The World Soils and Terrain Digital Database Applied to Amazonian Land Studies.

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ABSTRACT

A well-defined methodology for land resource appraisal in the underdeveloped tropics is essential for scientists, educators and administrators. The main objectives of this report are to summarize the way the World Soils and Terrain Digital Database (SOTER) file system was applied as a component of a Land Resource Geographic Information System (LR-GIS) developed for the Amazon and the central savannas of Brazil, and to highlight its application. The architecture of the LR-GIS system developed uses any combination of commercially available relational database software with GIS software. The SOTER file system formed the basis of its attribute database. The files for the LS-GIS were setup as a Personal Computer Users' Packet. The approach was applied in several studies over large extensions of Amazonia and the savannas of central Brazil. The first was a test study of the Geo-economic Region of Brasilia, which resulted in an improved knowledge base for the application of fertilizers and lime. This was followed by land resource studies of Bolivia's Amazon. These provided a database for the sustained development of that rich Brazil-nut tree region. Finally, a land resource study of the Brazilian Amazonian State of Rondônia, achieved the objective of evaluating that region's land potential as a basis for an orderly development of sustainable agricultural, pastoral, forestry and conservation activities. In conclusion, the digital LS-GIS methodology incorporating the SOTER file system is a well-proven, innovative approach for carrying out land resource studies in diverse regions, which should be of interest to decision makers, scientists and educators.

ABBREVIATIONS

CIAT – International Center for Tropical Agriculture

CSIC – Institute of Natural Resources and Agro-biology

EMBRAPA-CPAC – Empresa Brasileira de Pesquisa Agropecuária, Centro de Pesquisa Agropecuária dos Cerrados (Brazilian Savanna Agricultural and Animal Research Center)

FAO – Food and Agricultural Organization of the United Nations

GIS – Geographic Information System

ISRIC – International Soil Reference and Information Center

ISSS – International Soil Science Society

LR-GIS – Land Resource Geographic Information System

PC – Personal Computer

RDBMS – Relational Database Management Software

SAS – Statistical Analysis System

SDBm – multilingual Soil (profile) database software program of FAO-ISRIC-CSIC

SOTER – World Soils and Terrain Digital Database Project

UNEP – United Nations Environmental Program

INTRODUCTION

Over the past 25 years the compilation of digital databases has resulted in significant advances in understanding the nature of the land resources of the Amazon and its adjacent savanna lands. The first computerized study that covered this region was co-sponsored by the International Center for Tropical Agriculture (CIAT) and the Brazilian Savanna Agricultural and Animal Research Center (EMBRAPA-CPAC) in 1977. It was a low profile, low-cost study that was completed by late 1980 (Cochrane, 1980; Cochrane et al., 1981), and subsequently published in book-form in 1985 (Cochrane et al., 1985). This study illustrated the feasibility and benefits of compiling digital databases of the land resources of extensive tracts of land. It was essentially a computerized adaptation of the "land systems" methodology developed by Christian and Stewart for their study of the Katherine-Darwin region of the Northern Territory of Australia (1953). The then recently available 1:1,000,000 satellite imagery and side-looking imagery of the region facilitated the identification and delineation of the land systems. A land system was re-defined as "an area or group of areas throughout which there is a recurring pattern of climate, landscape and soils". The study permitted an unprecedented degree of analysis of the landscape, soils, climate, vegetation and land-use of the region and their inter-relationships. An example was the finding that the physiognomic vegetation classes of the well-drained soils of the region follow wet-season energy regimes (Cochrane and Jones, 1981).

The computerized land systems approach was subsequently adopted by the World Soils and Terrain Digital Database Project (acronym SOTER, an abbreviation of soil and terrain), which started as an International Soil Science Society (ISSS) initiative in the mid 1980s (Sombroek, 1984; Baumgardner and Oldeman eds., 1986), and is currently supported by the United Nations Environmental Program (UNEP), ISSS, International Soil Reference and Information Centre (ISRIC), and the Food and Agricultural Organization (FAO) of the United Nations (van Engelen and Wen eds., 1995). It was evident to ISSS members that computerization would play an increasingly important role in carrying out land resource studies. Further, it was seen as a means of minimizing the confusion associated with the many different taxonomic systems used to classify soils. Soil taxonomic systems vary from country and even within countries, and have often led to misunderstandings concerning the nature of soils by scientists accustomed to using a given soils classification system. In brief, the SOTER project was developed with the principal objective of creating a digital database file system of terrain and soil properties to be described according to internationally accepted definitions (Shields and Coote eds., 1988). By so doing, landscape and soil characteristics described in any one region of the world could be compared with those in other regions.

In the past, the role of soil mapping based on taxonomic classification was largely limited to indicating the geographical location of a general type of soil or complex of soils found in a given region. Soils were classified into pre-determined taxonomic classification systems, which were usually hierarchal groups according to a pre-chosen and limited number of parameters that provided an idea of their general properties. The soils of these groups were then identified with names derived from the classical languages. In contrast, the use of the SOTER digital database focuses on the description of the characteristics or “attributes” of terrain and soils according to their properties to provide a fundamental component of a LR-GIS. It should be noted that SOTER is not an alternative soil or land use classification methodology. It is a methodology for the systematic compilation of terrain and soil databases for multiple purposes. Soil and land use classifications may be derived from and, or compared using the SOTER database.

