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# GIS Analysis of Cropping Systems

Cornell University

International Crops Research Institute for the Semi-Arid Tropics

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## Abstract

Geographic information systems (GIS) have come a long way from obscurity in the 1980s to now become commonplace in universities, international research institutions, government departments, and private businesses where the technology is used for a wide range of applications. In the last few years, its application has been increasing in agricultural research and development. The International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, held 18-19 Aug 1997 at ICRISAT, Patancheru, India examined the current status of available software options, database requirements, availability of data, database storage and exchange procedures, options for GIS outputs and optimization of regional interactions in the use of GIS for cropping system analysis with respect to Asia. GIS specialists from international agricultural research centers (IARCs) and national agricultural research systems (NARS) of Asia reviewed state-of-the-art know-how in using GIS as a research tool for the characterization of target environments, soil, water and nutrient management, integrated pest and disease management, and sustainable land-use systems. The workshop focussed on three basic questions: "what information is available?", "in what form is the information available?", and "in what form should the GIS output be?"

Recommendations were made on the effective use of GIS and on the possibility of harmonizing datasets for common use by IARCs and NARS. The workshop was followed by a hands-on training program on the use of GIS in analysis of cropping systems of Bangladesh, India, Nepal, Pakistan, and Sri Lanka. The country case studies prepared during this training program will be published as a separate volume. The present publication includes status papers describing GIS as a research tool, types of GIS software available and its use in different institutions.

**The research activities were supported by the Asian Development Bank and donors supporting ICRISAT's unrestricted core activities**

# GIS Analysis of Cropping Systems

**Proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region**

**18-19 Aug 1997, ICRISAT-Patancheru, India**

*Edited by*

**S Pande, C Johansen, J Lauren, and F T Bantilan Jr.**

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**ICRISAT**

**International Crops Research Institute for the Semi-Arid Tropics**

**Patancheru 502 324, Andhra Pradesh, India**

**1999**

## Workshop Sponsors

Cornell University Soil Management CRSP

Rice-Wheat Consortium for the Indo-Gangetic Plain (RWC)

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)

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S Pande, Chairperson

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| N P Saxena | F T Bantilan Jr |
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| A Ramakrishna | |

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**Erratum:** On pages iv and 135, the correct spelling of the author is S Chater (and not S Chator) and his current address is: S Chater, Consultant Editor, Hawson Farm, Buckfastleigh, Devon TQ 11 OHX, United Kingdom.

# Preface

The International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region was held 18-19 Aug 1997 at ICRISAT, Patancheru, India. The Workshop was followed by a hands-on training program on the use of GIS in analysis of cropping systems conducted during 20-29 Aug 1997. The workshop and training program were developed by ICRISAT, the Rice-Wheat Consortium for Indo-Gangetic Plains, and the Cornell University Soil Management CRSP Project that has also initiated rice-wheat research activities in the Indo-Gangetic Plain. Both events were sponsored by and funded by these three partners, and these proceedings have been prepared and funded by the Cornell University Soil Management CRSP Project and the ICRISAT "Legumes in Rice- and Wheat-based Cropping Systems" Project (S4). This workshop was specifically designed as a prelude to a major S4 project workshop on "Legumes in Rice and Wheat Cropping Systems of the Indo-Gangetic Plain - Constraints and Opportunities" held 15-17 Oct 1997.

GIS specialists and interested scientists from several international institutions and Asian national agricultural research systems (NARS) participated in the workshop on database harmonization: International Center for Integrated Mountain Development (ICIMOD), Nepal; Centro Internacional de Agricultura Tropical (CIAT), Colombia; International Rice Research Institute (IRRI), Philippines; International Programs Division, Natural Resources Conservation Services, USA; Centro International de Mejoramiento de Maiz y Trigo (CIMMYT), Mexico; Nepal, Bangladesh, India, Pakistan, Sri Lanka, and ICRISAT, India.

The participants discussed the present status of GIS and its use in further characterization of cropping systems. Constraints and opportunities of using GIS by national agricultural research systems were identified specifically to supplement conventional approaches of research. In this context, training courses for specialized skill development, such as the one that followed this workshop, were appreciated for shared use. The workshop proved to be a timely initiative, and prospects of collaborative research in using GIS as an intelligent analytic tool are encouraging.

We sincerely believe that this volume on GIS analysis of cropping systems, with specific reference to harmonization of databases for GIS analysis of cropping systems in the Asia region, will provide a useful guide to the present status of GIS and its use in agricultural research. A separate volume on the case studies developed during the training course will further identify the need and usefulness of GIS in focusing agricultural research and development in the Asia region.

The Editors

# Welcome Address

**F R Bidinger**[1]

It is my pleasure to welcome you to this International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, and the associated hands-on training program on the use of GIS in analysis of cropping systems of Bangladesh, India, Nepal, Pakistan, and Sri Lanka. I understand that resource persons and participant trainees have already arrived for the hands-on training program and therefore I extend my welcome to them also.

This is a timely initiative of Dr C Johansen, Dr S Pande, and other colleagues of the "Legumes in Rice- and Wheat-based Cropping Systems" Project (S4) within the context of ICRISAT's Medium-Term Plan (MTP) (1998-2000). While the four targets of the MTP—prosperity, diversity, environment, and inclusiveness—capture ICRISAT's proposed focus for the MTP period, those familiar with the Institute will recognize that these are not inconsistent with the priorities, objectives, goals, and values of the past. The proposed 1998-2000 agenda is evolutionary, rather than revolutionary, since strategic research in close partnership with stakeholders requires a long-term approach, and emerges from a broad and continuous consensus-building process. Nevertheless, strong currents of change underlie this evolution, particularly in response to changing donor interests, new scientific developments, and the increasing strength of many other National Agricultural Research Systems (NARS) partners. This evolution, we think, has been captured in ICRISAT's operational mandate for the MTP period. In the new MTP period, we need to focus on the application of new scientific tools to more thoroughly characterize the genetic resources research that we hold in trust for the world community. In this process, we can assist NARS to strengthen their capacity and germplasm collections. In germplasm enhancement research, our emphasis will be more on basic and strategic research, especially the identification of molecular markers for resistance to biotic and abiotic stresses. We need to strengthen biotechnology, GIS, and modeling to supplement conventional approaches in crop improvement. In natural resource management research, we also need to harness the new tools available to allow us to conduct systematic, strategic analysis of the natural resource base. We also need to use the tools of GIS and modeling to develop extrapolation domains for technologies developed at particular locations, and to track their adoption.

Further, we will be focussing on enhancing research partnerships with NARS and non-governmental organizations (NGOs) and will increasingly replace in-service training courses for technicians and extension staff with more specialized scientific training aimed at strengthening NARS human resources. This should result in substantially increased numbers of visiting scientists to ICRISAT from NARS.

1. ICRISAT-Patancheru, Andhra Pradesh 502 324, India.

Through networks, strong NARS will be encouraged to take a lead in developing finished technologies that ICRISAT can no longer generate.

In this changed operational process, the respective roles and comparative advantages of various actors in the global R&D system need to be clarified. The ultimate purpose of such activities is to improve the quantity and quality of crops that farmers grow in the semi-arid tropics (SAT) and beyond. That is where we hope our unified efforts with you will continue. In this regard, the support and cooperation of NARS, NGOs, universities, and other organizations in Indo-Gangetic Plain countries and Sri Lanka is highly appreciated and is evident in this meeting. Therefore, not only do I wish to welcome you to this CIS workshop and training course, I also wish you a comfortable, successful, and fruitful stay here at ICRISAT.

# Inaugural Address

**S M Virmani**[1]

It is a great pleasure to welcome all of you to ICRISAT and to the Harmonization Workshop. In the GIS training program following the workshop, participants from Bangladesh, India, Nepal, Pakistan, and Sri Lanka will learn the use of GIS as a tool to interpret and analyze temporal and spatial datasets of crops, their distribution, environmental parameters and datasets on biotic and abiotic stresses. The purpose of this exercise is to apply GIS technologies to cropping system analysis.

We believe that the new arrangements and investments in the new approach, such as GIS, as mentioned by Dr F R Bidinger, will best position ICRISAT to respond to the dynamic external environment we face. We made the choices about our future research portfolios in the MTP in an analytical, interactive, and transparent fashion; and in this direction, the present workshop and training program on GIS is one of the steps we have taken under the changed research emphasis and portfolio.

Our future research portfolio is based on the close collaboration between NARS and ICRISAT. These joint research partnerships will include visiting scientists, who will constitute a central mechanism for strengthening NARS human resources. Increased personnel exchanges, secondments, and joint appointments with advanced research institutions will enhance complementarities and enable strong outputs, compensating for decreased internal staff numbers resulting from declining core resources. We will be focussing on such new science investments and tools as biotechnology, GIS, and modeling, to increasingly supplement conventional approaches of research. In this context, training courses for specialized skills, such as the forthcoming one on GIS, will be organized for shared use. We look forward to working together to ensure that our partnership reaps the rewards expected by our stakeholders, because unless we do so, their future support will be found more demanding than it is today.

I am confident that we will come away from this workshop satisfied with the efforts that each of us will have contributed in making it a success. I hope that the recommendations that evolve from this meeting will provide a sound basis to use GIS as a tool to analyze constraints and identify opportunities for crop diversification, especially with respect to opportunities for greater inclusion of legumes in the rice-wheat cropping systems of the Indo-Gangetic Plain region.

Once again, I welcome all of you to these meetings.

1. ICRISAT-Patancheru, Andhra Pradesh 502 324, India.

# Framework and Objectives of the Meetings

**Suresh Pande**[1]

I would like to extend my welcome to all of you to this International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, and to the hands-on training program on the use of GIS in analysis of cropping systems that will follow the workshop. In their introductory addresses, Drs F R Bidinger and S M Virmani have adequately explained the shift in ICRISAT's research portfolio and the need for using new scientific tools to supplement conventional approaches in crop improvement and natural resource management research. It is in this new MTP period that we are aiming at the application of GIS and modeling to more thoroughly characterize and analyze prospects for our target production systems.

At ICRISAT, we are implementing a special project on crop diversification in cereal-based cropping systems: legume technologies for rice- and wheat-based cropping systems of South and Southeast Asia (designated as the S4 Project). The objectives of this Project are to:

- quantify the scope for greater inclusion of legumes in rice- and wheat-based cropping systems;
- develop technological options (genetic and management) for alleviating the major biotic and abiotic constraints to adoption of legumes;
- evaluate improved technologies on farmers' fields to catalyze adoption and elicit feedback on further research needs and adoption constraints; and
- assess adoption and quantify the impact of improved legume-based technologies for rice- and wheat-based systems.

The S4 Project targets the Indo-Gangetic Plain where both rice and wheat are grown (often in high-input continuous rotations) and tropical rice-based systems (in tropical regions unsuitable for wheat). The Project is conducted jointly with the national agricultural research systems (NARS) of Bangladesh, India, Indonesia, Nepal, Pakistan, Sri Lanka, and Vietnam. The Project is linked with the Rice-Wheat Consortium for the Indo-Gangetic Plain, with respect to legume options for rice-wheat systems, and thereby it is also linked with other CGIAR institutions (e.g., CIMMYT, IRRI, IIMI) and advanced research institutes (ARI) (e.g., Cornell University, USA) with research and development interests in rice-wheat production systems. The operational aspects of the S4 Project are funded by the Asian Development Bank. The broad categories of activities of the S4 project are: characterization of target environments; soil, water, and nutrient management; integrated pest and disease management; and sustainable land-use systems.

1. ICRISAT-Patancheru, Andhra Pradesh 502 324, India.

This GIS Harmonization Workshop and the associated training program evolved in our attempts to address the first of these activities. Our initial questions included "what information is available?", "in what form?", and "in what form should our GIS. outputs be?" Similar questions were also faced by the Rice-Wheat Consortium in their intentions to better characterize rice-wheat systems. It was realized that most of the environmental and socioeconomic databases of relevance would be common across crops of interest such as rice, wheat, and legumes. This workshop and training program was developed along with the Rice-Wheat Consortium and the Cornell University Soil Management CRSP Project that was also initiating rice-wheat research activities in the Indo-Gangetic Plain. The workshop and training course were sponsored and funded by these three partners, and these proceedings were funded by the Cornell University Soil Management CRSP Project and the ICRISAT S4 Project. This workshop and training course were essentially designed as a prelude to a major S4 Workshop on "Legumes in Rice and Wheat Cropping Systems of the Indo-Gangetic Plain—Constraints and Opportunities" held on 15-17 Oct 1997.

The objectives of the GIS Harmonization Workshop are to:

- prepare an update on appropriate GIS software options, and establish protocols for interchangeability of GIS formats
- discuss database requirements and their availability
- establish database storage and exchange procedures
- prepare an update on options for GIS outputs, particularly hardcopy
- develop recommendations for optimizing regional interaction in the use of GIS for cropping systems analysis

I hope that our united efforts will be able to generate databases and identify regions where legumes can play a greater role in the sustainability of the cereal-based cropping systems in the Asia region. I wish you a comfortable, successful, and fruitful stay here at ICRISAT. I and my colleagues will always be with you to help you update your knowledge of GIS, and use in preparing country case studies.

# Session I

## Current Software Options

# Software in Use at Cornell University

**S D DeGloria**[1]

## Introduction

The Cornell University, USA, has served as one of the pioneering institutions in the field of remote sensing, i.e., the process of detection and analysis of reflected, emitted, and transmitted electromagnetic energy to discriminate environmental features. It was in the 1930s that Cornell University (CU) began offering academic courses and extension "courses" and workshops, and conducting research in the use of aerial photography and photogrammetric methods.

The Cornell Institute for Resource Information Systems (IRIS) evolved by combining and re-organizing long-established programs in resource inventory and remote sensing from the College of Agriculture and Life Sciences and the College of Engineering. The Institute, established in the Center for the Environment (CfE) during May 1996, was formerly known as the Cornell Laboratory for Environmental Applications of Remote Sensing (CLEARS), a program affiliated to the CfE since 1984.

The mission of Cornell IRIS is to advance the characterization, understanding, and evaluation of environmental systems through the application of resource inventory, aerospace remote sensing, geographic information systems, global positioning systems, and related spatial information technologies. This mission is founded on scholarship, teaching, and public service at local, regional, and global scales. The major objectives of the program are to:

- enhance the derivation of information from maps, aerial and satellite imagery, and other remotely sensed data.
- disseminate knowledge of map and image understanding, and spatial data processing, analysis, and management.
- operate an environmental information science and technology facility for access, exchange, study, and visualization of spatial data and information.

1. Center for Resource Information Systems, Cornell University, 917 Bradfield Hall, Ithaca, NY 14853, USA.

**DeGloria, S.D. 1999.** Software in use at Cornell University. Pages 9-15 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

## Organizational structure

To accomplish these objectives, Cornell IRIS is composed of three interdisciplinary programs:

- the *Resource Inventory Program* seeks to advance map and image understanding, improve the derivation of environmental information from remotely sensed data, and implement inventory and mapping methods for communities and organizations.
- the *Remote Sensing Program* seeks to develop advanced spectral pattern recognition algorithms, evaluate and enhance spectral and spatial image classification methods, and evaluate advanced sensor systems.
- the *GIS Program* seeks to advance spatial modeling and analysis methods, assess spatial data quality, and integrate spectral and spatial models for the characterization of environmental systems.

