Geo-Information System Modeling for Environmental Research Applications

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1. Abstract

Today's movement for sustainable agriculture is gathering support in a broad interdisciplinary context. We observe an increasing demand for GIS as a tool for understanding and integration of models for policy making. Despite the increasing concern for this topic, sustainability remains a contradictory concept for many people. The concept concerns attributes, actions, and effects that have to be sustained, but: at what levels, over what area and time period, by which means, and for which people?

EMBRAPA – CNPS recognizes the complexity of customizing generic tools for sustainable agriculture applications. Therefore, this paper presents a project that places proposals within specific research actions of geo-information system development. The project objective is to develop and supply methods and products of geo-information related to soil data organization and addressed interrelationships among entities from different domains. The expected result is a framework of basic procedures that provides a solid structure for agri-ecological research. Main actions include database design for related data sets, and research of new models for spatial representation of terrain objects.

At present, two products are in their final phase of development: SIGSOLOS and Geostat. In the near future, purposed actions will result in expansion modules ("SPRING" environment). They will offer: integration of natural resources data sets; a library of cartographic standards of environmental mapping; a knowledge based engine for soil suitability; a shell based on geo-information theory for development of domain and thematic interrelation models; and remote sensed image segmentation for soil patterns.

Key Words: Sustainable Agriculture; Soil Database; Interoperability; Geo-Information Modeling; Object-oriented Analysis and Design; Geostatistic Library; Dynamic Models .

2. Introduction

Tropical and sub-tropical ecosystems are characterized by a high biodiversity and great potential for exploitation of natural resources. On the other hand, increasing rates of environmental degradation, observed under different agricultural land management levels of technological input, show the fragility of these ecological systems. Deforestation, desertification, and severe soil erosion are usually stronger at the frontiers a expansion of agriculture. Association of environmental aspects with agricultural research becomes an evident need. Requirements include procedures to foresee, to simulate, and to monitor environmental processes as results of agricultural interventions. Research actions under the project presented in this paper increase our knowledge of processes for geo-information management applied to integration of environment related themes. Present and future developments may help to define better guidelines for policy making for Brazilian agriculture.

A variety of philosophies, policies and frameworks have contributed to development goals that balance environmental health, economic profitability, and social and economic equity. Although some hazardous collateral effects have taken place in the environment, this modern development has also brought improvements to the world's health care, education, and food production. The problem depends on how much our decisions and actions can be considered sustainable from an integrated social-economic and biophysical standpoint. Despite the increasing concern on this topic, sustainability remains an obscure and contradictory concept for many people. There are different opinions on what sustainability means, as well as on what techniques are required for attaining it. Besides, the reasoning on sustainability depends upon attributes, actions, and effects that have to be sustained, thus: at what levels, over what area and time period, by which means, and for which people.

An effort to approach the global change problem as a set of impact assessments and natural limits (e.g., social, demographic, economic, health, landscape aesthetic and potential evaluations, and community knowledge) is most likely to be unproductive and extremely complex. Hence, subdivision on broad themes of interdisciplinary study is usually addressed to run specific analyses. To achieve such context dependent analysis, it is necessary to identify meaningful sustainable indicators that link objects from different disciplinary descriptions according main aspects considered in specific sustainable development definitions.

The survey, mapping, monitoring and analysis of environmental and anthropologic impacts tend to be isolated in one disciplinary aspect, very complex in description and not clear about uncertainties or semantical changes according to scale and time. Indeed, research projects could represent a richer source of information for strategic levels of decision and policy making. The establishment of methods and models for interdisciplinary data integration requires generalization into more condensed and meaningful information. In this way, environment-related agencies could increase the social relevance and impact of research. For this reason, experiments are addressed to provide better understanding of both basic behavioral relationships, and uncertainty causes. In this way, research may effectively feed the vertical flow of information between different levels established in top-down and bottom-up frameworks (decisions and actions from farmers at lower level to policy makers at higher strategic level, or vice-versa).

Most of the thematic research agendas on the broad theme of sustainability analysis (e.g., sustainable agriculture, sustainable landscape design, sustainable tourism, sustainable industry, etc.) aim to define key parameters that could be meaningful to express social-economic and biophysical aspects as compound indicators in an analysis of sustainable scenarios. In addition, today's movement for sustainable agriculture is gathering increasing support and acceptance through interdisciplinary studies with well-defined approaches and goals. In this sense, we can observe an increasing demand for Geo-Information Systems (GIS) applications to analyze, understand, and integrate different contexts in policy making (Heberlein, 1995). A geo-information modeling approach, for environmental terrain objects, acts as a bridge-linking world pictures (thematic abstractions) and the machine representation (software abstractions).