It was also foreseen that the compilation of SOTER digital databases would not only facilitate understanding between different taxonomic and land use systems but also help bridge the gap between creating a classical soils map and the problems facing scientists of developing improved soil management technologies for crop production and land resource management generally, in a given region. The database would enable an in-depth analysis of soil and land properties. The SOTER approach, when combined with adequate sampling techniques during fieldwork and supported with detailed laboratory soil analysis, can also be used to guide the more effective design of field experiments, especially fertilizer and soil amendment experiments. Subsequently, the database can be used for the application and extrapolation of results of these experiments to develop better recommendations for crop production, and the more effective application of expert systems.

The SOTER project through the efforts of the UNEP, ISSS, ISRIC, and FAO has evolved into a worldwide initiative applicable to all land conditions. It was seen that the methodology is particularly useful as a basic component in compiling LR-GISs of extensive areas of the relatively unexplored tropical forests and savannas of the Amazon and central Brazil.

OBJECTIVES

The objective of this article is to provide a brief summary of the incorporation of the SOTER methodology as a component of a LR-GIS followed by an overview of the application of the latter in carrying out computerized land resource studies in the Amazon and the savannas of central Brazil. It is considered that the way this is carried out is of educational value. Some of the findings of those studies are highlighted. The article refers specifically to the following studies, carried out as opportunities arose, during the past decade:

1. A SOTER pilot project of the savannas of central Brazil at the 1:500,000 scale, which was supported by EMBRAPA-CPAC (Cochrane and Macedo, 1990).
2. Land resource studies of Bolivia's Amazon region at the 1:250,000 scale (Cochrane et al., 1992; Cochrane et al., 1993).
3. The land resource study of the Brazilian state of Rondônia in western Amazonia at the 1:250,000 scale (Cochrane and Cochrane, 1998).

A brief description of the application of the SOTER methodology as an integral part of the overall land resource GIS has been made with reference to the Rondônian study, as the SOTER file system was under development during the course of the previous studies. It should be noted that subsequent to carrying out the above studies, the SOTER project has developed specific "SOTER" software, currently available from ISRIC. However the use of the latter software is not necessary for the application of the SOTER file system in LR-GIS.

The purpose of integrating the SOTER file system into a comprehensive LR-GIS was to help the latter meet the following norms (Cochrane and Cochrane, 1998):

a) Adopt the use of standardized, internationally accepted descriptors for landscape, soils, climate, natural vegetation and land use.
b) Use a file system that organizes landscape, soil, climate, natural vegetation and land use attributes in a logical sequence.
c) Use a scale independent attribute file database.

In addition, it is noted that a land resource GIS should:
d) Use commercially available relational database management software (RDBMS) for the compilation and analysis of the attribute database in combination with commercially available GIS software that permits the linkage of the RDBMS with the GIS software. In this way the RDBMS facilitates both independent analysis and analysis integrated with the GIS software, including the production of thematic maps.

e) Be designed as a low-cost, user-friendly PC Users' Packet (Packet) that can be used by farmers, foresters and professionals working in diverse disciplines on their own computers. In this way not only land resource information is made available, but also an analytical tool is provided to facilitate the improved understanding and management of land. The Packet can be made available via the Internet.

MATERIALS AND METHODS

Background

In 1977 the senior author used Christian and Stewart's (1953) "land systems" approach to carry out a study of the land resources of Tropical America, which included the Amazon and adjacent savanna lands, Figure 1. The methodology was adapted to computerization by designing a rudimentary land resource Geographic Information System, LR-GIS (Cochrane et al., 1981). Essentially a land resource digital database was designed to record the many terrain, soil, vegetation, meteorological and land-use features for the mapped land system units. Information from the database, which was compiled using the Relational Database Concept of SAS (Barr et al., 1976), was linked to raster-based maps of the land systems. The latter were designed using FORTRAN programming language with 4 x 5 minute rectangular "pixels". Digital mapping software was not available at that time. Figure 1, which illustrates the physiognomic vegetation classes over the Amazon basin and surrounding savanna regions, is in fact a thematic map derived from a recent re-digitization and compilation of the original 40 1:1,000,000 scale land system maps of the study. The delineation of the land systems was facilitated using the then recently available 1:1,000,000 satellite imagery (black and white photographic prints of spectral bands 5 and 7), together with the side-looking radar imagery that covered most of the Brazilian Amazonia (1973). Fieldwork was carried out to record the characteristics of the land systems on computer input formats and check their boundaries (Cochrane et al., 1981). A Piper "Super Cub" short take off and landing aircraft was piloted by the senior author over representative transects of the Amazon during the course of the studies to cover this vast region.

Although by modern GIS program standards the work was rudimentary, it in fact incorporated the two basic components of modern GIS; a database and a mapping program. (The maps have since been prepared for use in ArcView (ESRI, 1998), and IDRISI (Eastman, 1993); the attribute database has been re-digitized for use in MS ACCESS.) The work was presented during the ISSS conference held at Massey University New Zealand in 1981, and acted as a catalyst for the eventual creation of the SOTER project.

<u>The World Soils and Terrain Digital Database, SOTER.</u>

At the outset of the development of the SOTER project, the ISSS recognized the importance of describing landscape characteristics in a universally acceptable manner and arrange such in a logical database. Underlying the SOTER philosophy was the identification of areas of land "with distinctive, often repetitive patterns of land form, lithology, surface form, slope parent material and soil" (van Engelen and Wen eds., 1995). These landscape units were termed SOTER (soil and terrain) Units. The approach is a refinement of the land systems methodology developed by Christian and Stewart (1953), which, as already mentioned, was adopted as a basis for the computerization of the land resources of tropical America by Cochrane et al. (1981).