## Audience

The primary audience of Cornell IRIS includes scientists, educators, and students at all levels of education; and professionals employed in the public and private sectors, primarily in the environmental science and management communities. The Institute's research, education, and public service activities support environmental assessment and sustainable development programs locally and globally.

## Research foci

The research program of Cornell IRIS seeks to optimize the use of remote sensing systems, GIS, and global positioning systems (GPS) to inventory and monitor environmental resources, particularly those associated with terrestrial and aquatic systems. Interdisciplinary research projects assess the distribution and diversity of environmental systems; map land-use dynamics in temperate and tropical ecosystems; model and visualize nutrient and pollutant transport at landscape scale; characterize plant stress using spectrometric methods; and develop spectral-temporal classification and mapping algorithms.

Creative contributions by Cornell IRIS include articles in scientific journals, trade journals, and newsletters; technical reports, guidebooks and technical manuals, and chapters in books; reviews of books, manuscripts, and proposals; invited presentations; analog and digital databases and archives; and videos.

In addition to its own research and teaching activities, the Institute collaborates with other research programs by offering scientific and technical support and consultation; providing access to information, instrumentation, and space; and co-authoring proposals, handbooks, scientific manuscripts, and technical reports.

## Education foci

The extension program of Cornell IRIS seeks to convey the knowledge gained in applied research projects related to the inventory, analysis, and management of environmental resources. The ultimate goal of its educational program is to sustain and enhance environmental assessment and sustainable development of communities. Cornell IRIS educates and assists technical and policy-making representatives, resource managers, and environmental professionals and educators. Current educational programs include: 1. "shortcourses" and workshops offered periodically in resource inventory, remote sensing, GIS, and global positioning systems, and 2. development of curricula, teaching materials, and laboratory- and field-based exercises for academic courses and workshops, as well as science and environmental education programs.

## Current research and outreach activity

- Inventory distribution and diversity of environmental resources; mapping of:
  - submerged aquatic vegetation (Hudson River, USA)
  - wetland vegetation dynamics (Hudson River, USA)
  - ecological communities and biological diversity (New York State, USA)
  - agricultural districts (New York State, USA)
- Map land-use dynamics in temperate and tropical ecosystems:
  - wetlands and land-use mapping (Tonawanda Creek, Niagara Frontier, USA)
  - enterprise mapping for conservation farming in tropical uplands (Philippines)
  - mapping forest fragmentation in tropical ecosystems (Costa Rica)
  - mapping land cover change in protected areas (Honduras, Costa Rica)
  - monitoring environmental impact of rural water development projects (Ghana)
- Model and visualize nutrient and pollutant transport to assess environmental impact:
  - estimation of nitrogen fate and transport (Fall Creek Watershed, New York, USA)
  - estimation of pesticide fate and transport (Canajoharie Watershed, New York, USA)
- Characterize environmental stress using spectrometric methods:
  - hyperspectral characterization of ocean color
  - spectral measurement of chlorosis in stressed vegetation
  - spectral detection of micronutrient stress in crops
- Develop and enhance curricula for formal and nonformal educators:
  - provide instruction and training to science teachers (New York State and region, USA)

- provide instruction and training to faculty and staff (Cornell University, USA)
- provide instruction and training to students (New York State, USA)
- provide instruction and training to environmental professionals (worldwide)

## Institute resources

Cornell IRIS maintains a collection of several hundred thousand aircraft- and spacecraft-derived images that features extensive and historic coverage of New York State. IRIS is also a repository for and distributor of New York topographic and wetland maps prepared by the US Geological Survey and the US Fish and Wildlife Service; New York Land Use and Natural Resource Inventory (LUNR) maps, and the official maps of New York State agricultural districts. Cornell IRIS also maintains a collection of technical publications related to remote sensing, GIS, and global positioning systems.

Technological resources include optical instruments for image analysis, GIS, laser spectroscopy, cartography, and field spectroradiometry. GIS and digital image processing are available for research projects and software development. Devices for noncomputer image analysis include zoom and nonzoom stereoscopes, monoscopic and stereoscopic transfer scopes, a color-additive viewer, and densitometers. The Institute also maintains a laser fluorosensing facility designed for analyzing water samples. Other equipment includes a diazo printer, a spectroradiometer and data logger, a thermal radiometer, underwater irradiance meter, and photographic cameras and darkroom equipment.

### GIS and image processing facilities and equipment

Cornell IRIS' GIS Program provides a shared computing resource for the Cornell community. This facility is supported by income from various grants as well as from direct university and college support. The laboratory maintains secured access 24 hours a day; normal laboratory hours are 0800-1800, daily.

The equipment and software have been installed over the last several years and represent a wide range of capabilities. The current configuration of computer hardware resources include UNIX-, Windows NT-, Windows 95-, and DOS-based systems sharing processing and data using a 100MB local area network (LAN) (Fig. 1). Internet connectivity is provided to the Cornell University backbone.

### UNIX

The UNIX system includes SUN Ultra2 (w/ 384MB RAM, 20" 24-bit monitor), SUN Sparc10 (w/ 96MB RAM, 19" 8-bit monitor), and a Sparc5 (w/ 64MB RAM, 19" 24-bit monitor) workstations. All workstations share access to approximately 48GB of disk space, an 8-mm tape drive, 150MB cartridge tape drives, CD-ROM drives, 1.2GB optical drive, and an Altek backlit digitizing tablet. Each workstation provides multi-user licensing for Arc/Info, ArcView, and ERMapper software.

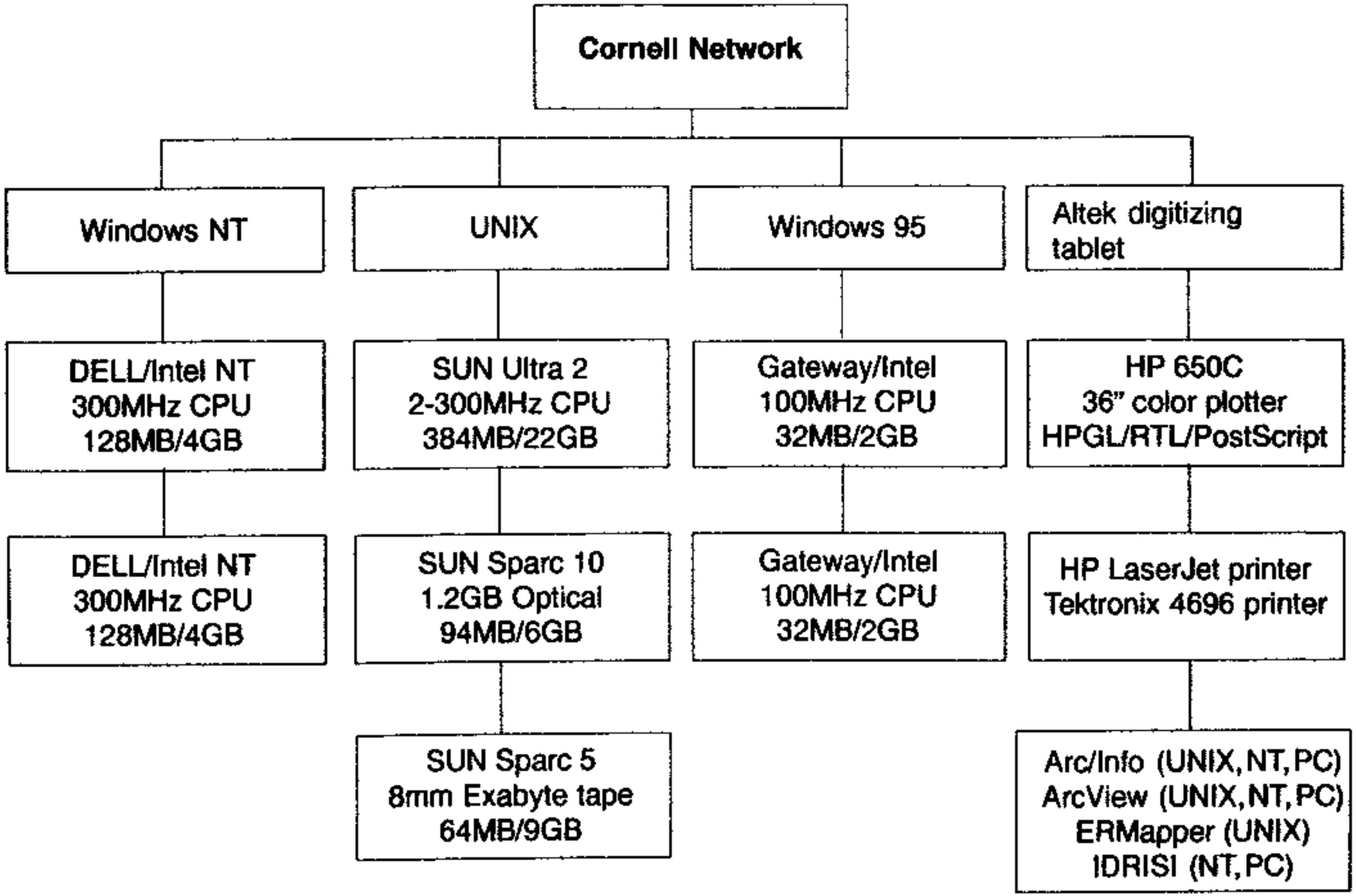


*Figure 1. Geographic information system program IRIS GIS facility, Cornell Institute for Resource Information Systems, Cornell University, USA.*

### Windows NT

The Windows NT system includes: two DELL GXPro 200MHz Pentium Pro workstations, each with 128MB RAM, 20" 24-bit monitor, 4MB video,. 4GB of SCSI disk space, CD-ROM drive, 16-bit sound, and IOMEGA JAZ cartridge drives; one DELL 300MHz Dual-processor Pentium II workstation with 128MB RAM, 21" 24-bit monitor, 8MB video, 9GB of SCSI disk space, CD-ROM drive, 16-bit sound. All systems are configured with NT Arc/Info, ArcView, Microsoft Office 97, and Exceed (for X-Window emulation). In addition, the NT version of ERMapper is installed on the Dual-processor workstation.

### Windows 95

The Windows 95 systems include two Gateway 2000 P-100 Pentium workstations each with 32MB RAM, 17" color monitor, 2GB disk space, and CD-ROM drive. Both systems are configured with Arc/Info, ArcView, Microsoft Office 95, and Exceed (for X-Window emulation). Anonymous file transfer protocol (FTP) is supported by a 486-33 Windows 95 workstation with 16MB RAM, 6GB disk space, IOMEGA Zip and JAZ cartridge drives.

All systems have access to HP LaserJet 5P and Epson LQ-510 printers. Large format (35" width, roll feed) color printing is provided with a HP DesignJet 650c. Complementing the above systems are:

- two IBM Windows 95 laptop computers with Arc/Info and ArcView
- five GTCO Rollup digitizing tablets (24" ` 20")
- four Trimble GPS units (two Pathfinder Pro, two GeoExplorer)
- four Colorado, and Zip parallel port backup devices

## Affiliated academic programs

Collaborative research and educational programs are routinely conducted with several academic units across several colleges, departments, and centers. Such units include: Colleges of Agriculture and Life Sciences, Engineering, Veterinary Medicine, and Architecture, Art, and Planning; the Center for the Environment; the Center for Theory and Simulation in Science and Engineering; and the Cornell Institute for Social and Economic Research.

Members of Cornell IRIS staff are responsible for the content and implementation of Cornell's academic program in remote sensing and geographic information systems. Remote sensing is offered as a major or minor area of concentration for a PhD, MS, MPS or ME degree in the Graduate Field of Civil and Environmental Engineering. The use of remote sensing, geographic information systems, and global positioning systems for spatial modeling and analysis of environmental systems is offered through the Environmental Information Science and Soil Science concentrations in the Graduate Field of Soil, Crop, and Atmospheric Sciences. Several undergraduate and graduate academic courses in remote sensing and GIS are offered by faculty affiliated with IRIS.

## Funding

IRIS receives core funding support for non-faculty academic salaries and operations from the College of Agriculture and Life Sciences. Rice Hall in the College of Agriculture and Life Sciences and the College of Engineering provide laboratory and office space for IRIS. The Department of Soil, Crop, and Atmospheric Sciences provides space and partial administrative support in Emerson Hall, and maintains the Bradfield Environmental Computing Classroom for academic teaching, extension and outreach, and research in environmental science. Support for research and extension projects comes from a variety of sponsored projects from several Federal and State agencies, and units of local government.

# Software in Use at CIAT

**G Hyman**[1]

An efficient and functional GIS laboratory has an infrastructure strong in both human resources and software and hardware resources that are capable of addressing the needs of the parent organization. Many GIS specialists report that as much as 80% or more of the cost of starting a GIS project can be attributed to the development of human resources in the form of training and labor costs, and to the processing of information needed for analyses. Although the selection and configuration of hardware and software are not likely to be the key determinants of the success of a GIS operation, they can certainly be the source of failure if they are not carefully considered in the design of the laboratory. The ultimate criteria for the design of a GIS facility should be how well the infrastructure will address the need to map and analyze agricultural systems and other aspects of the environment related to the organization's needs. The purpose of this short paper is to share perspectives of CIAT's experience in the design and configuration of GIS software and hardware for our GIS laboratory.

The Centro Internacional de Agricultura Tropical (CIAT—International Center for Tropical Agriculture), Cali, Colombia, and most other international agricultural research centers have been using geographic analysis technology since the founding of the CGIAR system. Computers have changed the way we analyze the spatial dimensions of crop production, natural resources, and genetic resources. We have progressed from interpretation and cartographic manipulation of paper maps through basic raster systems, to the now more complicated GIS packages that have sophisticated analysis capabilities. A common mistake is to assume that a sophisticated and high technology hardware and software configuration will translate into improved analysis and insight. Sometimes the opposite occurs, because we get mired in the complexities of the software and hardware when we should be focusing our attention on the agricultural problem and the best way to solve it.

Any hardware configuration must take into account project needs, staff size, software trends, and other considerations. Perhaps the most important consideration is the selection of the operating system. Most new GIS software development is targeted to networked PC systems. Windows NT is increasingly the platform of choice for software developers and GIS users. Networked PC systems also have the

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**Hyman, G. 1999.** Software in use at CIAT. Pages 16-18 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

advantage of being less expensive than building a UNIX-based workstation or minicomputer systems. Large GIS laboratories, however, will likely need the power of UNIX-based hardware systems. As CIAT has been developing large climate, administrative divisions, population, census and crop databases, it would be difficult for the Center to convert to networked PCs exclusively. Many GIS experts believe that for a large operation, the PC technology needs improvement and I believe this has been our experience at CIAT.

