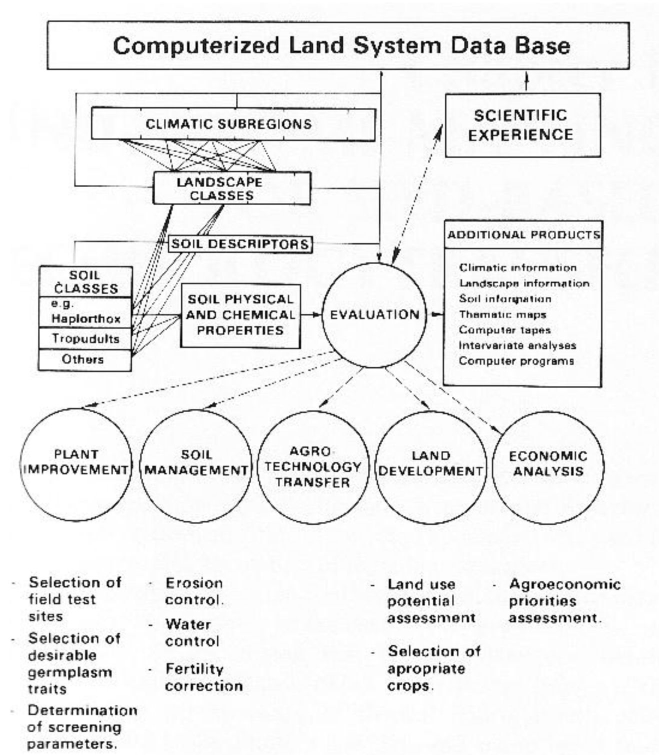


Fig. 7 Flow chart of relationship of land-system mapping with agrotechnological development. Solid lines indicate computer pathways for using the land resource study; dashed lines indicate contributions of the study to spheres of agrotechnological development.