SOTER units can be subdivided according to varying terrain characteristics into so-called "Terrain Components" if the mapping scale permits subdivision, which in turn may be subdivided into one or more "Soil Components". This procedure is essentially the same as used by Cochrane et al. (1981), who subdivided land systems into "land facets" and the later into "soil units". The SOTER attribute database was designed to be scale-independent and so facilitate linkage with GIS map files at any mapping scale. Details of the definition and delineation of SOTER units and their subdivisions are explained in the manual prepared by ISRIC (van Engelen and Wen eds., 1995).

<u>The SOTER database file system.</u>

The many attributes of the SOTER Units as defined by the ISSS working groups (van Engelen and Wen eds., 1995), were arranged in files that follow a logical hierarchical pattern for describing landscape. These have been summarized in Figure 2 that illustrates the architecture of the land resource GIS designed for the State of Rondônia, Brazil (Cochrane and Cochrane, 1998). On the lower right-hand quadrant of Figure 2 the TERRAIN file attributes describe the over-all characteristics of the SOTER Units. In turn, the TERRCOMP (Terrain Component) file and its complementary TCDATA (Terrain Component data) file describe the properties of the various terrain components of the SOTER Unit. Sequentially, the SOILCOMP (Soil Component) files describe the soils found within the Terrain Components. In addition to the foregoing files, the SOTER database has files for Climate, Vegetation and Land-Use, with attributes also described according to internationally agreed-upon parameters. The file system is open to facilitate linkage with other files that may be associated with the SOTER Units.

It is important to emphasize that the database system for describing soils and terrain was designed to be independent of the mapping scales of land resource surveys. The database files have been designed to support land resource mapping at any scale from large-scale generalized mapping to smaller scale, more detailed soil mapping. It was observed in practice, that for complex land situations only SOTER terrain units can be mapped at scales larger than 1:500,000; with smaller scales both terrain and soil components may be mapped and related to the database.

The architecture of the land resource GIS.

Up until the mid-nineties, the SOTER project was limited to the development of the file system for describing landscape characteristics and establishing internationally accepted definitions of those attributes. Consequently, in order that the SOTER attribute file set could be used for recording and analyzing land properties, it was necessary to develop a functional, integrated computerized GIS to systematize the overall land resource studies. This meant that the SOTER file set would have to be programmed into a suitable database management program. It could be used in a limited way in GIS software that incorporate databases, or alternatively used in a separate database program and linked to a GIS program. Integration either in or with, a GIS program was necessary for thematic map production.

In the case of the studies carried out to date by the authors, it was decided to choose separate database and GIS programs, and link these together by adding some additional identification fields to the SOTER file set. Clearly, the use of a separate database program would provide more flexibility in the system, and facilitate the integration of other databases. Commercially available Relational Data Base Management System (RDBMS) programs were chosen for the manipulation of the SOTER file set and likewise commercially available GIS software for map making and satellite image interpretation. Providing that the database and map files are prepared using popular formats, these can be imported into and used with different combinations of database and GIS software programs.

The Relational Database Management System (RDBMS) and GIS

The files of the land resource database describing the properties or attributes of the natural resources were managed using the RDBMS programs MS ACCESS, PARADOX, and dBASE for PCs. Files produced in these programs are readily linked with files produced in low cost GIS programs including IDRISI, and, or ArcView. IDRISI is a complete but very low-cost GIS program that is easy to use and facilitates the export and import of cartographic files in a wide range of formats. The inter-connection of data files of these programs is carried out either by writing simple ASCII files, or importing files directly as MS ACCESS or dBASE files, depending on the GIS used. In this way, the work developed database and map files that could be used in different combinations of RDBMS and GIS software, according to users preferences. Further, the approach ensured that the files produced would be compatible with new developments in such software.

An open system not limited by scale

The methodology used for the study is scale-independent and facilitates the integration of different databases. It is emphasized that the system is open not only in the sense of facilitating the integration of new files from diverse sources but also in the sense of being compatible for use with different combinations of RDBMS and GIS software programs. What is important is the architecture of the system (how the many files integrate one with another), and not the tools chosen for its implementation. Figure 2 as previously noted, summarizes the architecture of the system developed for the Rondônian study and illustrates the integration of the GIS programs with RDBMS software.

Figure 2 also shows an additional program incorporated as a part of the over-all system, namely the FAO-ISRIC-CSIC Multilingual Soil (profile) Database SDBm, software (FAO-ISRIC-CSIC, 1995). This is public domain software available from FAO for the digitization of soil profile descriptions, which enables the automatic printing of soil profile descriptions in three languages and some analysis. It is a very useful program that enhances the capacity of the over-all system. In the case of the Rondônian studies the files of the latter program were linked to the SOTER files via the creation of two additional files shown on Figure 2, the PROF_GR (profile group) and PROF_LST (profile list) files. In incorporating the SDBm software, care was taken to avoid duplication of attributes common to both the SOTER files and the SDBm files (Cochrane and Cochrane, 1998).

The hardware requirements need to run the system.

In keeping with the philosophy of using PC compatible software, it was axiomatic that the hardware needed to implement the LR-GIS system developed was minimal. It can be run on virtually any Personal Computer PC. In fact the hardware used for the test studies over the Geo-economic Region of Brazil (Cochrane and Macedo., 1990), consisted of a 33mhz, 486DX PC with a 140MB hard disk. Digitization of the maps was carried out using a low cost 12 x 12 inch SummaGraphics digitizing tablet. Clearly the cost of PCs has dropped substantially since the late 1980s, while their speeds and capacities have increased virtually exponentially. It is evident that the sky is the limit for optional equipment such as plotters, printers and so on.