Almost all GIS operations will need both raster and vector software capability. The general rule in planning software needs has been to use vector systems for data development and storage and raster systems for analysis and modeling. This approach is changing as vector analysis capabilities improve and as new data structures are developed. Vector systems are more efficient for data input, editing, and storage because they hold information for the geographic features where they occur. Raster systems hold information for grid cells throughout the entire area of interest whether each individual cell is a geographic feature or not. A great majority of GIS analyses and modeling is carried out with raster systems. The cellular grid structure is suited to overlay, flow, neighborhood, and other analyses because it is relatively simple and easy to implement when compared to vector systems. A smart hardware configuration will address the need for both raster and vector utilities and will have efficient programs for conversion between the two systems.

A clear trend in GIS development is the use of non-GIS software in the development of a laboratory. Figure 1 show the types of non-GIS software that are part of the CIAT facility. Most systems have always used some database software for management of tabular or attribute data. Using the organization's standard database software as the manager of tabular GIS data is usually a sound strategy. Some GIS software packages may not be able to handle an organization's standard database software. In this case, data conversion capabilities will be needed. At CIAT, we have also taken advantage of our center-wide statistical software package for analysis of tabular data linked to digital maps.

One disadvantage of standard statistical analysis software packages is the lack of spatial statistics capabilities. Many GIS packages are lacking in their capability to perform spatial interpolation, spatial regression, and other distinctly spatial statistical analyses. The need for these types of specialized capabilities should be analyzed in the context of the type of analyses that will be carried out.

Other mathematical and specialized software can add to the capacity for geographic analysis. CIAT is experimenting with the use of neural networks for classification problems and other analyses. These types of tools have not yet proved to be widely applicable, but may prove useful for specialized tasks. GIS visualization software can help researchers interpret geographic information in a more efficient manner. Specialized visualization software should be considered for sharing the results of CIAT's research with its partners and stakeholders.

Remote sensing capability is needed by most GIS laboratories focused on agricultural problems and natural resources management. Some laboratories may be able to outsource this work. Some GIS packages like IDRISI and Arc/Info have image

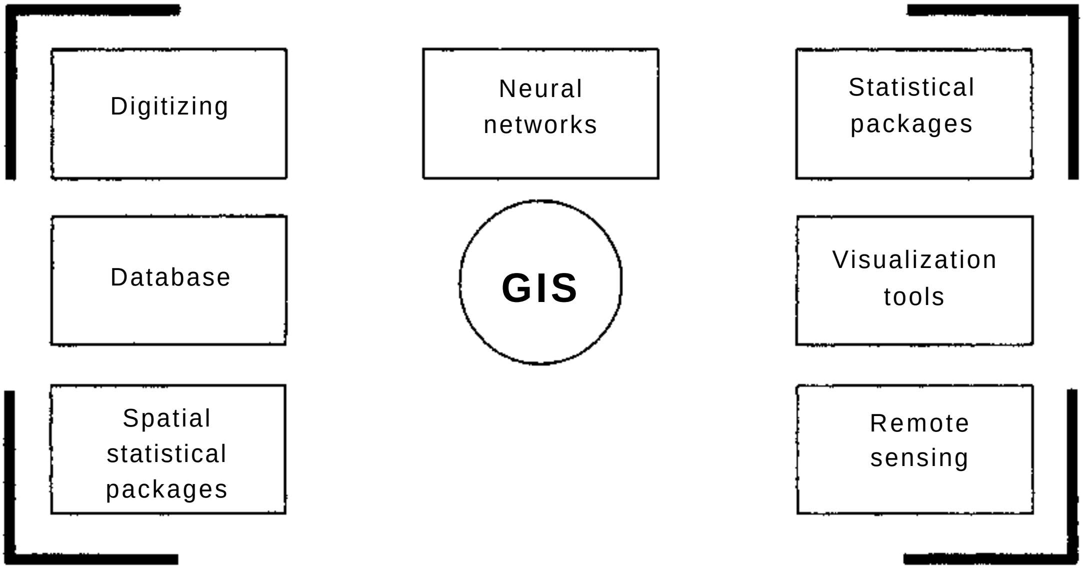


*Figure 1. Software used in relation to GIS at CIAT.*

processing capability. In other cases, the organization will need the capacity of high-end remote sensing packages. The need for remote sensing software will often depend on the scale of analyses. Broad-scale analyses of land cover may be difficult for small GIS labs. Remote sensing analysis of reference sites could easily be accomplished with basic image processing software.

# GIS Capacities and Activities at CIMMYT

**J W White[1]**

The development of GIS capabilities at the Centro International de Mejoramiento de Maiz y Trigo (CIMMYT—International Center for the Improvement of Maize and Wheat), Mexico, is founded on the principle that the Center should maintain a "credible mass" and not develop a major center for agricultural applications of GIS. CIMMYT requires in-house capabilities to apply GIS to maize and wheat research but just as importantly, the Center should be able to participate effectively in regional fora and in developing collaborations with national agricultural research systems (NARS) and other institutions. Underlying this strategy is the belief that GIS is such a large and fast-evolving field, that the Center is better advised to seek strategic alliances rather than trying to satisfy all maize- or wheat-related GIS needs internally.

Activities of CIMMYT's GIS/Modeling Laboratory are divided between supporting the Maize and Wheat programs in such areas as revision of their crop "mega-environments," and participating in the research activities of the Natural Resources Group, where the GIS/Modeling Laboratory is housed. Examples of ongoing research projects include developing methods for interfacing GIS and crop simulation models and characterizing wheat production environments of the Andean region. Major support projects for the Programs include revision of the maize and wheat mega-environment classifications and a detailed study of sub-Saharan maize production regions. We also process numerous requests for minor support in project proposal preparation, generation of crop distribution maps, and similar activities.

Awareness building is also a challenge. Researchers at CIMMYT are very interested in GIS, and there is a need to assist them in making efficient use of GIS. Our first step is to provide a one-day introduction to GIS in the context of CIMMYT's research needs. We expect to follow this with instruction in the use of simple GIS tools, but it is unclear whether we should start with ArcView or the simpler, ArcExplorer.

Recognizing our limited in-house capability, we rely on outside collaboration and on secondary data sources. Collaborators have included the Centro Internacional de Agricultura Tropical (CIAT), the Integrated Information Management Laboratory (IIML) of Texas A & M University, USA, and the Global Resource Information Data

1. Centro International de Mejoramiento de Maiz y Trigo (CIMMYT), Lisboa 27, P.O. Box 6-641, 06600 Mexico, D.F. Mexico.

**White, J.W. 1999.** GIS capacities and activities at CIMMYT. Pages 19-21 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

(GRID)-Arendal. As our laboratory gains experience, we expect to extend these links to a broader range of institutions.

Our laboratory has a single UNIX workstation and five PCs including a Windows NT file server. The main group of software we use is the line of Environmental Science Research Institute (ESRI) products including Arc/Info and ArcView. The other packages used occasionally include Surfer and IDRISI (DOS and Windows versions). We are in the process of evaluating various packages for spatial interpolation including ANUSPLINE (Hutchinson 1995). The cost of maintaining the only UNIX system within CIMMYT has been high, so we are also studying the option of migrating our workstation operations to an NT workstation.

Although many scientists and NARS collaborators express interest in using GIS, we have serious doubts whether "simple" GIS software such as ArcView will be cost-effective. Thus, we are exploring approaches for providing GIS or map viewing functions with lower-cost software such as MapObjects, MapObjects LT and ArcExplorer (all products from ESRI, Inc.). The former two packages require interfaces written in Visual Basic or similar languages and seem best suited for linking to databases such as the International Crop Information System (ICIS) and the Sustainable Farming Systems Database (SFSD). ArcExplorer is essentially a map viewing tool and would allow us to distribute large sets of maps in electronic format, either as compact disks (CD-ROM) or via the Internet.

Another approach to make GIS more useful is to develop tools that a scientist can use together with a GIS specialist to conduct common types of queries of spatial data. The Spatial Characterization Tool (SCT) developed by John Corbett and associates at Texas A & M permits users to query climate, soil or other gridded surfaces to define zones that are similar to a given point set of data or zones that fall within a user-specified range of values. The SCT is written in Arc/Info Arc Macro Language (AML) for UNIX workstations, but the system is being ported to Windows NT, which will make it more accessible.

For GIS tools to be used effectively, users, whether in NARS, non-governmental organizations (NGOs) or in the Consultative Group on International Agricultural Research (CGIAR) Centers, will require access to large sets of spatially referenced data. Such data will become increasingly available over the Internet, but it is unrealistic to assume that individual researchers will have the time to search for all relevant data. Thus, CIMMYT may need to serve a data organizing and re-distribution function. We have already produced a compact disk of soil and weather data for CIMMYT staff in sub-Saharan Africa and are collaborating with Texas A & M University in the production of "Country Almanacs" that combine diverse sets of spatially referenced data with map viewing tools programmed with MapObjects.

Developing capacity to interface GIS with crop models is a priority for CIMMYT since this will permit the combined investigation of spatial and temporal trends in production. To minimize the time dedicated to re-programming GIS interfaces, we prefer to use standard model and input and output formats, as evolved out of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) concept of "minimum datasets" and now being promoted by the International Consortium for Agricultural Systems Applications (ICASA) (Ritchie 1995). Two tools for linking GIS to models are currently under review. One is AEGIS/WIN (Engel and Jones 1997), which is written in the Avenue macro language of ArcView. The other is the Mapping and GIS Analysis Tool of DSSAT 3.1 (Thornton et al. 1997). This tool links to GIS through file exchange and can be used with various GIS file formats.

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# Software in Use at NBSS & LUP

**A K Maji**[1]

## Introduction

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India, was established in the year 1976. It is a premier institution of the Indian Council of Agricultural Research (ICAR), New Delhi, India. The objectives of NBSS&LUP are to prepare soil resource maps at national, state, and district levels and to provide research inputs in soil resource mapping, soil correlation and classification, soil genesis (including soil mineralogy and soil micromorphology), remote sensing applications, land evaluation, land-use planning, land resource management, and database management using GIS to optimize land use. These activities are carried out at six regional centers located at Bangalore, Calcutta, Jorhat, Nagpur, New Delhi, and Udaipur. The Bureau maps agro-ecological and soil degradation at the country and state levels to assess and monitor soil health as a guide to viable land-use planning. These research activities whose ultimate objective is sustainable agriculture development have resulted in the identification of soil potential and problems. The Bureau has the mandate to correlate and classify Indian soils and to maintain a National Register of all established soils series. The institution provides in-service training to staff of the soil survey agencies in soil survey interpretation and land evaluation for land-use planning.

## GIS at NBSS & LUP

The need for a computer-based GIS to manage soil and land resource data was felt essential as early as 1987. As a first step, NBSS&LUP scientists were sent for training to UK and USA. In 1989, a modest PC-based GIS with SPANS Version 4 software was obtained from the Natural Resources Institute (NRI), UK. This was the beginning of application of GIS in soil resource management at NBSS&LUP. At present, the Bureau has a Pentium PC-based GIS system with digitizer, plotters, printers, etc.

1. National Bureau of Soil Survey and Land Use Planning (Indian Council of Agricultural Research), Nagpur 440 010, Mahrashtra, India.

**Maji, A.K. 1999.** Software in use at NBSS & LUP. Pages 22-24 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

## Activities using GIS

The NBSS&LUP, being the nodal agency of the country in soil resource inventory, and management uses GIS to maintain and characterize a huge volume of data every year. Major GIS activities include:

- creating and updating the soil resource database (spatial and nonspatial)
- spatial modeling for interpretative results
- land use/land cover mapping
- landscape ecological studies
- studies on assessment land degradation
- agro-ecological zoning
- thematic mapping
- harmonization of datasets for interpretation
- information dissemination for district-level planning
- development of expert systems for land evaluation and land-use planning
- design and development for suitable database management systems

To further the goals and mandate of the Bureau, the National Soil Resource Information Center (NASRIC) has been created. This will be the first soil resource database in India based on thorough ground truthing and intensive soil survey work. The newly established Agricultural Research Information System (ARIS) Cell of ICAR will also benefit from the NBSS&LUP database and GIS laboratory.

## GIS packages

The NBSS&LUP has a host of GIS packages that are being used to accomplish the activities listed earlier. Some of them are also used for training and teaching. The GIS software available at NBSS&LUP are:

| *Software* | *Source* | *Platform* |
|---|---|---|
| SPANS Ver 5.1 | Intra Tydac, Canada | (PC-based) DOS |
| SPANS Explorer | Intra Tydac, Canada | (PC-based) Windows |
| PAMAP Ver 4.0 | PAMAP Graphics, Canada | (PC-based) Windows |
| IDRISI Ver 4.0 | Clarke University, USA | (PC-based) DOS |
| ILWIS Ver 4.1 | ITC, The Netherlands | (PC-based) DOS |

Some of the above software are now being upgraded to latest versions.

## Future of GIS at NBSS & LUP

NBSS&LUP has plans to establish an advanced workstation-based GIS laboratory with better map printing/map generation facilities. It has been proposed under the National Agricultural Technological Plan (NATP) to acquire a highend workstation compatible for GIS with a large working memory and bigger data storage capacity. The software front is also proposed to be enriched with an advanced image analysis system and GIS.

# Software in Use at ICRISAT

**F T Bantilan Jr**[1]

The GIS software in use at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, since 1991, when GIS was first introduced, has been vector- and PC-based. The sharp definition of geographic features that is possible with vector-based systems is an attractive feature contributing to their wide use. It is well suited to dealing with phenomenologically structured data (e.g., soil areas, land-use units, etc.) and network analyses (telephone or transport network).

However, a raster-based system is more suitable for dealing with continuously varying variables such as temperature, rainfall, elevation, etc., that are variables dealt with in agriculture applications. Useful datasets available from other CGIAR centers and other institutions are often in a raster format. Most applications of GIS require a unified environment for vector and raster processing. The foregoing reasons were the motivation for the recent acquisition of a Unix workstation machine with a corresponding software system that can deal with both raster and vector data structures.

## Software

A list of software in use at ICRISAT includes:

### *GIS software*

- Arc/Info 3.4.2 (PC)
- ArcView 2.0 (PC)
- Arc/Info 7.01 (Unix Workstation)
- ArcView 3.0 (Unix Workstation)
- Integrated Land and Water Information System (ILWIS)
- IDRISI for Windows 2.0

1. GIS Unit, ICRISAT-Patancheru 502 324, Andhra Pradesh, India.

ICRISAT Conference Paper no. CP 1377.

**Bantilan, F.T., Jr 1998.** Software in use at ICRISAT. Pages 25-26 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T, Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

***Database software***

- FoxPro
- Access

## Ongoing applications

The ongoing applications of GIS at ICRISAT are:

- delineation of production systems in southern and eastern Africa using the FAO Length of Growing Period and Digital Elevation Model
- characterization of production systems in southern and Eastern Africa using the continental datasets in the Spatial Characterization Tool CD-ROM from Texas A & M University, USA
- relating area and yields of major legumes (including grain, oilseed, forage, and green manure legumes) and their trends, to influence of factors of the physical environment, biotic stresses, alternative cropping options and socioeconomic considerations in order to determine prospects for increased use and production of these legumes in rice and/or wheat cropping systems of the Indo-Gangetic Plain
- estimation of spillover effects of sorghum germplasm and parental materials using the FAO Agro Ecological Zones (AEZ).

asm mapping of wild relatives of groundnut in Latin America in relation to climate, in order to assess gaps in collections and to understand the basis of distribution of diversity

- mapping of potential areas for peanut clump virus disease and identifying high-risk areas in the peanut-growing regions of India, based on pedoclimatic characteristics of the survey points.