Nature is complex and unstable, and natural ecosystems maintain themselves by adaptation. Change is usually the common case and not the extraordinary. Therefore, not all environmental changes can be blamed on human actions. Distinction between natural and human-induced change can be quite difficult to detect. Efforts have been made to point out reliable parameters in terms of pure abiotic impact. There is increasing importance attached to the use of dynamic quantitative and qualitative simulation models. These developments need to link environmental models (spatial and thematic aspects) and formal data models (computational aspects) within a GIS environment. These subjects are even more challenging because of the difficulties of the integration of environmental variables.

Associated methodological problems are data generalization and creation of composite indices (Oliveira, 1996). Regionalization, is in itself an effort to standardize methods and parameters for survey, monitoring and interpretation for broader areas of analysis resulting in small-scale information abstraction and geometric representation. Generalization should be understood as both the fulfillment of certain context- dependent criteria (conceptual abstraction - class generalization) and topological relationships (containment or adjacency - object aggregation). Lastly, problems of feature size constraints for cartographic representation are part of the providing limitations.

The main areas of research of the described project can be summarized as follows:

- Development of alternative land use, farming systems, and agribusiness scenarios.
- Improvement of monitoring of agricultural sources and impacts on/of environmental change.
- The modeling of sources and impacts from a holistic approach.
- Development of consistent standards for description and exchange of land related information.
- Development of information technologies for optimizing the use of natural resource data bases.

The Brazilian Agricultural Research Organization – EMBRAPA - has, over the past twenty-two years, generated and adapted most of the technologies, products and services for high productivity of the Brazilian agribusiness complex. However, a new organization paradigm (EMBRAPA, 1992) set environmental quality as its priority in guiding current and future research for rational practices on farming and forest extraction. At EMBRAPA - CNPS (National Center for Soil Research), researchers are involved in interdisciplinary projects where concepts and methods from the Brazilian soil classification have been correlated by means of GIS. Furthermore, the enterprise recognizes the importance and complexity of customizing such generic tools for sustainable agriculture applications.

3. Material and methods

At process implementation level, CNPS has made a great investment in terms of operational infrastructure and technical training of soil scientists, system analysts, and cartographers. The emphasis is on building a goal-oriented interdisciplinary team. Available GIS environments for spatial data processing are: SGI VGA, ILWIS v.2.1 and ARC/INFO v.3.5 for DOS/Windows; and SPRING for UNIX. CASE (Computer Aided Software Engineering) environments adopted for modeling activities are: Rational Rose / C_{++} v.4.0, IDL ENVI, and Visual Café / Java. In addition, the organization, as a hole, is engaged in a joint effort with the Brazilian National Spatial Research Institute (INPE - Instituto de Pesquisas Espaciais) for the development of an object-oriented GIS. This software system is called SPRING (Sistema de PRocessamento de INformações Geo-referenciadas), and its programming code is open for customization and/or improvements in line with EMBRAPA's environmental research.

The project, named Integrated Environmental Geo-referred Information System, has as its objective to develop and make available methodologies for management of environmental data surveyed by EMBRAPA. The proposed geo-information system development for environmental and agricultural research applications is coordinated by the CNPS, in association with other research institutions as EMBRAPA - CPAC (Agricultural Research Center for Cerrado Ecosystem) and CNPTIA (Research Center for Information Technology in Agriculture), alongside partner organizations with strong technical capabilities as: INPE, IME (Army Engineering Institute), PUC-RJ (Rio de Janeiro Catholic University), and Institute of Mathematics at UFRJ (Rio de Janeiro Federal University). The expected result is a framework of basic procedures that provides a solid structure for improvement of agro-ecological research and policy advice. Main actions include both database design for a cooperative of environmental related data sets, and research of new models for spatial representation of terrain objects.

The project is composed of five sub-projects of different research subjects, as follows:

- SIGSOLOS – A relational database analysis, design, and implementation having as objective the storage and retrieval of Soil Information at the national level
- New models for spatial representation - A system module implementation with the SPRING-LIB (Object Class Library) interface for geoestatistic and fuzzy set procedures for studies of natural phenomena
- A prototype system development for soil interpretation and land use monitoring, which considers an integration of image processing (satellite, radar, and laser) and knowledge based systems (KBS) standards
- An object-oriented geo-information system application for goal-oriented integration of simulation models applicable to sustainable agriculture
- Cartographic process standards for production and management of digital soil maps and derived interpretations, for future research of automatic generalization.