<u>The PC Users' Packet.</u>

The objective of producing a "PC Users' (land resource database) Packet" was to ensure that the digitized land resource information would be made available to interested professionals working in diverse disciplines. By obtaining and learning how to use two low-cost, very user-friendly programs, workers can access the land resource information, and analyze it according to their many needs.

In the case of the recent Rondônian studies (Cochrane and Cochrane, 1998), the PC Users' Packet was designed to contain:

a) The SOTER files of the study adapted for use in MS ACCESS and PARADOX-DBASE (or for that matter any other RDBMS that can accept these files), including a "blank" set of these files for the convenience of the user.

b) Map files of the delineated SOTER units of the study prepared for use in IDRISI in both vector and raster formats (the latter prepared with different sized "pixels" generally ranging from 1ha to 100ha pixels), and as ARCVIEW shape files. Further, a series of thematic map files was produced according to the specification of the study. These files can be imported into and used with most other commercially available GIS software systems.

c) A copy of the FAO-ISRIC-CSIR (1995) Multilingual Soil (profile) database adapted for the tropical or other specific soils of the region, and containing a selection of representative soil profiles and their analytical data for the region of interest in both English and Portuguese.

d) A set of spreadsheet files prepared in both EXCEL and QUATTRO PRO containing the soil analytical data.
e) A digitized copy of the manual prepared for use with the major word processor programs, to describe the installation and operation of the system, together with details of the methodology, the files used, their fields and the definition and classification of attributes. The manual also contains prepared field input forms for recording the land, vegetation and soils data.
f) A hard copy of the manual to accompany the PC Users' Packet.

The procedure for carrying out the digitized land resource studies.

The procedure for carrying out the digitized land resource studies followed the same basic pattern:
1. Compilation of the PC Users' manual, detailing the attribute file system. Forms for inputting the attribute data were prepared as annexes to the manual.
2. The setting up of the PC Users' Packet. It was considered that the PC Users' Packet should be put in place right from the start of the studies, and used both as a type of "back-up" and means for monitoring progress. This also means that information on completed sectors of the study and their specific problems may be made available during the course of the studies.
3. Review of the literature on the land resources of the study region.
4. Examination of the satellite imagery of the region and preliminary demarcation of SOTER units. This work is preferably carried out using a GIS with the capacity for examining and integrating imagery recorded electronically. In the case of the Rondônian and Bolivian Amazon studies the SOTER units were drawn on 1:250,000 scale, Landsat Thematic Mapper satellite imagery, false color composites of bands 3, 4 and 5 following field-work and on 1: 500,000 scale black and white imagery in the case of the central Brazilian savanna pilot study.
5. Compilation of climate data. This activity proceeds parallel to the other initial activities.
6. Organization of the fieldwork program to determine definitive SOTER unit boundaries, to fill in the landscape attribute input forms for the field observations and to examine and sample soils for subsequent analysis. In-so-far-as it is possible, statistically significant numbers of soil profiles should be examined and sampled for the principal soils found in the study following the approach of Cochrane et al. (1985).

7. Field work alternating with office work.

8. Soil analysis in the laboratory of the samples collected during fieldwork. Analytical results should be inputted directly into the appropriate database files of the PC Users' Packet.

9. Digitization of the in-field observations of the landscape attributes. Procedures 7 to 9 usually run concurrently during the course of the studies, as digitization is mainly routine secretarial work.

10. Definitive digitization of the SOTER unit boundaries and digitization of any other required map features. The geographic map base, datum and scale will vary according to standards used in any one region or country.

11. Final revision of the PC Users' Packet.

12. Analysis and report preparation based on the information compiled in the PC Users' Packet.

The foregoing briefly summarizes the general procedure for carrying out the land resource studies, and indicates the complex of integrated skills needed for assessing land resource potential. It is observed that should land resource scientists (including soil, vegetation, land usage and land use monitoring specialists), wish to carry out additional computerized studies in the future, they can build on an existing PC Users' Packet as it can be used for any type of study at any level of precision or scale. They would not only have the convenience of a ready-made land resource GIS to avoid re-inventing the metaphorical wheel, but also have the advantage of using internationally defined criteria for describing the attributes of landscape, soils, climate, vegetation and land usage, the result of considerable time and expenditure on the part of the ISSS.

RESULTS AND DISCUSSION

Over the past decade, the foregoing PC Users' Packet LS-GIS approach incorporating the SOTER file system, has been used in several different studies over large extensions of both the tropical savanna lands of central Brazil and the Amazonian forests of Brazil and Bolivia. Some findings from the main studies, which were carried out as opportunities arose, follow:

The test study of the Geo-economic Region of Brasilia

In coordination with the SOTER program centered at ISRIC in Wageningen, Holland, a test study using the methodology in a preliminary format according to the provisional SOTER manual then available (Shields and Coote eds., 1988), was carried out over the Geo-economic Region of Brasilia (Figure 3). The latter is predominantly a mid-altitude tropical savanna area found on the Pre-Cambrian plateau formation of central Brazil, with the capital of Brazil as its epicenter. It covers a region about the size of the country of Uruguay. The work was based on a land systems survey of the region (Cochrane et al., 1987).