# Software in Use at ICIMOD

**B Bajracharya**[1]

The Mountain Environment and Natural Resources Information Service (MENRIS) at the International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, has been working for the dissemination of GIS and remote sensing technology in the Hindu-Kush Himalaya (HKH) region. Its major activities are: 1. capacity building of the national institutions of the regional member countries through training, hardware, and software support; 2. building a digital database of HKH at district level; and 3. conducting case studies for the application of GIS/ remote sensing (RS) to mountain-specific issues.

The main GIS and image processing software in use at MENRIS/ICIMOD are:

- Arc/Info 7.0.3 Unix version
- Arc/Info 3.5 (PC)
- ArcView 3.0
- Earth Resources Digital Analysis Software (ERDAS) PC 7.5
- ERDAS Imagine 8.0 for Windows 95
- Integrated Land and Water Information System (ILWIS) 1.4 DOS Version
- ILWIS 2.0 for Windows
- IDRISI Version 4.0 for DOS
- IDRISI Version 2.0 for Windows

MENRIS is in the process of acquiring the Spatial Analyst and Network Analyst extensions of ArcView GIS. It is using Arc Explorer, a free software from the Environmental Systems Research Institute (ESRI) that can be downloaded from the internet to train policymakers. Another software, MapObjects, obtained from ESRI is used to develop a computer-based training (CBT) program on GIS. Through special arrangements with ESRI and United Nations Environment Programme-Global Resource Information Database (UNEP-GRID), Bangkok, Thailand, ICIMOD has been facilitating the distribution of ESRI software at special UN prices to its collaborating institutions.

1. International Centre for Integrated Mountain Development (ICIMOD), PO Box 3226, Kathmandu, Nepal.

**Bajracharya, B. 1999.** Software in use at ICIMOD. Pages 27-28 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

The hardware used for GIS and remote sensing (RS) at MENRIS are:

- IBM RISC 6000 3 BT servers
- IBM 43P workstations
- Pentium PCs with 32 to 64 MB RAM
- Computer compatible tape (CCT), Exabyte, optical drivers, zip drives and a CD writer for data backup.

# Session II

## Environmental, Agricultural Production, and Socioeconomic Databases

# Climate and Soil Surfaces

**J W White[1], J Corbett[2], and G Coutu[2]**

Climatic and edaphic conditions are primary determinants of crop production. They affect crop species both directly and through influences on agronomic practices, diseases, pests, and weeds, and socioeconomic factors; Thus any attempt to examine spatial variation in crop production or of impacts of production must consider the effects of climate and soil.

Traditionally, spatial variation in climatic and edaphic data have been presented through maps. To reduce the potential number of maps and facilitate interpretation, the information was often summarized as agroclimatic zones or soil groups. GIS offers tools for manipulating and presenting such data in a more dynamic and quantitative manner. Zones or groups may be defined for a specific set of crop or system-dependent criteria. And the data may be coupled with such other tools as crop models, to improve the accuracy and scope of the analyses.

Climatic and edaphic data can be represented in GIS systems using both raster (grid) and vector (polygon) formats. However, since such data usually show continuous variation, raster formats are preferred. For example, total precipitation, mean maximum temperature or surface soil pH may be represented as a raster surface where each cell is assigned a value equal to the mean value for that map unit (Fig 1).

Source data usually come from measurements at specific points, such as weather stations or soil sample locations. Thus, surfaces have to be created by interpolating point data over the study area. There is still considerable controversy concerning the best approach for interpolation. Simple methods such as minimum curvature and inverse-distance-squared weighting may be adequate for relatively uniform areas with high density of source data. However, for the more complex situations that are typical of agricultural systems, co-kriging (Kitanidis 1997), thin plate splines (Hutchinson 1989, 1995) or other methods of geostatistics are preferred. These allow auxiliary data to be used to further improve interpolations, and some methods produce estimates of interpolation error.

1. Centro International de Mejoramiento de Maiz y Trigo (CIMMYT), Lisboa 27, PO Box 6-641, 06600 Mexico, D.F. Mexico.

2. Texas A & M University, College Station, Texas 77843-2475, USA.

**White, J.W., Corbett, J., and Coutu, G. 1999.** Climate and soil surfaces. Pages 31-36 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18—19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

Since elevation often has strong relations with temperature, precipitation, and solar radiation (Fig. 2), elevation is the "covariate" most commonly used to improve interpolations of climatic data within a region. Data for elevation are obtained from digital elevation models (DEMs) such as GTOPO30, that provide elevation data on a 30 arc-second (approximately 1 km) grid (Anonymous 1997). In generating surfaces at the regional or continental level, problems have been noted in detecting rain shadows and accounting for effects of large bodies of water. These might be overcome with additional covariates such as wind-direction and distance from coastlines. Alternative approaches include using neural networks (Elizondo et al. 1994) or more complex weather models (Daly et al. 1994).

Interpolating soil traits is more problematic since they are influenced by parent material, climate, and processes of deposition and erosion. Under the SOTER project, efforts are underway to use DEMs and remote sensing to improve regional soil mapping (Baumgardner 1995).

For the rice-wheat region, the only climate surfaces available appear to be those recently developed by the International Irrigation Management Institute (IIMI) and the University of Utah (Fig. 1). These surfaces were based on the World Meteorological Organization (WMO) data and other sources, and were interpolated on a 2.5 km grid. They include both basic weather parameters and derived variables such as potential evapotranspiration. The developers of these surfaces recognize that these are preliminary surfaces and welcome other researchers to participate in efforts to improve the surfaces (D. Molton, IIMI, personal communication). The GTOPO30 DEM (Anonymous 1997) may also be used to produce regional surfaces with a finer grid size (approximately 1 km).

Although detailed soil maps (1:250,000 or 1:50,000) are available for most of the Indo-Gangetic Plain region, these are not in digitized formats. The main regional map that can be used in CIS is the FAO 1:5,000,000 map. Besides identifying soil groups, these have semi-quantitative data on depth, water holding capacity, texture, pH, and other traits that are more directly applicable to models.

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**Baumgardner, M.F. 1995.** Toward soil spatial information systems (SSIS) for global modeling and ecosystems management. Annual report - Year 2. NASA Grant No: NAGW-3862. USA: Purdue University.

**Daly, C., Neilson, R.P., and Phillips, D.L. 1994.** A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33:140-158.

**Elizondo, D., Hoogenboom, G., and McClendon, R.W. 1994.** Development of a neural network model to predict daily solar radiation. Agricultural and Forest Meteorology 71:115-132.

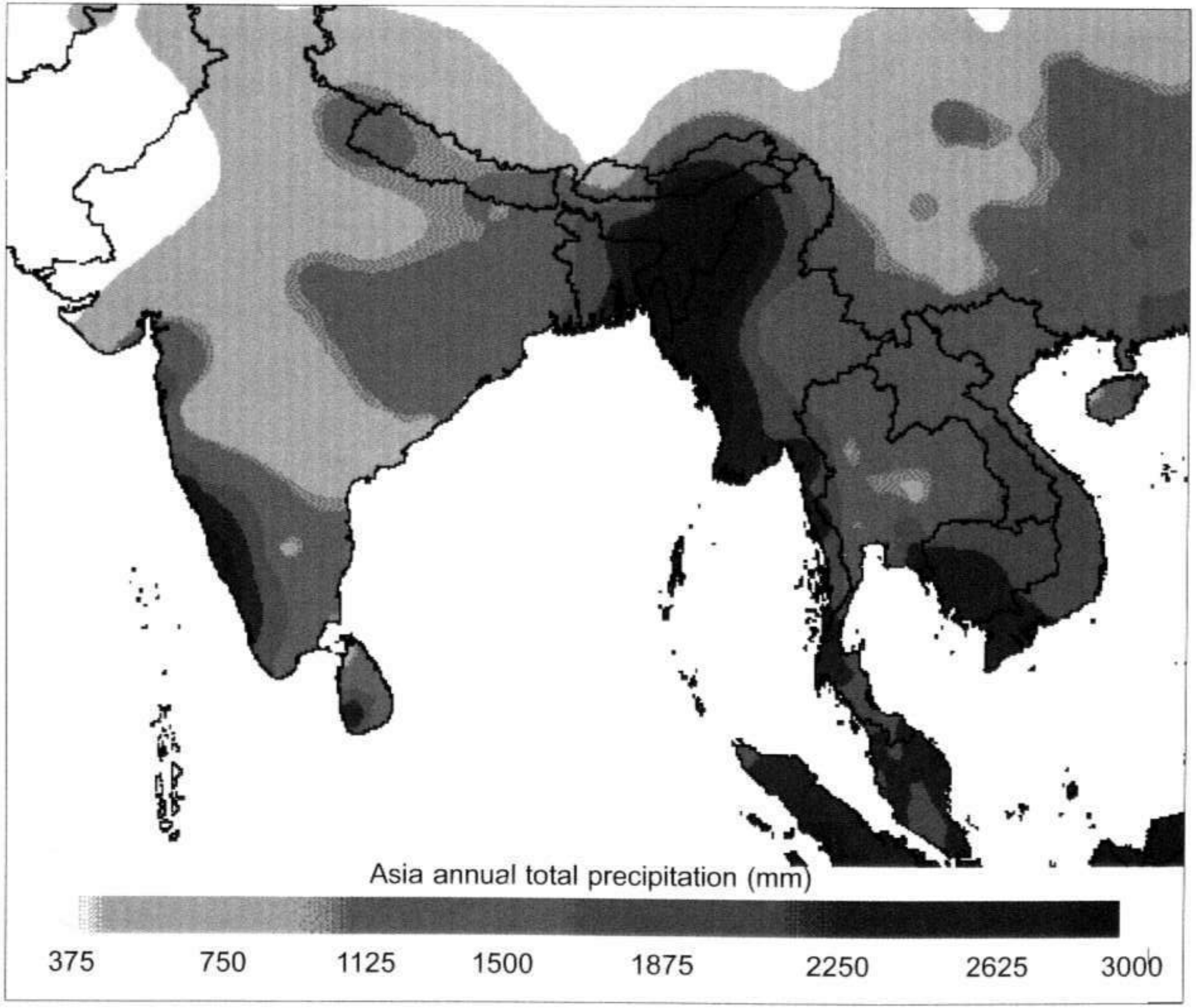


Figure 1. Annual total precipitation for the rice-wheat region. Source: IIMI World Water and Climate Atlas (IIMI 1997).

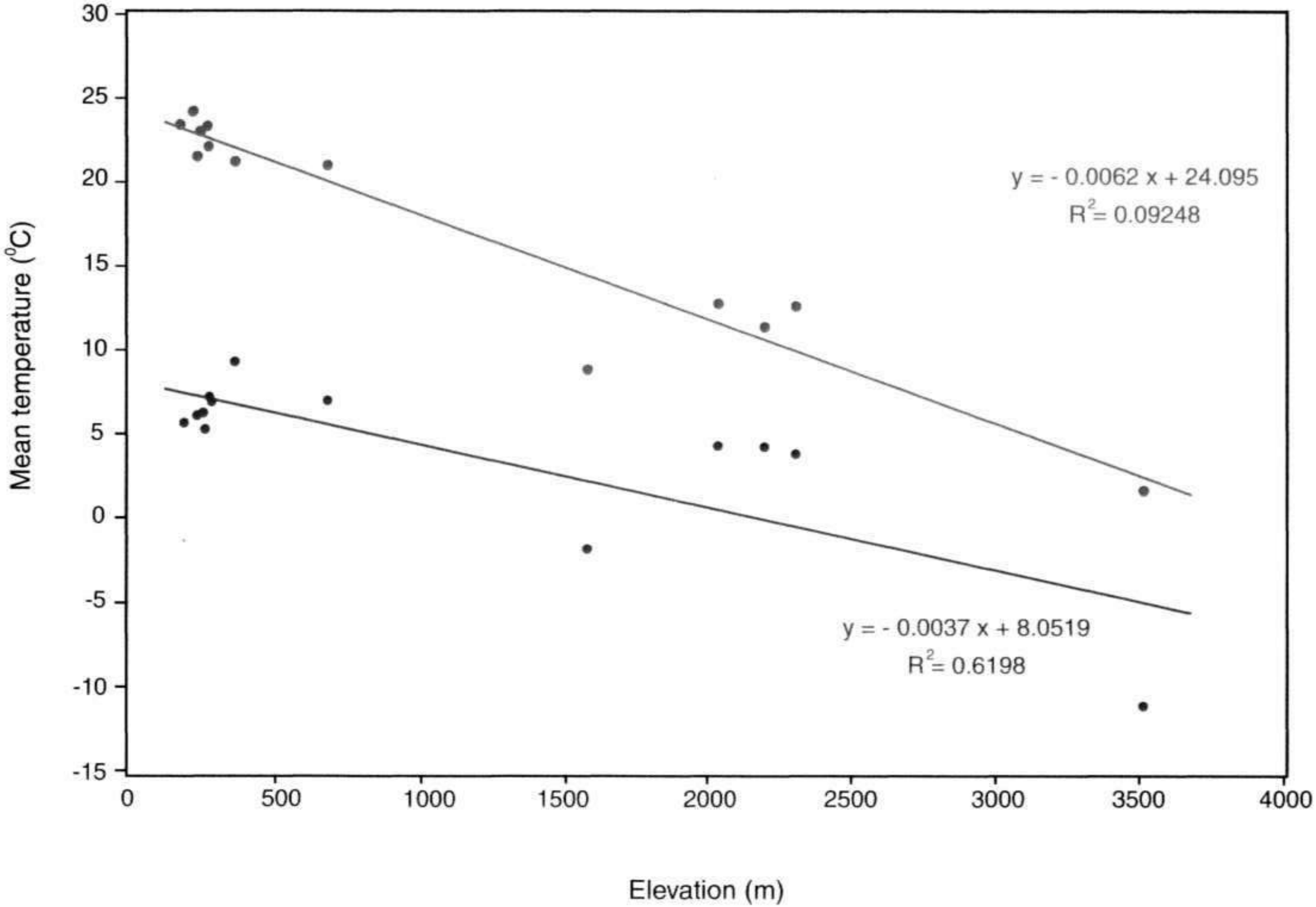


*Figure 2. Relation between mean daily maximum and minimum temperatures and elevation for locations in northern India.*

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**Hutchinson, M.F. 1995.** Interpolating mean rainfall using thin plate smoothing splines. International Journal of GIS 106:211-232.