In general actions will result in the expansion of SPRING functional modules such as a shell for integration of internal data sets. Soil researchers will have available: a library of cartographic standards; a knowledge based engine (data mining) and image segmentation for soil suitability classification considering three distinct management levels (low input, intermediate, and high input); options for new spatial representation models; a shell of geo-information modeling applied to semantical integration of thematic models for dynamic simulations. Besides, improvements of already available prototype systems (Geostat and SIGSOLOS), will provide detailed results of sub-projects in an advanced stage of execution.

In SPRING the following main aspects can be discerned (Freitas, 1997): 1) conceptual model based applications driving interface customization to accommodate the user's domain; 2) single object-oriented system environments for image processing, digital terrain modeling, thematic database management, and geometric data manipulation; 3) operations defined at the conceptual level independent of system implementation levels; 4) object-oriented implementation (C_{++}) for UNIX environments; 5) easy integration with commercial relational database management systems (RDBMS); and 6) interactive interface windows, OSF-MOTIF compatible, in Portuguese and English. Further important details on its user friendly interface are related to the semantical component of thematic applications. The user can manipulate model elements at the conceptual level, with selection of objects by category. Semantical consistency is preserved during integration of data of a distinct nature, because functionality is not previously associated with representation models. This is represented in Figure 1, which also presents different levels of geo-information modeling with related disciplinary domains

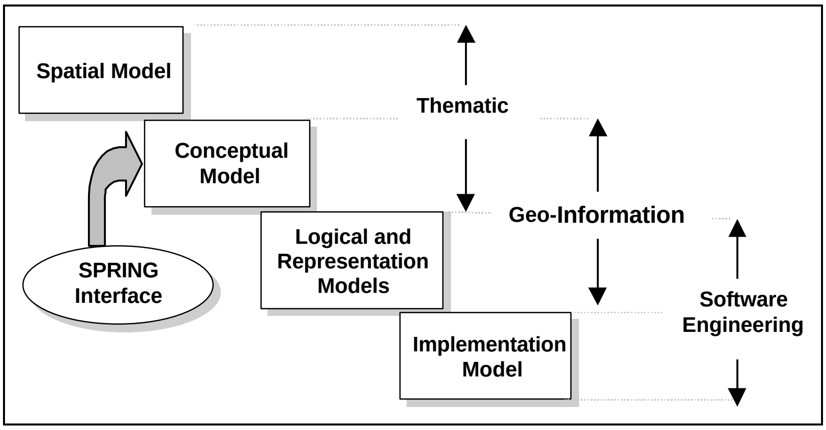


Figure 1. SPRING conceptual interface level.

Recent publications regarding environmental modeling present constructs that try to express the semantics of natural phenomena. They are based on object-oriented methods at research levels. Object-oriented models support the description of both structural and behavioral properties. Structural properties are concerned with the static organizational nature of the databases. Behavioral properties are dynamic and related to the nature of possible changes allowed in the information and the database (Worboys et al., 1990). This has proven to be especially suitable in application areas, such as the design of GIS that have a richly structured knowledge domain and are associated with multimedia databases (Câmara et al., 1992).

Sub-projects in preliminary phases follow the same object-oriented principles in terms of implementation. Moreover, they emphasize analysis and design phases considering a formal geo-information modeling approach extending object-oriented constructs with geometric context, and exploring thematic links for encapsulation of characteristics and processes. Analysis focuses on identification of a set of actors that can match both requirements of critical state transitions from identified processes, and available data. The expectation is that potential indicators of sustainable agricultural practices will play the role of interactive state variables as suggested by O'Neill (1988) important for interrelations and/or confrontation of simulation models from different disciplines.

Still, GIS specialists are committed to assess given input maps and attributes in order to formulate data and process models for dynamic management. Molenaar (1996) proposes a linguistic geo-information modeling approach, which considers representations of both semantics and uncertainty as elementary components integrated into the formal syntax for statements that are formulated. Thus, the relevant parts to be considered in different stages of the geographic data abstraction (Figure 2) are:

- Semantics **-** the thematic context of the description of the world
- Syntax **-** the way to structure (model) the problem and its geometric features
- Uncertainty **-** likelihood limitations related to measurement, classification, and time.