An interesting finding of the survey was that it provided statistical data to show that the basic reason for the existence of savannas on the soils throughout the region was the presence of an imbalance between Ca and Mg in those soils (Cochrane, 1989). The finding illustrates the usefulness of statistically adequate sampling of soils during the course of the field studies. Past practices of describing and sampling one or two profiles to represent a given soil, and classifying such on the basis of some pre-specified criteria, does not provide a sufficient basis for understanding the properties of soils. Clearly, the finding draws attention to the need for applying statistics to soil-vegetation relationships. It is the first time a statistically significant relationship has been established between a soil property and its natural vegetative cover, and should indicate the need for land resource scientists to acquire statistical skills.

One of the many practical benefits to farmers of the Geo-economic Region of Brasilia study was that it has provided a knowledge base for the improvement and application of fertilizers and lime for crop production. For example, it provided an improved base for the application of an expert system developed by the University of Hawaii for the application of lime to amend the predominantly acid soils found throughout this region (Yost et al., 1990). The Hawaii expert system for determining the need and amounts for lime application was based on ameliorating the effect of Al toxicity in acid mineral soils and used the equation developed by Cochrane et al. (1980) as its starting point. As a result of the land resource studies, it was necessary to modify the expert system, to make it applicable to the region. The finding that there was an imbalance between Ca and Mg in the savanna soils of central Brazil had to be taken into account in the expert system for making recommendations to farmers growing crops on soils with, or susceptible to, this problem.

The land resource studies of Bolivia's Amazon

A land resource study of a substantial area of western Amazonia, the Brazil nut region of northern Bolivia (Figure 3), was carried out in 1992 with World Bank financing (Cochrane et al., 1992), at the 1:250,000 scale. This was followed by a territorial Land Use Zoning study of a large part of that region, the Pando Department of Bolivia, which was financed by the Dutch Government (Cochrane et al., 1993). The work was carried out to provide a land resource database for the sustained development of the region. In the case of the Pando study, a Land Use Zoning map, Figure 4, was prepared to identify extractive reserves for non-timber forest products including Brazil nuts, national parks and other uses, to be put into effect by the local government. Figure 4 was only one of many thematic maps derived from the SOTER unit map of that region.

The land resource study of the Amazonian State of Rondônia, Brazil

The objective of the soils and terrain land resource survey of the Amazonian State of Rondônia, Brazil, Figure 3, was to make an evaluation of its land potential, and so provide a basis for the orderly development of the state through zoning of sustainable agricultural, pastoral, forestry, and conservation activities.

The SOTER studies showed that Rondônia has a complicated mosaic of land and soil conditions. Soils vary quite significantly from place to place in terms of both their physical and chemical conditions. Figure 5 is a soils map of the State of Rondônia, using the Brazilian soil classification system, that was one of the many thematic maps derived from the SOTER Unit map of the region. It illustrates the diversity of soil conditions seen throughout the State. Nevertheless, the overall picture of the soils seen throughout Rondônia is relatively encouraging when they are compared with the Pando soils of Bolivia and the majority of Amazonian soils. It was found that many of the soils in Rondônia have been derived from relatively mineral-rich parent materials. Unfortunately, the indiscriminant destruction of the native forests seen over much of the region cannot be condoned, as it has resulted in a considerable loss of biodiversity.

It should be mentioned with regard to the SOTER study of Rondônia that approximately 3000 soil profiles were described and sampled during the 18-month duration of the soil studies, by only four teams of two technicians per team. The work was speeded by the systematization the description of the soil profiles for subsequent digitization using the FAO-ISRIC-CSIC Multilingual Soil (profile) Database SDBm (1995), software program. The latter as mentioned earlier, was integrated with the SOTER file system. However, it was necessary to make up an additional database of the of the soil profile sample chemical analytical data, as the SDBm software had serious limitations for the recording of such data and their subsequent grouping and statistical analysis. The chemical analytical data files prepared in the laboratory were imported into electronic spreadsheet programs including EXCEL and QuatroPro for eventual statistical analysis. In this way, the study has provided the State of Rondônia with perhaps the best soil analysis database of any state or country in Latin America. The approach outlined in this article is of considerable economic benefit to farmers in terms of estimating fertilizer and amendment needs for their soils.

The land resource database of Rondônia was recorded as the PC Users' Packet titled "SIGTERON" (The Geographic Information System of the Terrain and Soils of Rondônia) (Cochrane and Cochrane, 1998). This database should provide a wealth of information for many years to come. It could be used as a model for future studies not only throughout the Amazon but also throughout other under-developed tropical regions, and help with the education of future land resource scientists.

SUMMARY AND CONCLUSIONS

During the past two decades computerization has opened up a new era for carrying out land resource studies. In the late 1970s it was demonstrated that the land systems approach was ideally suited to the systematic digitization of landscape features over Tropical America. The ISSS so-called SOTER project adapted this methodology to create a file system for describing terrain and soil attributes and succeeded in developing a digital file system with internationally agreed-upon attribute definitions. The SOTER file system was incorporated as a fundamental component in the LR-GIS, PC Users' Packet methodology that has been well tested over vast regions of the central savannas of Brazil and the Amazon.

The land resource studies referred to in this report were organized from the outset as PC Users' Packets for use with commercially available, user-friendly and low-cost GIS and RDBMS software. This approach not only provided for a strict quality and progress control during the course of the studies but also resulted in land resource database PC Users' Packets that can be used by professionals with diverse interests and computer-smart farmers and foresters.