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# GIS Database for Mountain Agriculture

**B Bajracharya**[1]

## Background

The mountain areas of the Hindu-Kush Himalaya (HKH) region present great challenges to the efforts of development. The socio-ecological diversity, marginality, and fragile ecosystems of the mountains make the issues of sustainable development, environmental sustainability, and economic growth more difficult. The region sustains over 150 million people. Further, it affects the lives of more than three times that number in the plains and river basins of South Asia. The rapidly increasing mountain population is adding to the poverty and illiteracy problems in the region. These problems are strongly related to agriculture, forestry, livestock, urbanization infrastructure, and a host of other interlinked issues. There are issues involving food and forest production, marketing and manufacturing, and maintenance of sustainable production systems, and locally specific issues of farmers struggling to make a living amidst scarce resources.

The International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, works mainly at the interface between research and development, and acts as a facilitator for generating new mountain-specific knowledge of relevance to mountain development. With the primary objective of helping promote the development of an economically and environmentally sound mountain ecosystem and improving the living standards of mountain populations in the HKH region, ICIMOD attempts to ensure that new knowledge is shared among all relevant institutions, organizations, and individuals in the region.

## Importance of agricultural development

Over two-thirds of the population in the HKH are dependent on farming as their primary source of livelihood. Hence, the task of overcoming poverty and improving the well-being of mountain people must begin by addressing the problems of mountain agriculture. The millions of small mountain farms must be seen as a focal point of problems and also opportunities in sustainable mountain development.

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1. Mountain Environment and Natural Resources' Information Service (MENRIS), International Centre for Integrated Mountain Development (ICIMOD), PO Box 3226, Kathmandu, Nepal

**Bajracharya, B. 1999.** GIS database for mountain agriculture. Pages 37-44 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

The need for primary focus on agriculture is also valid in the plains of the developing countries in the region. The decisive factor for development lies in the improvement of the socioeconomic conditions in rural areas where the majority of the population lives and whose main occupation is agriculture (APO 1997). Almost all the rural development programs in this region specifically aim to raise farm productivity, with additional objectives of generating employment opportunities and providing adequate housing, schooling, and health facilities.

## Need for an integrated approach

There has been a general lack of understanding of the natural and human processes affecting these mountains in the past. The development interventions that were designed were often sectoral in nature and mainly addressed the symptoms rather than the causes of the problem. The available data on resources and environment are generally dispersed among many agencies and cannot be compiled efficiently for multisectoral, problem-oriented analysis. What is now needed is an integrated approach to sustainable development that reconciles the economic needs and aspirations of the people with the requirements for maintaining biological productivity and ecological balance.

### GIS as a tool for integration

Advances in computer and communications technology have presented a unique opportunity for planners and decision-makers to apply specific systems and techniques to address the issues of rural development in an integrated manner (APO 1997). GIS, remote sensing, and global positioning systems (the 3-S technology) are evolving as efficient tools that integrate biophysical and socioeconomic data which can be used to develop alternative strategies to address complex and multidimensional problems. Advances in satellite image processing and computer analysis have made it possible to evolve a realistic, accurate, and uniform database to facilitate the decision-making process.

### Database as a foundation to a successful GIS

GIS is a computer-based system capable of holding and using data describing places on the earth's surface. A strong database is the key to its successful application. It is characterized by two forms of data: 1. attribute data, statistics or textual, and 2. geographical information, spatial or locational data (FAO 1988). Through analysis of these two types of data using GIS techniques, it has now become possible to more effectively answer questions like 'where?', 'what?' and 'what if?'

## Database design concepts

A successful database is one that provides the principal users and stakeholders with the information they need to make sound and timely decisions and in a format the principal users can understand and manipulate (Lund 1994). A good design from the very beginning is necessary for developing a successful database. Database design is a structured decision-making process about organization of geographic and attribute data in a GIS. Design allows the database to be viewed in its entirety and evaluation of how various aspects of the database need to interact. It allows for the early identification of major issues, potential problems, and design alternatives (ESRI 1991).

## Special aspects of GIS databases

The use of location as a special kind of key in a GIS is the major conceptual difference from conventional database systems. Since the spatial data represent the features of a real world, there are issues of appropriate projections and coordinate systems to be dealt with. Accuracy, precision, and timeliness are among the various questions that arise during implementation of GIS as we have to rely on old maps and secondary data which were designed in a totally different framework.

Designing a database for GIS application should have a broader perspective than the traditional management information system (MIS). The design process of a database has several steps (ESRI 1991). Any database should be designed with the user in mind. The needs of users inside the organization and the potential users outside should be assessed before beginning the design process. Strong management, and user support and involvement is necessary for a useful and practical design (Lund 1994). Data availability needs to be assessed and the data sources, issues related to data acquisition, scale, accuracy, and cost should also be resolved. The system should be implemented over a specified area to test for functionality, performance, and flexibility before real implementation. The need for major changes in the structure may be realized while dealing with the real-life problems during the pilot study.

The final system should be able to meet the expectations put forward by the users during the needs assessment. However, the system should be flexible enough to make some minor changes as may be required in the course of time. Open-ended systems that offer possibilities for future expansion are more sustainable (McCloy 1995).

## Case studies for GIS applications in agriculture

The Mountain Environment and Natural Resources' Information Service (MENRIS) at ICIMOD was established in 1990 as a resource center for the HKH region for the study and application of GIS technology. Since then, it has focused its activities on training and capacity-building for application of GIS and remote sensing (RS), establishment of a digital HKH database for institutional networking, and computer applications and development.

MENRIS has carried out a number of case studies with specific focus on the mountain areas. Two of its recent case studies are related to the application of GIS/RS to mountain agriculture: "Application of GIS for Planning Agricultural Development in the Gorkha District" and "Lamjung District Information System for Local Planning and Assessment of Natural Resources Using GIS and RS Technology". Both studies are supported by Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ), the German agency for technical cooperation. Some of the approaches and findings of the Lamjung study are presented here as an example of GIS database development and its application to the real world situation.

## The Lamjung Case Study

The scope of the project was to build up a district information system that would enable the decision-makers in Lamjung District and the GTZ-supported project, and its project partners to better visualize existing natural and infrastructural situations, integrate natural science and socioeconomic data, and use the information thus gained for improved area-specific planning, and monitoring of programs and natural resources (Trapp 1995; Trapp and Mool 1996).

### Database design and development

The information system is based on primary as well as secondary data (Tables 1 and 2). There are two principal divisions in the group of primary information layers:

- information on natural resources and land use, retrieved from maps published by the Land Resource Mapping Project (LRMP 1986), the "One Inch" topographical maps of the Indian Survey (IS), and two sets of satellite imagery of Feb 1984 (Landsat MSS) and May 1994 (Landsat TM).

**Table 1. Lamjung District Information System: baseline data layers.**

| Data layer | Map scale/ resolution | Source |
|---|---|---|
| Lamjung District boundary | 1:50,000 | LRMP 1986 |
| Drainage system (rivers) | 1:63,360 | One Inch (IS 1960) |
| Elevation contours in 500-foot intervals and spot heights | 1:63,360 | One Inch (IS 1960) |
| Land utilization in 1979 | 1:50,000 | LRMP 1986 |
| Land utilization in 1960 | 1:63,360 | One Inch (IS 1960) |
| Satellite imagery | 80m | Landsat MSS, 3 Feb 1984 |
| Satellite imagery | 30m | Landsat TM, 13 May 1994 |
| Land capability in 1979 | 1:50,000 | LRMP 1986 |
| Land systems | 1:50,000 | LRMP 1986 |
| Ecology and ecological zones | 1:250,000 | after Dobremez et al. 1970-81 |
| Meteorological data of stations in central and western Nepal | | HMG Nepal 1966-86 |
| Road and trail network | 1:125,000 | Central Service Map, SBD 1989 |
| Bridges and fords | 1:125,000 | Central Service Map, SBD 1989 |
| Village Development Centre boundaries | 1:20,000 | HMG Nepal 1989 |
| | 1:50,000 | One Inch (IS 1958-62) |
| Settlement locations | 1:63,360 | One Inch (IS 1960); field survey |

**Table 2. Lamjung District Information System: settlement database.**

| Item | | Parameters |
|---|---|---|
| 1. | Households and population | men/women, caste/ethnicity, landholding, age |
| 2. | Food sufficiency | number of months |
| 3. | Employment | number of months and where |
| 4. | Education/schools | boys/girls attending school: school type |
| 5. | Services | agriculture, health, post office, bazaar, police |
| 6. | Distance to services | in miles and hours |
| 7. | People trained | agriculture, health/cottage industry, masonry |
| 8. | Livestock | types, number |
| 9. | Land use | type, agriculture, crop production |
| 10. | Community forestry | location, size, user group, management plan |
| 11. | Grazing area of sheep | winter/summer, other district |
| 12. | Nurseries | type (fruit, forest, vegetable), year, ownership |
| 13. | Landslides | location, year, area affected |
| 14. | Drinking water facilities | source, schemes, cost, status |
| 15. | Irrigation facilities | source, schemes, cost, status |
| 16. | Cottage industries | type, number |
| 17. | Development agencies | NGO, year, number of households, sector |

- information on population figures and other socioeconomic data, compiled from the National Census 1991 and from a settlement level baseline survey covering 1110 settlements conducted by Rural Development through Self-help Promotion, Lamjung, in 1995 in collaboration with the District Development Centers (DDC), Lamjung, and the Village Development Centers (VDC).

This information was then applied to acquire more knowledge by creating secondary layers, e.g., on the topography (aspect, slope gradient), elevation zones, climate (temperature and moisture regimes), agroclimatic zones, and land cover. Primary and secondary information layers were used to build on models using raster GIS (100 m resolution) in order to arrive at an approximation of: 1. land-use changes over the last three decades, focusing on forest cover; 2. changes in accessibility to road infrastructure; and 3. potentials in horticultural/potato development.

## Hardware and software

PC Arc/Info 3.5 was used for data input and digitizing. ILWIS on a PC platform was used for image processing. Arc/Info 7.0.3 on an IBM RISC System/6000 and AIX Operation System was used for geographic analysis.

## Data storage

The data are stored in PC Arc/Info format compiled in subdirectories, i.e., coverages. The database is either stored in <coverage name>\PAT.DBF files (i.e., polygon or point attribute tables) or <coverage name>\AAT.DBF files (i.e., are attribute tables).

The \PAT.DBF and \AAT>DBF database files can be retrieved and updated using dBASE software.

## Constraints and limitations

Despite technological advancement of GIS and RS, their dramatic declining costs, and improved user-friendly software, the potential benefits of GIS have not been fully exploited (Pradhan and Shrestha 1997). The use of GIS and RS must involve awareness of the limitations of not only the available data but also the understanding of environmental processes and the technology in use.

In the HKH region, it is not always the technological hurdles that prevent successful GIS implementation. There are such other limiting factors as data standardization, data access and exchange, deficient institutional framework, complex topography, and lack of trained personnel.

## Data quality and standards

One of the key issues facing GIS usage today is the absence of acceptable standards in the region. GIS can be useful only if the accuracy and accessibility of information is standardized. As in the case of Gorkha and Lamjung studies, data accuracy was limited by the fact that the main features of the database were digitized from maps on different scales. Maps of Village Development Center (VDC) boundaries available from the cadastral survey are not complete and are without proper reference points. The quality of the database on settlements varies from VDC to VDC due to the varying degree of accessibility and inconsistency of enumerators. The initial idea to apply GPS technology for this purpose had to be dropped due to the lack of a handy instrument and the large number of settlements that made it impossible to visit each of them.

## Data access

Unnecessary restrictions of topographical maps in the region limit their use. The policy in this respect should be rational, keeping in mind the pace of modern trends, without compromising the specific needs of individual countries. There is also a need for institutional arrangements, both within the individual countries and within the region, to facilitate mutual sharing of data. The ultimate goal should be to develop national and regional GIS capabilities with appropriate networks interlinking them.

## Conclusion

There are many hurdles and limitations in applying GIS in the mountain areas, specially in a less-developed region like HKH. However, it is essential to make the best use of what is available and take advantage of the developments in global technology trends. With more case studies and pilot projects, there is a need for developing methodologies and models to address mountain-specific problems. And above all, it is important to share the knowledge thus gained and disseminate the technology for the benefit of the people. The fruitful sharing of knowledge or information demands standardization of databases, data definition, and methodologies.

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# Farming Systems and Socioeconomic Database for the Hindu-Kush Himalaya Mountain Region

**P M Tulachan**[1]

## Background

Mountain ecosystems in the Hindu-Kush Himalaya (HKH) region are complex and characterized by what the International Centre for Integrated Mountain Development (ICIMOD) calls mountain specificities, such as inaccessibility, marginality, fragility, diversity, niche, and adaptation mechanism. They consist of a range of unique agro-ecological zones; each has specific agricultural/farming systems, and a mosaic of socioeconomic diversity such as diverse ethnic groups and communities with specific socio-cultural values and local dialects or languages.

Presently, there is a lack of systematically collected and collated data characterizing each agro-ecosystem in each unique agro-ecological zone, which can be used to effectively address the specific needs of peoples under different mountain farming conditions. Therefore, one of the major programs for sustainable mountain development should be a systematic, quantitative exploration and characterization of agricultural systems and societies in the HKH.

These comprise a valuable resource to characterize specific agricultural systems and farming communities to formulate mountain-specific development strategies and policies for alleviating poverty and conserving the environment.

This paper briefly describes five broadly classified farming systems in the HKH. It addresses specific issues like, "Why is there a need for a different approach in collecting agricultural systems and socio-economic data in the mountains", and "What kinds of data are important and how are these data going to be used for modeling?" The relationships between these data and GIS and remote sensing (RS) technologies are described. Finally, some practical issues of collecting reliable field data are also presented.

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1. Mountain Farming Systems Division, International Centre for Integrated Mountain Development (ICIMOD); PO Box 3226, Kathmandu, Nepal.

**Tulachan, P.M. 1999.** Farming systems and socioeconomic database for the Hindu-Kush Himalaya mountain region. Pages 45-52 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, IGRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds). Patancheru 502324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

## Mountain farming systems

Mountain farming systems represent various specific bio-physical conditions and socioeconomic circumstances of mountain communities. The five broadly classified farming systems in the HKH are described below:

### Pastoral farming systems

Pastoralism is an entirely livestock-based farming which includes nomadic, transhumant, and sedentary systems. Animal herds graze on high pastures and rangelands during the summer. During the harsh winters of feed scarcity, they are taken to the foothills and mountain valleys and graze fallow fields. Crop residues, straws, and stovers supplement the feed needs. Pastoral farming is commonly practiced in the high northern mountains of Nepal, Bhutan, and bordering areas between Pakistan and China. The landscape comprises highland pasture and rangeland.

### Agro-pastoral farming systems

This is predominantly a livestock production system complemented by subsistence foodgrain crop cultivation. Subsistence crops are grown on river beds or on the flat land of narrow valleys. Animals are raised on highland pastures during the summer, and taken to the valleys and foothills (lower hills) during the harsh winters. Livestock is the main source of cash income. Such farming systems are most common in the high mountains of Pakistan, Nepal, India, and Bhutan.