Different semantic levels for topology should be considered to handle the structural complexity of terrain objects' geometric representation. The relationships are established at three levels: between geometric elements, between terrain feature objects, and between geometric elements and terrain feature objects.

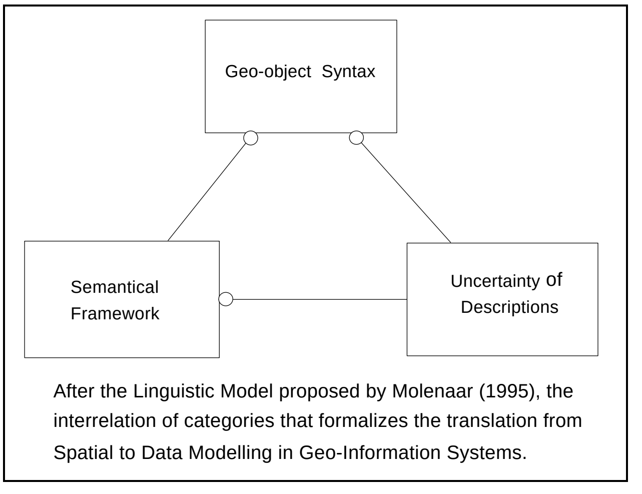


Figure 2. Three stages of spatial data abstractions.

GIS processes are usually driven by thematic descriptions within a given context. For this reason, it is relevant first to consider the attribute quality aspect that is related to: substance, values, and object characteristics. Furthermore, attribute structure varies according to its class, attributes are thus classified into discrete (e.g. land use and soil) or continuous (e.g. slope steepness) variables. The problems associated with the management of the input maps are in part determined by the problems of data quality assessment, which is data type dependent. The strategy to handle uncertainty associated with data inputs is to analyze characteristics that affect their usefulness as presented in Table 1.

Table 1. Aspects of uncertainty associated with geo-information.

Micro level	Logical consistency, resolution, attribute accuracy, and postional accuracy
Macro level	Completeness, time, and lineage.
Usage	Accessibility; direct and indirect costs.

Imposed by the user needs for dynamic and adaptive geo-information manipulation, intelligent spatial databases represent part of the paradigm in the evolution of GIS technology. This requires the dynamic interoperability of GIS (Glover, 1996) with environments as: Knowledge-Based Systems (KBS), Neural Networks, Image Processing, Geostatistical Interpolations, Fuzzy Classifications, and Domain Simulation Models. In contrast to the revolution introduced so far in geographical information storage and management, GIS is still not completely adequate to handle fully dynamic environmental studies. The most challenging requirement for system coupling is the interoperability of systems. Interoperability is defined as the integration of distributed generic services (functional units of software, hardware, or both) by means of mediators that maintain the information flow integrity and requires little or no knowledge from users about unique characteristics of those services (Egenhofer, 1996). The differences between data transfer and interoperability should be clear for GIS users (Table 2), since principles of cooperative interfaces (multimedia, hypertext, function wizards, and knowledge base facilities) influence the ability to manage open data and process sets for specific application modeling at the conceptual level.

Table 2. Differing aspects of data transfer and interoperability among systems

	Transfer	Interoperability
Scope	Data	Data and Process
Data Unit	Data Set	Object (Data Set or Lower)
Communication	Blind (1-way)	Negotiated (2-way)
Integration	In Target System	In Server or During Communication

4. Results

At present, two products are already in their final phase of development: SIGSOLOS (Geo-referenced Soil Information System) and Geostat (Geostatistical Interactive Procedures Module). The SIGSOLOS beta-test version is available for data input by means of RDBMS (Relational Data Base Management System) as ACESS, for Windows platforms. Furthermore, it has links to the geometric component of soil units, either within the Arc/Info or SPRING environment, or by ODBC (Open Data Base Connectivity) functions. These facilities are planned to be expanded to provide: access via Internet for data input and retrieval; soil data management at national level; support of the Brazilian Tropical Soil Classification; and open data format for interoperability with external modules. The Geostat module for SPRING-LIB makes use of all cartographic and interface facilities previously offered by SPRING and provides spatial analysis for interpolation and simulation according to geostatistical principles. Algorithms for data variographic analysis and Kriging interpolations have been reused from the GSLIB geostatistical procedures shareware library (Deutsch and Journel, 1992). This module works for two dimensional analysis and offers: input data conversion to GSLIB format; univariant and bivariant statistics at point locations, dispersion and dependency analysis; automatic generation of pair comparison file (PCF); semi-variogram analysis and adjustments for regular and irregular sample distribution; model validation; and kriging interpolations. The development of a climate information system, compatible with the SIGSOLOS data structure, has been done by CPAC, and it represents the first concrete step towards the integration of disciplines under a joint structure of environmental data sets.