The land resource database PC Users' Packet that incorporates the SOTER file system provides a wealth of data that can be analyzed for many different purposes. Examples have been given. One such example was the use of data from the Geo-economic Region of Brazil study to demonstrate statistically significant inter-relationships between soils and natural vegetation. In a more down-to-earth sense, it provided the farming industry of that region with an improved base for the application of an expert system to amend the crucial soil acidity problems. A similar study of the Bolivian Amazon has provided a base for conservation zoning amongst many other uses. The State of Rondônia study in the western Brazilian Amazon has provided a basis for its orderly development in addition to many other benefits including a unique soil analysis database for the farmers and foresters of that region.

In conclusion, the philosophy of producing a LR-GIS that incorporates the SOTER file system, with its RDBMS and map files organized as a PC Users' Packet, is a technological approach that has been well proven over the central savannas of Brazil and the Amazon. The work has provided a wealth of readily available, analyzable information of use decision makers, scientists and educators. The methodology results in a useful and attractive product for people with different interests and should specifically help with the training of land resource specialists. It is a proven model that could be used for carrying-out future studies not only throughout the Amazon but also in other under-developed tropical regions of the globe.

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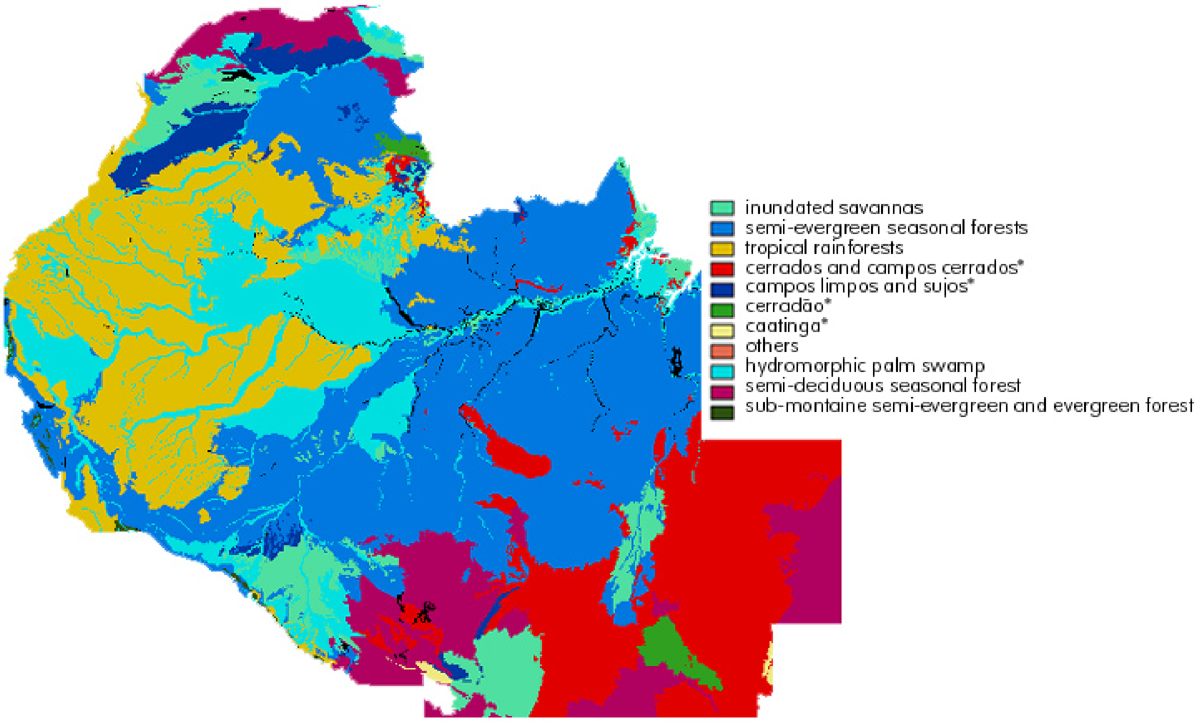

*Note: cerrados and campos cerrados - savannas and open savannas; campos limpos and sujos - treeless savannas and savannas with shrubs; cerradão - savannas with predominance of trees; caatinga - dry shrub lands.

Figure 1. Amazon basin physiognomic vegetation map based on the pioneering digital land resource geographical information system maps by Cochrane et al. (1981 and 1985).