### Farming systems dominated by foodgrains or mixed crops

Subsistence food crops such as wheat, maize, barley, potato, and millet dominate the system with a few head of livestock integrated with crop production. Some pocket areas, having access to road networks, grow cash crops such as potato, onion, and garlic for commercial purposes. Generally/flat valley and fertile river bed fields are used for the cultivation of major foodgrain crops such as rice and wheat. Cereal food crops such as maize and millet are grown on upland slopes, and steep terrain is used to grow potato. This is a common practice in Nepal, India, and Bhutan.

### Farming systems dominated by orchards or horticultural crops

This type of farming system is also called niche-based farming of high-value cash (HVC) crops. Various pockets in the mountains have extremely favorable agroclimatic and soil conditions suitable for a variety of fruits, vegetables, vegetable seeds, spices, herbs, and medicinal plants. While apple farming in Baluchistan (Pakistan) is in flat valley bottoms, it-is mostly on upland slopes in Himachal Pradesh (India) and in the Rapti Zone (Nepal). Citrus, mainly mandarin, is mostly cultivated on upland slopes of mid-mountains of Nepal and Bhutan. Wherever irrigation water is available, the cultivation of fruits is intercropped with the production of vegetables, vegetable seed, leguminous forages, and fodder grasses. There has been an increasing trend of growing off-season vegetables on upland slopes.

### Shifting *jhum* farming

Commonly practiced in northeastern India, Bhutan, some mid-mountains of Nepal and bordering areas between Myanmar and China, *jhum* or shifting agriculture in these areas is now at a crossroads due to increasing population pressure resulting in less time for regeneration of vegetation. Traditional approaches for *jhum* cultivation are still being employed and are sustainable in some parts of the HKH. Alder tree based *jhum* farming in some areas of Nagaland is an example. *Jhum* fields are also afforested with indigenous tree species. Ecologically, *jhum* farming is a favorable option if sufficient time is allowed for regeneration of natural vegetation, but in order to make it economically viable, the sound development efforts made by local people should be complemented by the introduction of improved seed and fertilizer technologies.

## Database of mountain farming systems in HKH—attempts at ICIMOD

It is generally agreed that the national governments' official agricultural statistics are inadequate to deal with the data gaps in agricultural systems (Rhoades 1997). ICIMOD, as an international center for mountain development, has a comparative advantage in creating a systematic database and information system on mountain agricultural/farming systems, with the ability to retrieve, store, and integrate data in a computerized form that is complementary to other databases. A systematic database on mountain farming systems and communities is needed not only for research targeting and prioritization, but also equally important for agricultural planning, policy analysis, and advocacy.

ICIMOD has begun creating a systematic computerized database by using Microsoft Access for Windows 95. The purpose is to capture specific mountain farming and socioeconomic data in a systematic and user friendly way in the form of graphs, figures, tables, and trends. Presently, we are using secondary sources such as government statistics, gray literature, travel reports, consultant and project reports, case studies, and monitoring and evaluation reports of various projects.

We are also making sure that the data structure is compatible with GIS applications. We can establish a link between attribute data created in a separate Database Management System (MS Access 95) and GIS software to present specific socioeconomic attributes/characteristics of mountain communities and farming as graphics or maps.

The database should be like the Himalayas and the Himalayan people: always changing, shifting, and adapting (Rhoades 1997). By having a sound database, ICIMOD will have a unique opportunity to assist HKH countries in planning, and program and policy formulation for the agricultural development of mountain areas.

## Remote sensing (RS) technologies

Although GIS/RS technologies are powerful enough to do spatial analysis, there are many non-spatial attributes that would become equally important for planning and programming, policy analysis and decision-making. For example, diversity in terms of socio-cultural values of different mountain communities and their farm economies; profitability or economies of farm enterprises, and farm technologies; interactions among different crops; and lowland-upland linkages cannot be captured by GIS/RS technologies, but these are crucial in the decision-making process. Agricultural productivity and soil fertility data need to be collected to examine trends in productivity in relation to the declining/increasing level of soil fertility. Many other data such as the use of different crop varieties and inputs such as composts, chemical fertilizers, and pesticides are required for policy analysis and planning purposes.

## Need for a different approach for collecting agricultural systems and socioeconomic data in the mountains

This is crucial in view of the fact that much of the past work on agriculture and socioeconomic surveys conducted by various organizations has not emphasized mountain characteristics (landscape, aspects and types of farming systems, etc.) while collecting data. Much emphasis was given to a sampling framework based on farming population irrespective of mountain specificities and farming systems types. As a result, the data collected do not represent specific farming and socioeconomic conditions, and consequently are of limited use for research targeting and prioritization, and area-based planning or micro-level planning and policy analysis.

Landscape largely determines the type of farming system. The fertile valley, river basin, and semi-irrigated terraced fields are generally cultivated with summer rice and winter wheat. On upland slopes and steep terrain, subsistence crops such as maize and millet are grown. However, the relatively accessible areas have upland slopes being used for cash crops such as off-season vegetables and fruits. Farming communities and their socioeconomic circumstances may also influence the type of farming system under a specific mountain condition.

Therefore, there is a need to develop a survey research methodology which considers the biophysical and socioeconomic diversity of the mountains with an objective of identifying comparable areas for the exchange of knowledge, experience, and technology in the region.

### Contents of database

Ultimately, the aim is to create a Computerized Mountain Agriculture and Socioeconomic Database that will assist in forming effective decision support systems for sustainable agriculture development. The emphasis will be on:

- information profiles of socioeconomic attributes of mountain farming communities.

- characteristics of agricultural systems in each unique agro-ecological zone to fill the knowledge gaps about diversity of mountain agriculture systems and farming societies of HKH.

- systematic delineation of comparable farming systems within each ecoregion, and identification of constraints and opportunities of each comparable farming system for research planning, targeting, and priority setting.
- economic importance of the farming systems in question, and potential for extrapolation of knowledge/results at appropriate scale levels, and technologies between similar systems (Rhoades 1997).
- farm economies of farming systems in each unique agro-ecological zone, including their economic roles in the light of the rapid transformation in the HKH.

Field-level data from a few selected representative mountain districts in each of the HKH countries will enrich the agriculture and socioeconomic database system. However, emphasis should be on GIS/RS technologies, ground truthing of secondary data, and collection of primary data.

## Modeling for agricultural development planning and decision-making

District data can be used for modeling the district as a whole concentrating on problems like food security for evaluating different interventions. Such models can concentrate on:

- enhancing agricultural productivity and food security
- improving farm income and employment

For this purpose, we can first assess the present agricultural situation in terms of productivity, farm income and employment, food security status, and constraints and opportunities. Based on this assessment, simple agricultural models can be developed focusing on food security and farm income with intervention options that can be controlled by planners and decision-makers. The model can provide a series of different options (attribute data output) as a decision menu for agricultural planners. For example, a model can be developed on government policy: input subsidy versus output subsidy—which one is cost-effective in addressing the food security issue in accessible areas versus inaccessible areas? Agricultural decision-makers will be interested in such practical issues that are directly relevant to their planning processes.

The data output can be generated first by using linear programming conducting sensitivity analysis. Then, a GIS expert needs to establish links between these attribute data output and existing spatial information (remote sensed or otherwise) using GIS software, resulting in maps, showing land-use plan, crop suitability, food surplus/deficit area, and accessibility for appropriate targeting of different segments of the population within a particular district/state/province.

Field-level data need to be collected by survey methods, rapid rural appraisal (RRA) and primary rural appraisal (PRA). With these data/any of several specific models, e.g., the optimal land-use system, can be developed to deal with specific farming systems, population and area within an administrative unit (e.g., district). Mountains have location-specific problems because of diverse biophysical and socioeconomic conditions. For example, the present GIS-based crop suitability model that takes into account biophysical suitability might misrepresent areas growing certain crops very specific to a particular mountain environment and whose specific parameters are difficult to be used/identified in the model.

## Practical issues of reliable agriculture and socioeconomic data collection

While we collect primary data on agricultural systems and socioeconomic data, we need to generate reliable and relevant data. Use of unreliable data misleads planners and decision-makers. So, it is crucial for both top-level planners and field workers to understand practical issues of collecting reliable field data.

- ***Questionnaire design.*** Including relevant questions is absolutely essential. This will save both the researcher's as well as the farmer's time. With a properly designed questionnaire, an interview with a farmer should not last more than 2 hours. In the mountains, because of various socio-cultural settings, some interviewees are conservative and some are open. The checklist and survey questionnaire should be framed in such a way that they do not include sensitive issues that may offend local farmers.
- ***Coordination and database.*** There are some cases in Nepal of the same institutions conducting the same type of interviews 4 to 8 times at the same site and district. Such overload would cause reluctance by farmers to cooperate in the future. Maintaining a systematic database, and making a thorough review of the available data can avoid such problems.
- ***"Bossism".*** An aggressive attitude makes farmers nervous and reluctant to answer openly, leading to unreliable data gathering. Farmers should be approached in a manner that will make them comfortable. Mountain people are proud people—no matter how poor they are and how hard they have to work, they like to live with dignity.
- ***Selection of enumerators.*** In most of the projects, the enumerators are recruited from city or urban areas and are given little training. Such enumerators will have both socio-cultural and communication problems in the mountain areas. Only enumerators who know the local dialect and culture should be recruited.
- ***Expert judgment.*** The researcher's expertise and judgment, and field observations are important to cross check the data filled in by the enumerators. Furthermore, asking for data on income is sensitive. It will always be preferable for a researcher to compute or estimate the income status of a farm household instead of directly asking the farmer.
- ***Elite and male farmer bias.*** A common practice for a researcher is to target elite farmers or influential farmers. Secondly, there is a general tendency to only talk with the household head—usually a male farmer—and not necessarily the real workers. In order to get reliable data, the interview should be conducted with those family members who are directly involved in a particular farm activity. For example,

90% of livestock management activities are being carried out by women in the mountains of Nepal, hence they should be targeted for interviews about this activity.

- ***Disciplinary bias.*** This is a serious problem. A researcher's background could make a big difference in terms of the purpose of data collected and its implementation. A multidisciplinary team is therefore needed.
- ***Wrong approach.*** Scene setting is important to explain facts and purpose of data collection. The confidence of the target group needs to be gained. The ultimate use of the data and information should be explained and expectations regarding the outcome should not be raised.
- ***Wrong timing.*** In order to obtain reliable data, farmers should be approached at the right time and/or in the right season. For some ethnic groups, during the off-season, it would be in a tea shop where many farmers relax. During the peak season, it may be the lunch hour around noon. For some ethnic groups, it is during the evening when they are relaxed. Wrapping up of the interview should be done tactfully.
- ***Training and monitoring.*** All personnel conducting the survey need proper orientation and training about the objective of data collection. For formal surveys, enumerators from the local area must be well trained, and they need to be supervised during the survey work. Proper monitoring during and after data collection is necessary.
- ***Efficiency and cost effectiveness.*** This depends on proper planning and defining the objectives and usability of the data collection. There is always a danger of collecting too much data. Framing data in a clear and concise manner for users' convenience is another important consideration. Entering only relevant data in a computer; analyzing relevant data and information; and presenting them in a concise and readable form will increase efficiency and cost effectiveness of the database being assembled.

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# Prospects for Legumes in the Indo-Gangetic Plain—Database Requirements

**M Ali[1] and S Pande[2]**

The Indo-Gangetic Plain (IGP) is spread over Sind, Punjab, Baluchistan, and part of North-West Frontier Provinces of Pakistan; parts of Punjab, Haryana, Uttar Pradesh, North Bihar, and West Bengal States of India; the western and central parts of Bangladesh adjoining the border of West Bengal (India), and the southern Terai of Nepal. Agriculturally, this region is highly productive and contributes substantially to food security in the component countries. Rice and wheat are the predominant cereals often grown in sequential cropping under irrigated conditions, and sugarcane, cotton, and potato are the major commercial crops. Important food legumes include chickpea, lentil, peas, pigeonpea, groundnut, soybean, urdbean, mung bean, and cowpea; they are generally grown on marginal lands in rainfed areas in diverse cropping systems.

Cultivation of rice and wheat in sequential cropping over the years has led to problems of "soil sickness", nutrient deficiency, soil salinization, and a lowering of the water table. These problems have raised concern among agricultural scientists, policymakers, and farmers as to the sustainability of wheat cropping systems. The inclusion of legumes as cash, intercrop, green manure or main crops is widely acknowledged as an important management practice to increase sustainable crop production of the total system.

In recent years, new cropping systems that involve legumes e.g., rice-wheat-cowpea/mungbean, rice-chickpea/lentil, cotton-chickpea, groundnut-wheat, soybean-wheat, pigeonpea-wheat, etc., are being popularized. However, the low and unstable productivity of legumes due to several biotic and abiotic constraints slows the rate of adoption. It is therefore imperative to systematically analyze the climatic, edaphic, biotic, and socioeconomic factors and farming systems of the IGP, and identify the most productive environments for legumes. This can be done by using databases for each legume to be popularized/introduced in the cereal-based cropping systems.

Databases on the following aspects are needed if GIS is to be used to analyze and develop cropping systems with particular emphasis on prospects for legumes.

1. Division of Agronomy, Indian Institute of Pulses Research (IIPR), Kanpur 208 024, Uttar Pradesh, India.

2. ICRISAT, Patancheru 502 324, Andhra Pradesh, India.

ICRISAT Conference Paper no. 1378.

**Ali, M., and Pande, S. 1999.** Prospects for legumes in the Indo-Gangetic Plain—database requirements. Pages 53-54 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

## Climatic

Quantitative datasets (time series) on such climatic variables as rainfall (amount, distribution (weekly), onset, intensity, withdrawal, dependable period, and coefficient of variability, drought-intensity, period and frequency, probability of hailstorm); temperature (ambient mean, maximum and minimum (weekly), frost probability, period and intensity of occurrence); wind (period and intensity of hot winds); relative humidity; sunshine hours; evapotranspiration, etc., are essential for temporal and spatial analysis and characterization of the environment of the IGR.

## Edaphic

Physiography (topography, latitude, longitude, altitude, drainage); physical properties (soil texture, structure, bulk density, permeability, depth, presence of hard layer, water-holding capacity); chemical properties (soil pH, soil organic matter, cation exchange capacity, available nutrient status, nature and extent of sodicity, salinization and acidity), and quantification of soil biota are the important and most needed time series data.

## Biotic

Time series datasets on insect pests, diseases, nematodes and weeds, their occurrence, intensity, yield loss caused by them, their natural enemies, and alternate hosts on which they survive or perpetuate in the off-season are needed for the meaningful characterization of the rice-wheat-legume cropping systems of the IGR

## Farming systems

Detailed information on the nature and type of enterprises and their relative contribution to family total income; crops and cropping systems (area, production and productivity of different legumes district-wise); irrigation (resource-capacity, source, method, cost) etc., are needed to identify the role of legumes and assess prospects for greater inclusion of legumes in rice- and wheat-based cropping systems.

There is also a need to quantify availability and use of farm machinery and equipment (type of farm implements and machineries, extent of mechanization, custom hiring of heavy machines), and other production inputs (seeds, fertilizers, chemicals, etc., and their availability, use, cost benefit ratio), and related variables for the economic assessment of the present system and scope for legumes in the existing cropping system.