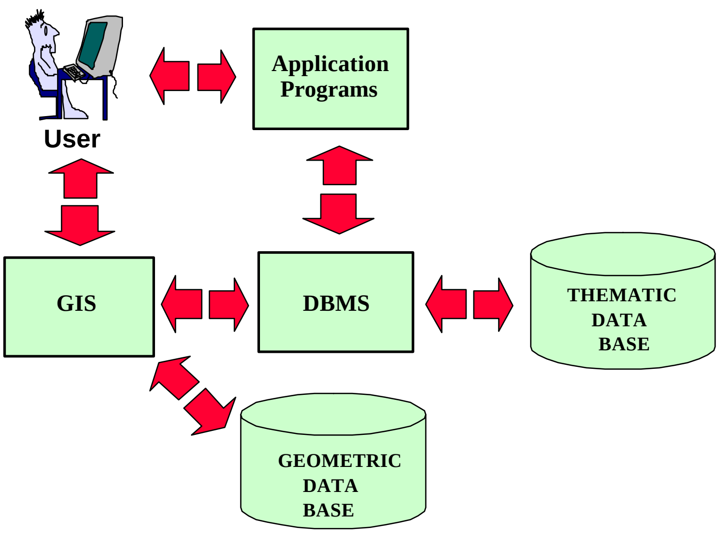


Figure 3 SIGSOLOS dual system architecture

4.1 Sigsolos

The conceptual model 'SIGSOLOS' was designed to store and retrieve existing information from soil surveys at national level. Its main entity is the observation point, with the coordinates for geo-referencing as integration factor (Bhering, 1997). Observation points can represent a profile, a complementary profile, or an extra sample. The beta version systems for soil and climate were projected in a dual architecture integrating DBMS and GIS as complementary environments, but having distinct interfaces. This architecture has facilitated the management of both tabular data and digital maps (Figure 3), and they have a live link that makes the different structures appear as one at the user interface level. This link is characterized by a unique terrain object identifier for both thematic and geometric aspects; an example of the system interface is in Figure 4.

SIGSOLOS aims:

- To support the development of the Brazilian Tropical Soil Classification System by statistical procedures to determine possible quantitative parameters; data mining procedures support classification decisions;
- To generate soil suitability maps according to customized rule sets for specific classifications;
- To facilitate several forms of soil derived cartographic production for specific land zoning interpretations, as well as integration of environmental attributes that are required by the Environmental Database Cooperative of EMBRAPA.

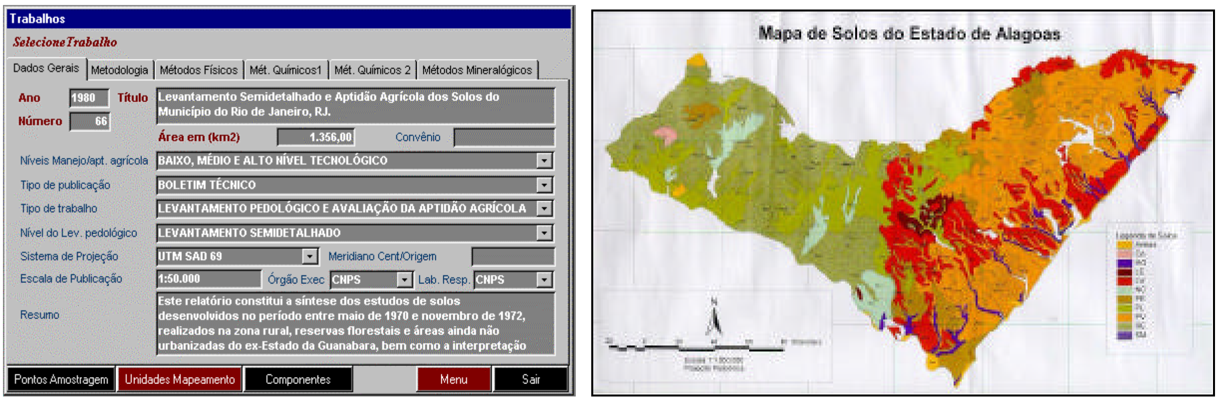


Figure 4. Interface examples for attribute and geometric descriptions.