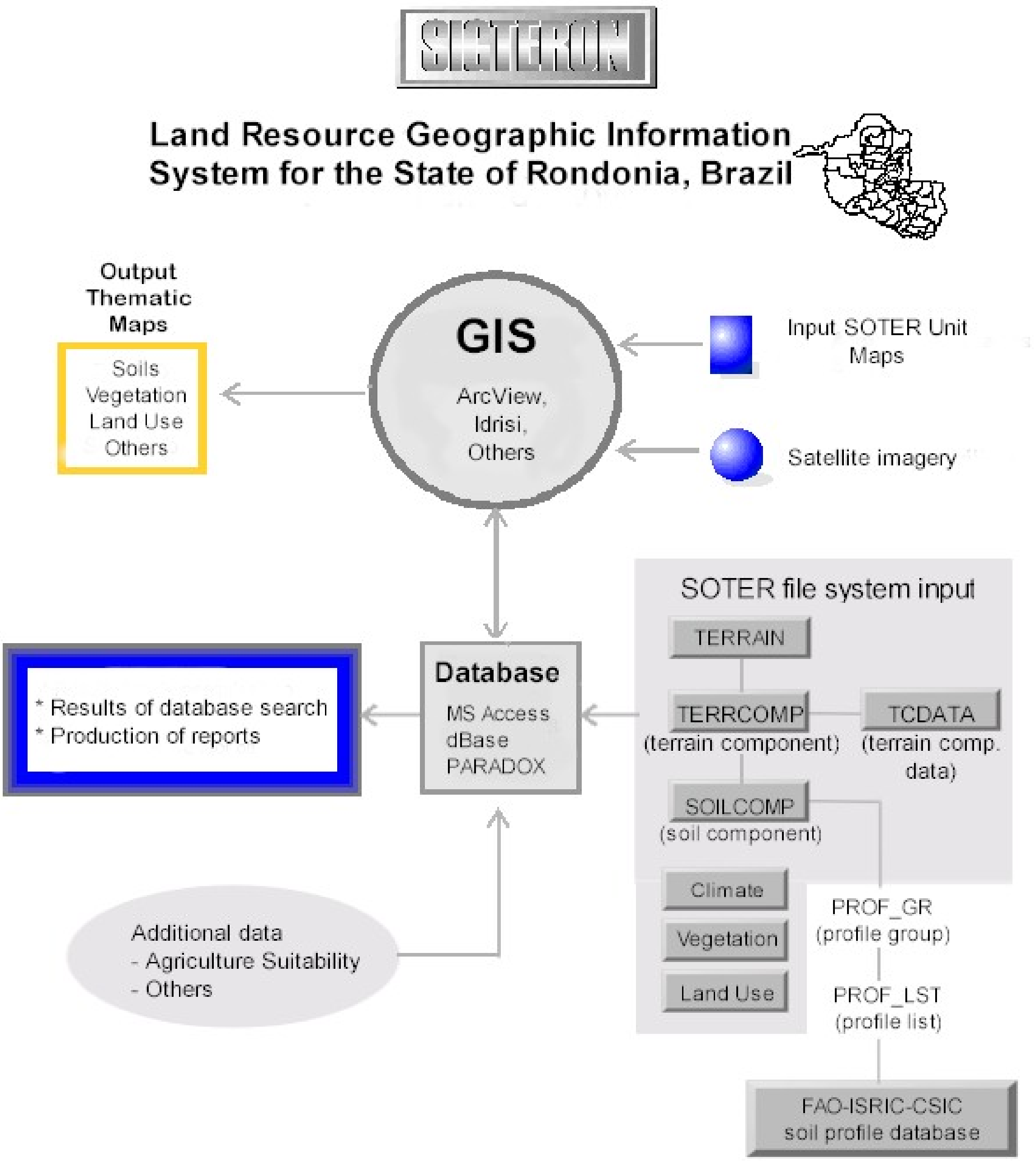

Figure 2. The land resources geographic information system (LR-GIS) developed for the state of Rondônia, Brazil, which integrates the SOTER file system with commercially available database programs and GIS software and the FAO-ISRIC-CSIC Soil (profile) Database (Cochrane and Cochrane, 1998).

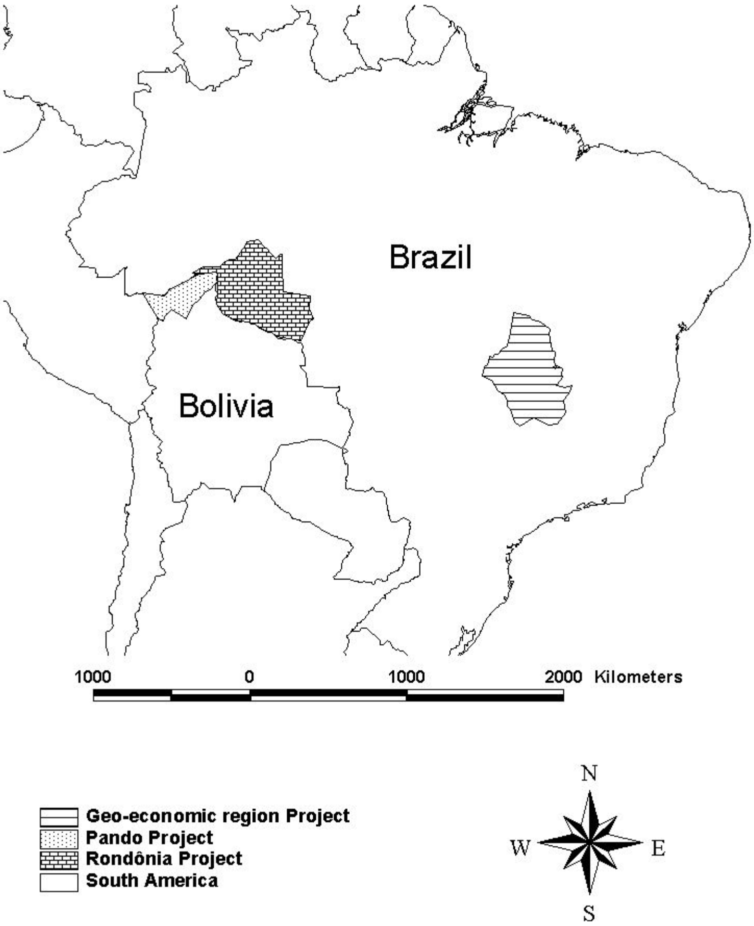

Figure 3. SOTER-based projects and studies conducted in Bolivia and Brazil.