## Socioeconomic

Socioeconomic datasets of farm family size, income, and purchasing capacity, literacy, size of holding, marketing infrastructure, price index, domestic requirements, credit facility, agro-based industries, etc., are required to work out the economical feasibility of including legumes in cereal-based cropping systems.

# Socioeconomic Datasets and Use of GIS

**P K Joshi, S Pande, and M Asokan[1]**

## Introduction

GIS is one of the most powerful tools, now widely used, to understand various agricultural problems more precisely. Voluminous and complex datasets on socioeconomic variables complemented by a range of agroclimatic and environmental data can be analyzed and projected more effectively with the aid of GIS. The use of GIS in socioeconomic research can be grouped into the following important areas: 1. characterization of production systems, 2. delineation of regions according to adoption of improved technologies, and distribution of welfare gains, and 3. identification of regions which may respond to policy and technological interventions for social welfare. Each research area needs large datasets and adequate understanding of GIS application.

The main objectives of this paper are to: 1. list the essential datasets needed for GIS application, 2. refer to socioeconomic data sources and analysis using GIS, and 3. cite a few examples of GIS application in socioeconomic research.

## Essential datasets for GIS

Socioeconomic datasets alone are of little significance unless appropriately supported by agroclimatic and environmental data. The following datasets are useful for GIS applications in analytical socioeconomic research:

- *Land-use pattern.* Geographical area, forest area, area put to nonagricultural uses, barren and uncultivable land, permanent pastures and other grazing lands, land under miscellaneous tree crops and groves not included in the net area sown, cultivable wasteland, permanent fallow, current fallow, net area sown, area sown more than once, gross cropped area.
- *Area, production, and yield of principal crops.* Spatial and temporal information on area, production, and yield of all cereals, pulses, oilseeds, cash crops, fruits, and vegetables.

1. ICRISAT, Patancheru 502 324, Andhra Pradesh, India,

ICRISAT Conference Paper no. CP 1379.

Joshi, P.K., Pande, S., and Asokan, M. 1999. Socioeconomic datasets and use of GIS. Pages 55-64 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

- ***Input use.*** Spatial and temporal statistics on area under high-yielding varieties, irrigation, human labor, animal draft, fertilizer, pesticide, machinery, and the cost of cultivation.
- ***Output and input prices.*** Spatial and temporal information on farm harvest and retail prices of important crops and the prevailing input prices will be required to examine the cost, profitability, and competitiveness of different crops in the region. The crops should include all cereals, pulses, oilseeds, cash crops, fruits, and vegetables. Data on input prices must include the prices of seed, fertilizer, pesticide, labor wages by operation and gender, animal (bullock) rental values, machinery hire charges, and cost of irrigation.
- ***Information on irrigation.*** Gross irrigated area, net irrigated area, irrigated area by source, number of private tubewells, number of public tubewells, number of pumpsets (oil and electric), irrigation potential, cost of water.
- ***Economic variables.*** Total work force (by gender), dependence on agriculture, agricultural laborers, poverty indicators (per capita income, number of poor, etc.), import and export of agricultural commodities.
- ***Demographic information.*** Total population, urban population, rural population, distribution by age and gender, literacy indicators (proportion of literate males and females), mortality rate.
- ***Rural infrastructure.*** Density of roads in rural areas, and number of regulated markets, rural banks (nationalized, cooperative), electrified villages, sugar factories, other processing mills, research centers, technology transfer agencies, staff engaged in technology transfer.
- ***Biotic and abiotic constraints.*** Information on the extent of damage caused due to biotic constraints such as pests, diseases, and weeds, and application of pesticides, insecticides, and weedicides. Similarly, information on the extent and damage caused by drought and other abiotic constraints is essential.
- ***Degradation of natural resources***
    - Land degradation and waterlogging. Type of problem (a problem may be defined as soil erosion, rills, gullies, waterlogging, soil salinity, runoff, etc.), extent of land degradation, soil type, soil depth, area affected by waterlogging, duration of waterlogging, water table, extent of rainwater run-off, estimate of yield loss due to land degradation.
    - Resource allocation to affected areas. Crops grown in affected areas, use of different inputs for crop production in affected areas, yield, and net returns under different levels of degradation and waterlogging.
    - Alternative use of degraded land. Area under forest, area under grassland, area reserved for animal grazing, any other use of degraded land.
- ***Land and ownership.*** Owned land (irrigated/unirrigated), leased-in land, leased-out land, operated area, fallow land, quality of land, number of fragments, location of fragments, cropping pattern by season.

- ***Adoption of improved technologies.*** Adoption of improved technologies by crop and by variety, yield gains due to improved technologies, income and other benefits due to improved technologies.
- ***Climate and soil.*** Information on rainfall, temperature, evaporation, soil type, soil depth, etc., are essential for the meaningful use of GIS in identifying the suitability of weather and soil for particular cropping systems.

## Data source

National, district and block-wise information may be collected on the above variables depending upon the analyses and objectives. Major data are available from published and secondary sources. However, there is often a need to supplement data from primary sources.

- Important sources of State-wise data in India are as follows:
  - Area, Yield, and Production of Principal Crops
  - Agricultural Situation in India
  - Fertilizer Statistics
  - Agricultural Census
  - Season and Crop Reports of different States
  - Population Census
  - Bulletin on Food Statistics
  - Livestock Census
  - Economic Survey
  - Indian Agriculture in Brief
  - India Meteorological Department
  - National Bureau of Soil Survey and Land Use Planning (NBSS&LUP)
- For other countries, statistical bulletins of respective countries can be consulted. These can be supplemented by the FAO Production/Trade/Fertilizer Year Book.
- Information on land and water degradation is not readily available from published sources. In India, some State-wise estimates are available and documented in the publication "Indian Agriculture in Brief". District-wise statistics on waterlogging and land degradation are rarely available. One has to rely more on survey data at benchmark sites. The survey may be undertaken to measure the extent of waterlogging and land degradation. In India, the following sources could provide this kind of information:
  - National Bureau of Soil Survey and Land Use Planning (NBSS&LUP)
  - National Remote Sensing Agency
  - Central Soil and Water Conservation Research and Training Institute
  - Ministry of Environment

- Ministry of Irrigation
- Soil conservation departments in different States

• A literature review will provide substantial information about biotic and abiotic constraints to agricultural production.

• Published information is now available on the adoption of improved technologies (particularly improved varieties, use of fertilizers, irrigation, application of pesticides). However, reconnaissance surveys are necessary for detailed datasets on variety-wise or specific technology-wise adoption. Similarly, yield gains and distribution of benefits can be generated through reconnaissance surveys.

## Analysis using GIS

The datasets listed above can be used in a variety of ways. GIS can aid in delineating regions to understand the production systems more systematically; a few examples are cited below:

- delineation of production systems
- high- and low-growth regions in foodgrain production
- food surplus and deficit regions
- target technologies according to constraints and technology traits
- target policies according to resources and socioeconomic structure
- extent and damage due to degradation of natural resources
- extent and severity of damage caused by biotic and abiotic stresses

## Case studies

### Differences in agricultural performance in the semi-arid tropics of India

A study was conducted to understand agricultural performance in the Indian semi-arid tropical (SAT) regions (Joshi et al[1].). The study was confined to the 136 districts in India (now reorganized to 156), that have the characteristics of a SAT environment. District-level data on key variables were collated from various published and unpublished sources, including the District-Level Dataset maintained at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) from 1960 to 1990.

A wide range of crops can be cultivated in the SAT region due to its wide agroclimatic diversity. These range from high water use crops like rice and sugarcane to low water requirement crops like millets, oilseeds, pulses, etc. To better identify constraints and propose appropriate solutions, prominent cropping systems were

1. Joshi, PX, Asokan, M., Chandel, B.S., Virmani, S.M., and Katyal, J.C. 1997. Agriculture performance differences in the semi-arid tropics of India (Unpublished).

delineated using cluster analysis. The share of each crop in the gross cropped area during the triennium average ending 1990-91 was used as a key criterion to delineate clusters of districts with similar crops and cropping systems. The cluster analysis yielded 13 major cropping systems that were mapped with the help of G1S (Fig. 1).

To examine agricultural performance in the Indian SAT, the following indicators were compiled: 1. agricultural income, 2. crop yields, 3. risk and uncertainty, 4. crop intensification, 5. crop diversification, and 6. sustainability. These indicators were superimposed over the cropping systems using GIS. Some resultant observations are listed below:

- rice-wheat, and rice-based cropping systems were located in the most favorable and well-endowed regions in the SAT
- cropping systems, like sorghum, pearl millet-sorghum, and cotton-sorghum, were confined to marginal and fragile environments that were vulnerable to degradation of soil and water resources. These systems were characterized as rainfed, subsistence, poverty ridden, and prone to degradation.
- rice-wheat and rice-based cropping systems were high-growth and low-risk zones, while sorghum, and pearl millet were low-growth and high-risk zones.
- adoption of improved technologies was much faster in well-endowed regions than in poorly endowed regions.

## Adoption of wilt-resistant pigeonpea variety ICP 8863

A series of studies have been undertaken at ICRISAT to track down the spread and impact of improved cultivars in farmer's fields, and thereby to demonstrate, in quantitative terms, the benefits that flow from research investment in genetic resources, genetic enhancement, pathology, and technology transfer. One such study by Bantilan and Joshi (1996) reported the results for ICP 8863, the wilt-resistant, and medium-duration pigeonpea cultivar released as *Maruti.*

Pigeonpea is generally grown in highly variable SAT environments, where adoption is not expected to be uniform. GIS was used to identify the target pigeonpea zones, where the wilt (*Fusarium oxysporum*) problem existed. Figure 2 shows the distribution of pigeonpea throughout India, and highlights regions where the crop occupies a relatively high percentage of gross cropped area. Figure 3 shows the wilt-endemic areas in central India identified during the 1975-80 international survey of pigeonpea diseases. GIS maps were used to identify the study tracking areas and the major findings were:

- there has been a significant adoption and impact of ICP 8863, which now dominates the pigeonpea tracts of northern Karnataka.
- diffusion to districts in the neighboring States of Andhra Pradesh, Maharashtra, and Madhya Pradesh also occurred.
- the cultivar occupies almost 60% of the pigeonpea area in the wilt-affected districts of northern Karnataka, and the bordering districts of Andhra Pradesh and Maharashtra.

- non-availability of seed has constrained adoption in the wilt-endemic areas of eastern Maharashtra, but an informal sector has evolved to meet the demand.
- farmer-to-farmer seed distribution will remain the major source of adoption of this variety in Maharashtra unless its release is facilitated in this State.

## Conclusion

On the basis of the above discussion, it can be stated that GIS application can systematically improve the quality of socioeconomic and policy research. Socieconomic datasets need to be supplemented by agroclimatic and environmental data for effective use of the GIS approach.

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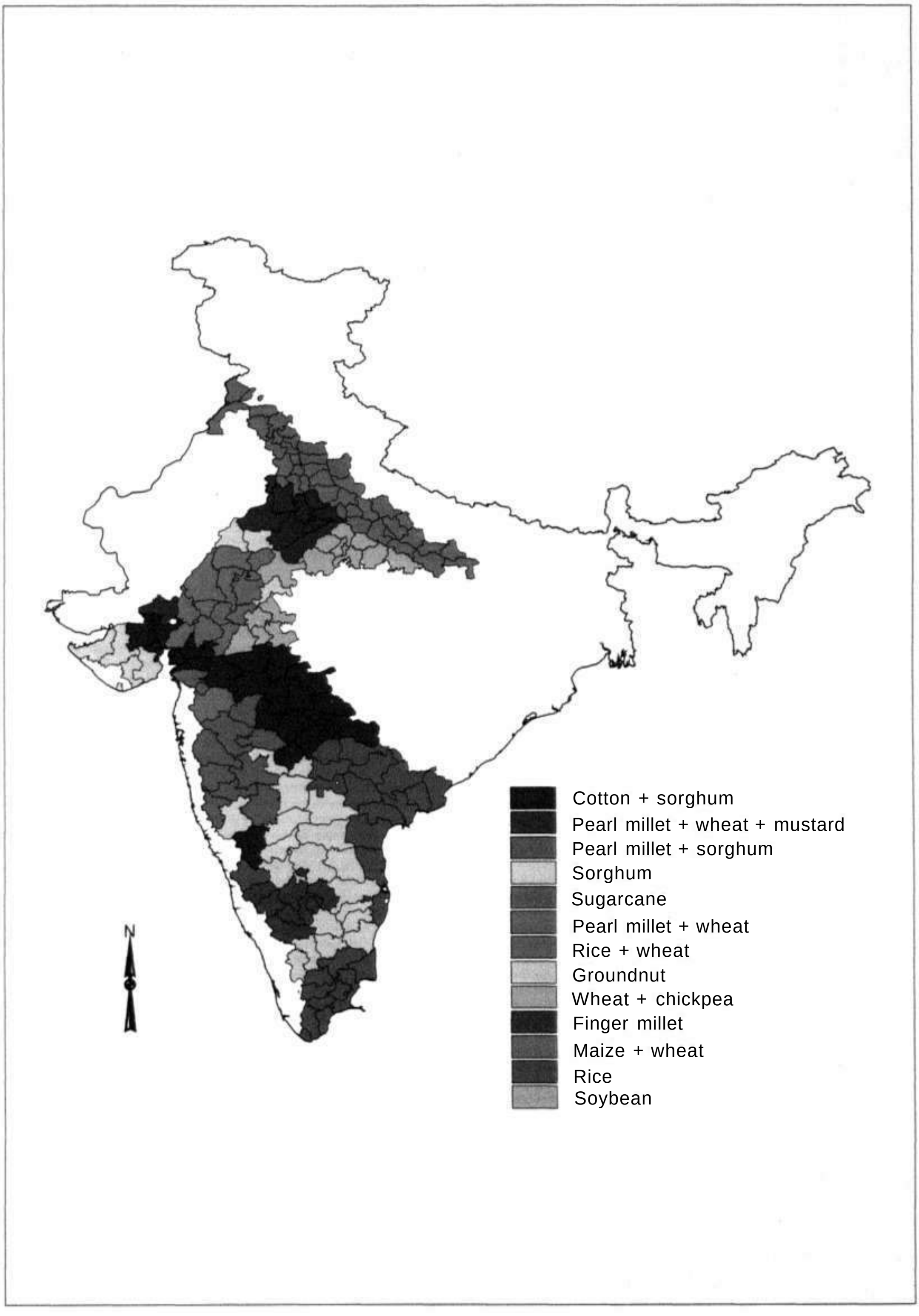