Identified during the analysis phase, the main system requirements can be described as: software independence; adaptive to changes; software modularity; data orientation; consistency check at data input; geometric interface for data query. Data requirements are: independence of data for both soil profiles (points) and mapping units (polygons); integration of point and polygon by unique object identifier; scale and survey detail level independence; and coalition to the Brazilian Soil Taxonomy (Mansilla Baca et.al., 1997).

4.2 Climate database

The Climate System offers accessibility of data derived from traditional agri-meteorological surveys by CPAC (Assad, 1997) and can also import data from other agencies which have similar climate data sets (IBGE, DENAI, INEMET). Besides, it can be reached by world wide web (WWW) as shown in Figure 5.

4.3 Geostat:

The beta version of a geoestatistical module for the SPRING system, named Geostat, is already available, and it offers friendly interface access to a geostatistical procedure library (GSLIB) for the understanding and modeling of spatial variability natural phenomena. Geostat procedures have as objective a two dimensional analysis for interpolations of surfaces generated from geo-referenced samples at point locations. Besides, it offers translation of data from external systems through interfaces for data transfer, file selection, and sampled distribution visualization. Still, this module aims also to generate stochastic continuous images from variables values collected at point locations. However, this beta version is limited to interpolation capabilities. Using spatial covariance models, Geostat has the possibility of semi-variogram modeling by automatic adjustment (minimum last square ponderation) and anisotropy treatment. The spatial covariance is an essential step for kriging interpolations and stochastic simulations.

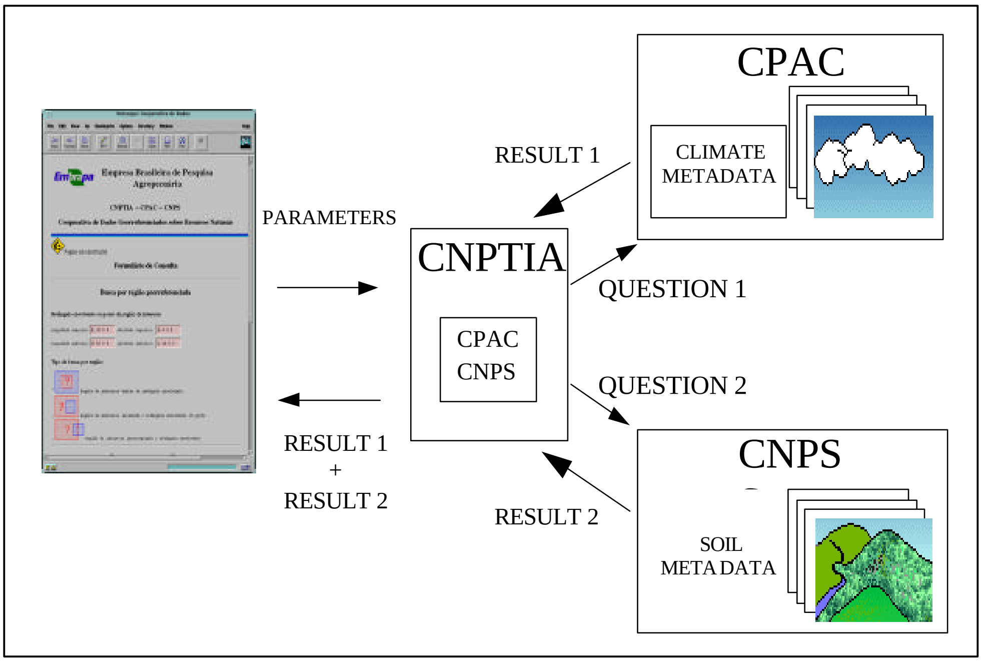


Figure 5. Cooperative online query.