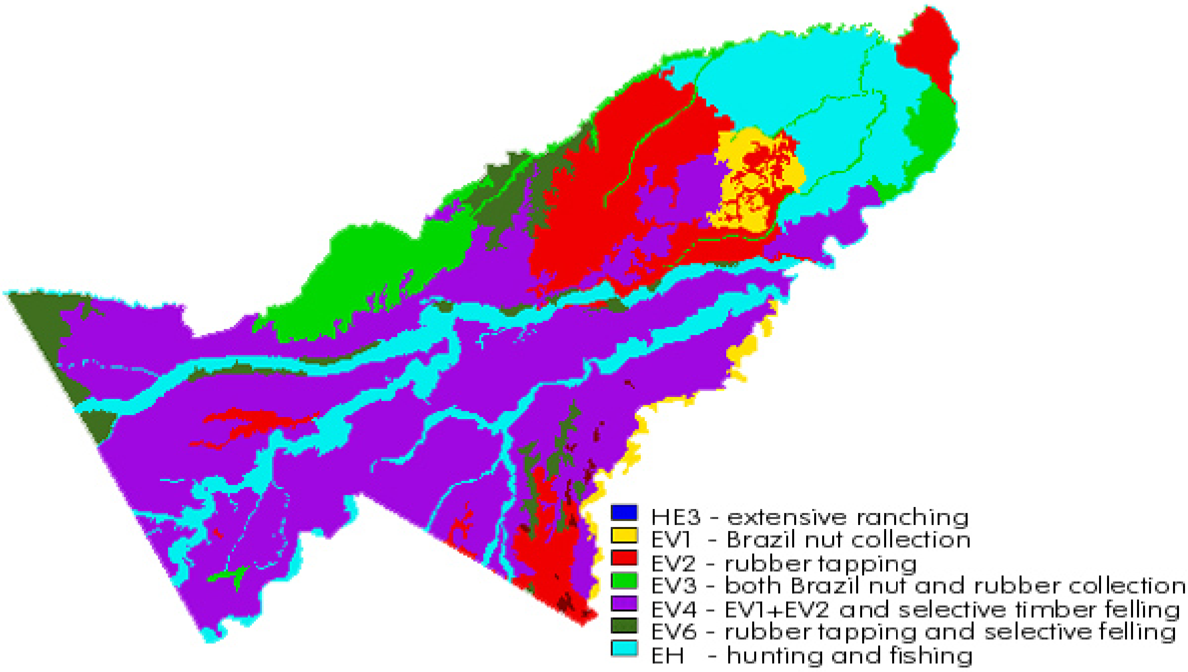

Figure 4. Pando land use zoning categories derived from the SOTER unit map.

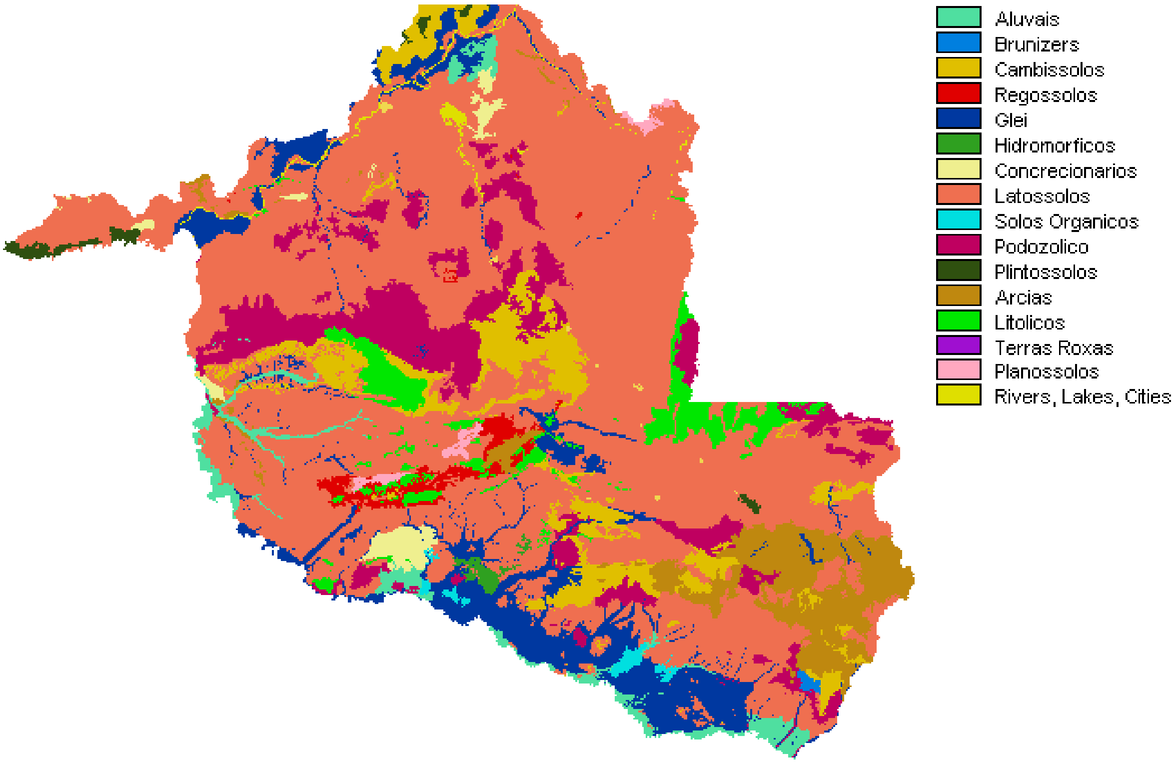

Figure 5. A summarized soil classification map of the soils in the State of Rondônia using the Brazilian soil classification system (Camargo et al., 1987), which was derived as a thematic map from the SOTER unit map and database.