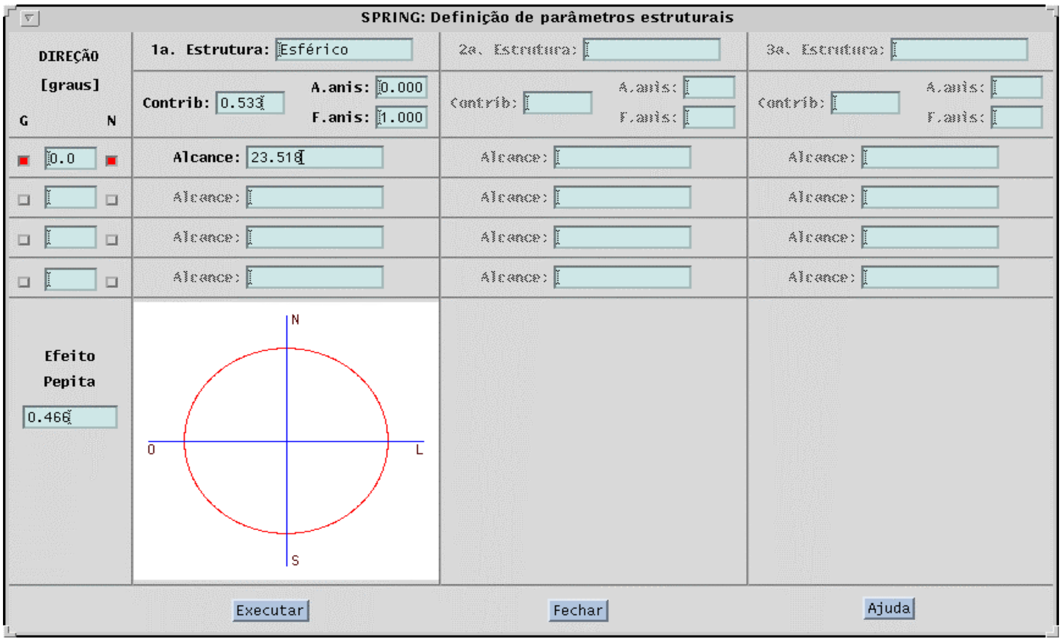
The GSLIB library was built by Deutsch and Journel (1992), as a research development at Stanford University. Today it is available as shareware that can be easily downloaded from Internet. The programs include tools for development, and this facility has been the starting point for other well-known, public domain, geostatistical systems as Geo-EAS and Geostatistical Toolbox. Its source code is written in standard ANSI (American Standard National Institute) programming language, Fortran 77, allowing platform independence from personal computers to work stations. Further detailed descriptions of program conventions and formats are found in Deutsch and Journel (1992). Its structure is basically formed by four modules, viz. utility functions to show and to analyze data and its results; variographic functions to generate variograms starting from samples spaced regularly and irregularly; Kriging functions to execute interpolations based on Kriging techniques (Simple Kriging, Ordinary Kriging, Co-Kriging and others); and simulation functions to execute stochastic simulations.

At present, the system module Geostat can be further detailed through the following list of functions:

- Exploratory data analysis is available by means of univariant and bivariant statistics. The option for univariant procedures enables variable selection, histogram and numeric visualization of results, and normal probability graphics. The bivariant option enables the selection of two variables and visualization of the dispersion diagram
- Automatic pair comparison analysis generates a binary file (PCF) that contains pairs of two-dimensional samples sorted by the minimum distance between them (lag) in any direction

- Experimental semi-variograms (Figure 6) can be generated for regular and irregular sample sets, by the adjustment of families of variogram models. Besides this adjustment, automatic or visual is done by user-given structural parameters such as: Nugget Effect; Sill; Range; and Anisotropy angle and factor. These are further used during model validation and Kriging 2D. In this beta version, the adjustment is limited to the following theoretical models: Spherical, Exponential, Power and Gaussian. Other models as Cubic, Pentaspherical, and Gap Effect are future implementations. The interface is composed of three choices: calculation of anisotropy angle and factor; calculation and drawing of anisotropy ellipsoid; and storage of given structural parameters. Moreover, available choices of variogram types are unidirectional by surface, either univariant or bivariant. Available univariant statistics are: Semi-variogram, Covariance, Correlogram, Semi-madogram, Semi-rodogram, and Indicative Semi-variogram. The option Bivariant is understood as Crossed Semi-variogram
- Model validation involves re-estimation of well-known values through structural parameters from the adjusted model of the semi-variogram. In this whole sequence, there always exists an uncertainty degree about adjusted model parameters. This uncertainty is the potential error of the estimate. Validation procedures supplied are the following: error distribution spatial diagram, histogram, statistics, and a cross diagram of estimates versus true values. Besides graphic results, the validation procedure supplies a screen containing numeric results

- The Kriging 2D procedure developed in this work includes the basic code for ordinary Kriging 2D. It can easily be modified to calculate Simple Kriging.



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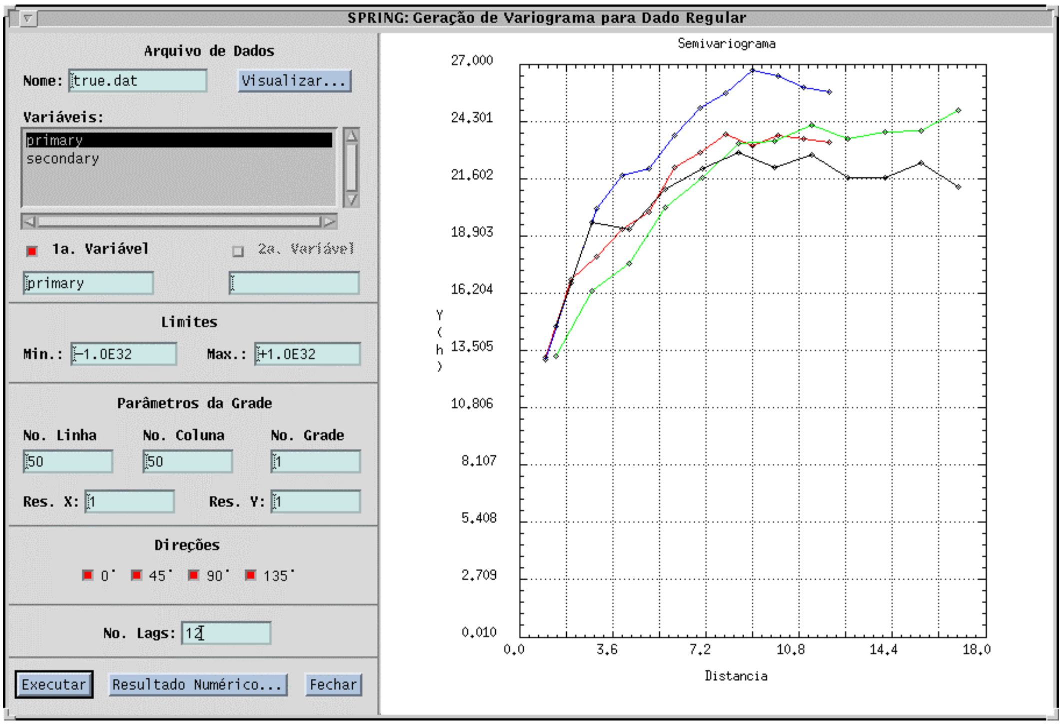

Figure 6. Examples of Geostat interface.

5. Final Remarks

Food systems extend far beyond the farm and involve the interaction of actors often with contrasting goals including farmers, farm workers and advisors, researchers, suppliers, unions, agribusiness, consumers, and policy makers. Relationships among these actors should be understood as it changes over time according to new technologies that promote social-economic and political changes. However, natural limitations of the modeling activities of such complex and dynamic systems must be understood as a justification of the proposed model simplifications.

Results from conceptual terrain objects analysis indicate that well-defined objects (class and aggregation hierarchies) under a user-friendly interface environment offer an adequate means of sustainable agricultural analysis to researchers. Furthermore, mastering of object-oriented concepts matures during research requiring a proper organizational setup for infrastructure, and training. It is also part of the requirements of a multidisciplinary team of domain researchers and system professionals, who are involved with modeling activities during all phases of the development. So, they would be assembling a common sense language as a bridge for proper semantical model representation.

It is a fact from the research experience that the coupling of constructs from object-oriented and geo-information modeling approaches improves abstraction of thematic attributes, topological relationships, and geometric representation. The development and customization of the algorithms and software modules for spatial analysis require high levels of interoperability among systems and services (Oliveira, 1996). In this sense, the use of object-oriented technology is becoming a standard to solve complexity, in particular to interface and interoperability aspects.

Object-oriented developments have not solved the problem of standardization, but offer a more open interface protocol for interoperability. Many libraries of basic object classes are already available for use. It is clear that some problems still exist for the full exchange of classes, libraries, and modules. These limitations have been addressed during recent years, and many libraries handling interfaces widget, images, three-dimensional display functions, and geometric algorithms already represent a big potential source for coupling of GIS applications. In the GIS environment, the development of standard object class library has still to be done.

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