*Figure 1. Major cropping systems in the semi-arid tropics (SAT) of India.*

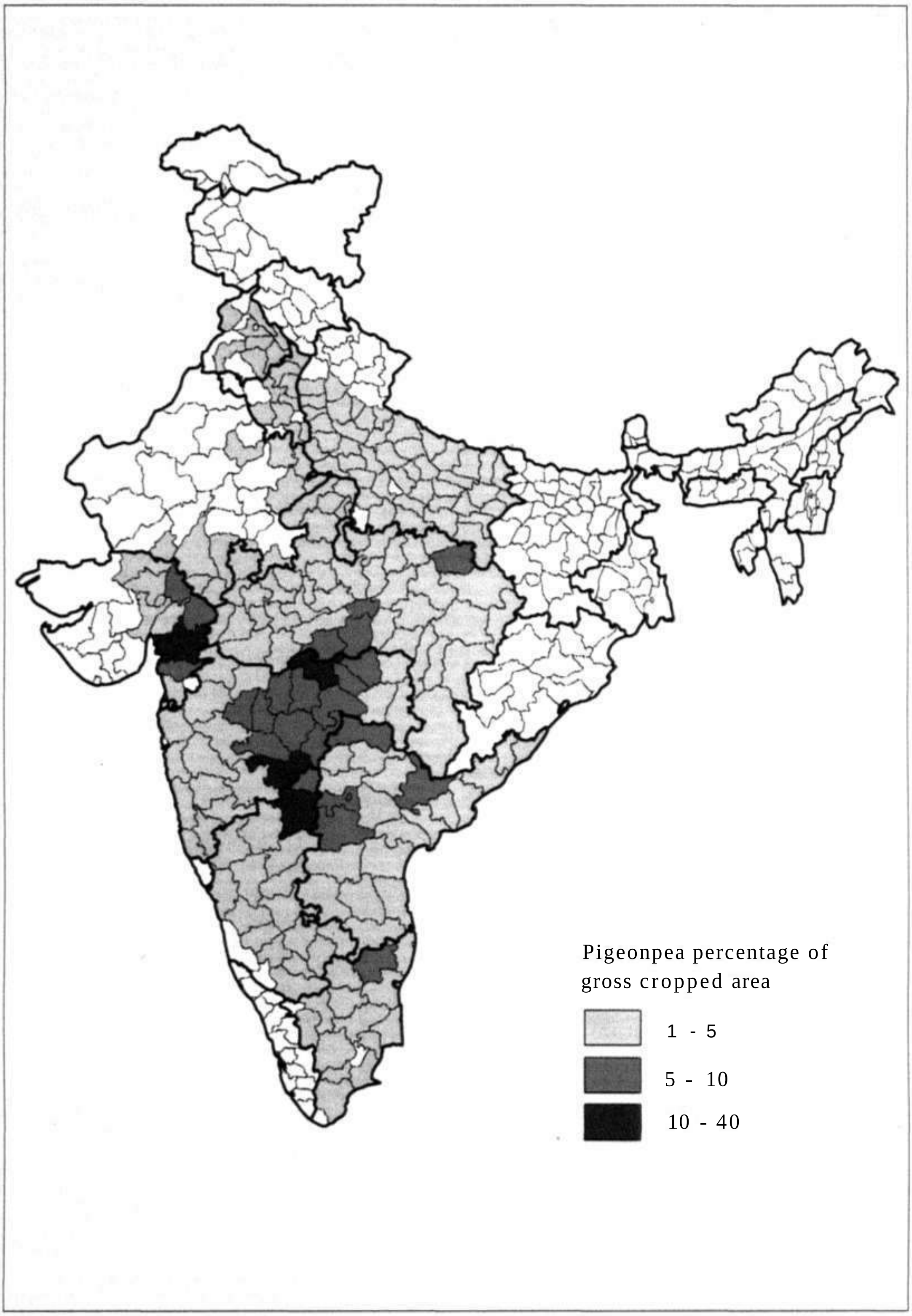


*Figure 2. Distribution of pigeonpea in India.*

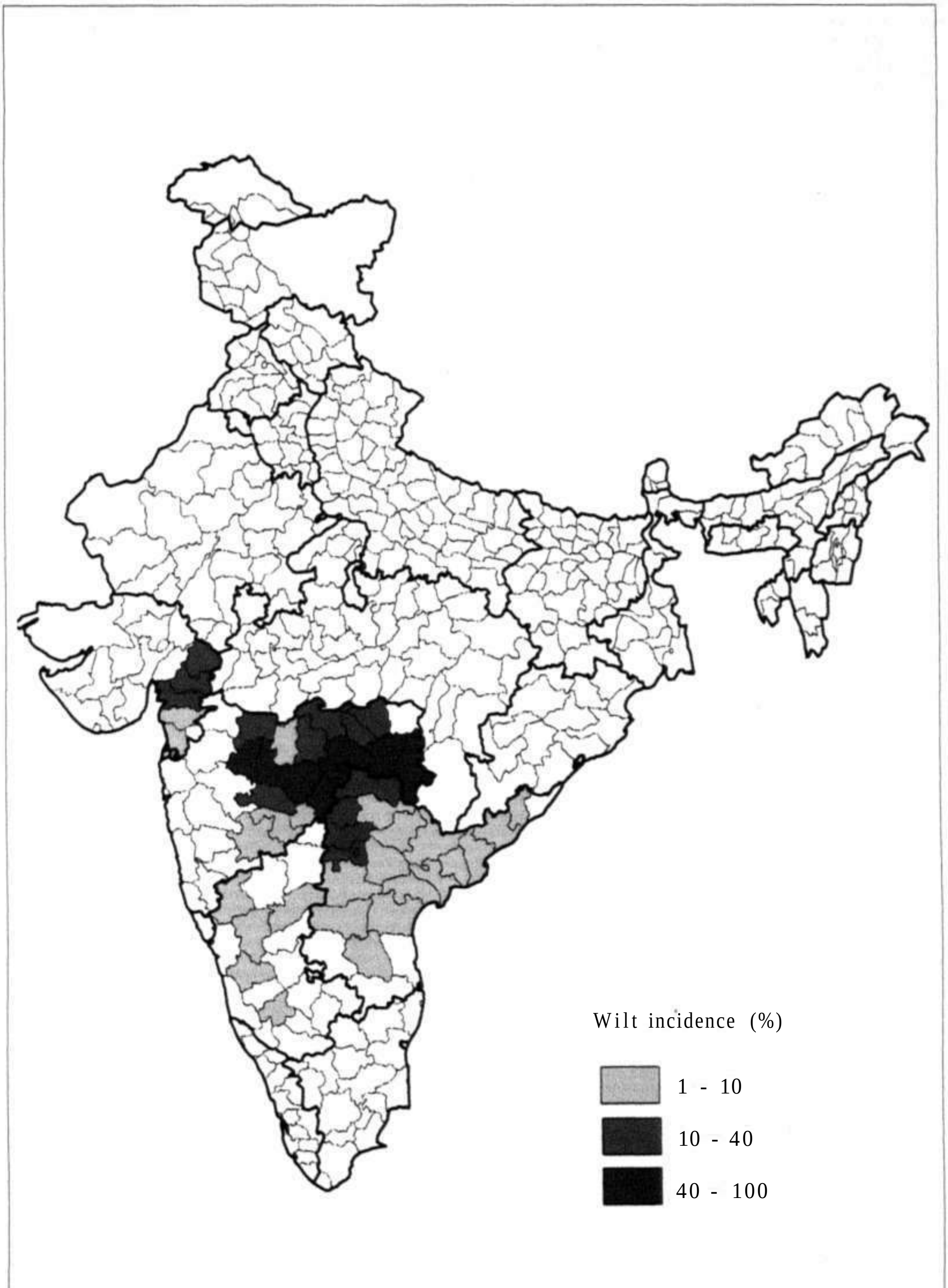


*Figure 3. Incidence of fusarium wilt of pigeonpea in India, 1975-80.*

# Session III

## Application of GIS and Remote Sensing

# Production Systems Concepts

**C Johansen**[1]

## Introduction

Definition of target production systems is essential for proper focusing of any agricultural research and development (R&D) endeavor. Specification of application domains should be the first step in the R&D process. This applies to genetic improvement as well as natural resource management (NRM) or agronomic improvement efforts. Prior to this decade, most publicly funded plant breeding efforts have aimed at wide adaptation, which would potentially favor widespread release and use of improved lines and ease of seed production. However, in recent years, a consensus has been building that breeding for specific adaptation may be the best pathway to increase yields region-wise and ensure the advantages of biodiversity (e.g., Wallace and Zobel 1995). This requires precise definition of assets and constraints in target environments such that genotype x environment (G x E) interactions can be unraveled. Similarly, in NRM/agronomic research in tropical agriculture, it is increasingly being acknowledged that there has been limited adoption in farmers' fields of research station, site-specific, research findings. This suggests that application domains for such research had not been adequately defined in the first place, and that it should be done in the future.

To better ensure reasonable return on R&D investment, and help in prioritizing what should be done, it is advisable to conduct ex ante analyses. A key factor determining how realistic such calculations will be is the ability to assess over what area an improved technology is likely to be applicable and adoptable. Furthermore, clear definition and display of target production systems for R & D efforts is likely to improve communication with such stakeholders, as counterpart scientists, administrators, donors, and farmers in targetted areas.

This paper summarizes recent ICRISAT attempts to better define target production systems relevant to its mandate: a geographical mandate of the semi-arid tropics and a commodity mandate for sorghum, millets, groundnut, chickpea, and pigeonpea.

1. ICRISAT, Patancheru 502 324, Andhra Pradesh, India.

ICRISAT Conference Paper no. CP 1381.

**Johansen, C. 1999.** Production systems concepts. Pages 67-74 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA: International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

## Existing agro-ecozones

As in any mapping exercise the question of scale arises, which must be appropriate to the purpose (e.g., a city map to locate a particular building or a country, regional, or world map to locate a particular city). On a global scale, the Food and Agriculture Organization (FAO) has defined nine agro-ecological zones (AEZs) appropriate to developing country agriculture (TAC 1991):

1. Warm arid and semi-arid tropics
2. Warm subhumid tropics
3. Warm humid tropics
4. Cool tropics
5. Warm arid and semi-arid subtropics with summer rainfall
6. Warm subhumid subtropics with summer rainfall
7. Warm/cool, humid subtropics with summer rainfall
8. Cool subtropics with summer rainfall
9. Cool subtropics with winter rainfall

FAO has also proposed a scheme of regional AEZs (RAEZs) to approximately coincide national boundaries with AEZ boundaries, to facilitate use of nationally available data on crop statistics, etc. However, these AEZs and RAEZs are on too large a scale to be of much use in targetting ICRISAT research—the geographical mandate is applicable to only AEZs 1 and 5 although commodity mandates do extend into other AEZs. Similarly, national AEZ Schemes are on a regional basis, and, furthermore, classification systems can differ between adjacent countries, thus complicating extrapolation across national boundaries. Therefore, for ICRISAT's purposes it appeared that a zonation of intermediate scale was required.

## Development of ICRISATs production systems

It was initially conceived that a production system (PS) should be a geographic region primarily defined by similarities in climate and soils. Further, the PS should encompass an area within which similar farming systems exist or are possible (e.g., sorghum/pigeonpea intercropping). While the climate and soil parameters, primarily temperature regime, length of growing period (LGP), and soil type, would be precise, quantifiable and relatively constant over time, the particular farming systems may vary over space and time. Thus it was recognized that PS boundaries could not be rigid and may change over time. A set of 12 PSs for Asia were initially described (ICRISAT 1995):

1. Transition zone from arid rangeland to rainfed, short-season millet/pulse/ livestock. Eastern margins of the Thar Desert.
2. Subtropical lowland rainy and postrainy season, rainfed, mixed cropping/Central/ eastern Indo-Gangetic Plain.

3. Subtropical lowland rainy and postrainy season, irrigated, wheat-based. Western Indo-Gangetic Plain.
4. Tropical, high-rainfall rainy plus postrainy season, rainfed, soybean/wheat/ chickpea. central India.
5. Tropical, lowland, rainfed/irrigated, rice-based. Eastern India, Myanmar, Thailand, Southeast Asia.
6. Tropical, lowland, short rainy season, rainfed, groundnut/millet. Saurashtra Peninsula.
7. Tropical, intermediate rainfall, rainy season, sorghum/cotton/pigeonpea. Eastern Deccan plateau, central Myanmar.
8. Tropical, low-rainfall, primarily rainfed, postrainy season, sorghum/oilseed. Western Deccan plateau.
9. Tropical, intermediate-length rainy season, sorghum/oilseed/pigeonpea interspersed with locally irrigated rice. Peninsular India.
10. Tropical, upland, rainfed, rice-based. Eastern India, Southeast Asia.
11. Subtropical, major groundnut and sorghum. China.
12. Subtropical, intermediate elevation, winter rainfall and rainfed, wheat-based. West Asia and North Africa.

Figure 1 provides a preliminary GIS map of these production systems in South Asia (more refined mapping is underway). A minimum dataset of descriptors was formulated to give a basic description of the main characteristics, particularly in relation to ICRISAT's mandate. Table 1 gives an example for PS1. There has also been further tabulation of the major production constraints and environmental threats in each PS.

Production Systems were similarly defined for Africa (PS 13-24) and Latin America (PS 25-29) (ICRISAT 1995 pp. 68-70). The ICRISAT PSs are thus subsets of the FAO AEZs, but national-level agro-ecozone units are usually subsets of the ICRISAT PSs. The preliminary definition of these PSs required that they assist in the prioritization required for development of ICRISAT Medium-Term Plans. It also allowed for better focusing of projects to particular PSs, and of activities within projects.

However, further work on defining a PS is needed so that it can regularly be used as a tool for ICRISAT research planning, implementation, and assessment (impact analysis). More detailed descriptor sets are needed to better define boundaries, particularly with respect to farming systems and socioeconomic parameters. Database formats need to be decided upon. Plotting of all PSs in GIS format is needed—this work has so far only proceeded to some extent in South Asia (Fig. 1) and West Africa. In defining PS boundaries, it would be essential to ensure compatibility with other AEZ systems, global and national, to permit up- and down-scaling. It would be counter-productive for the ICRISAT PS system to be interpretable only to ICRISAT researchers. It is intended to produce a research bulletin describing ICRISAT's PSs, including their GIS maps, and their relationship to other AEZ classification systems.

Table 1. **Minimum dataset for describing ICRISAT production systems (PS); the example of Production System 1 (PS1).**

| | |
|---|---|
| Production system | 1 |
| Relevant AEZ | 1 and 5 |
| Geographic zone | Arid semi-arid transition rangeland and rainfed zone |
| Latitude | 23-29° |
| Political subdivisions | Western and central Rajasthan, Haryana, northern Gujarat and eastern Pakistan |
| Length/time of growing season | < 90 days |
| Growing season(s) temperature | Mean rainy season temperature 30-35°C |
| Growing season rainfall | <500 mm |
| Major soil type(s)/WHC | Sandy Entisols, Aridsols |
| Type of agriculture | Mixed subsistence |
| Base cereal crop | Dual-purpose millet |
| ICRISAT crops | Millet, winter chickpea |
| Other crops | Mungbean, mothbean, sesamum, guar |
| Importance of animal systems | High for milk and meat; tractorization important |

## Further refinement of agro-ecological zoning

The principles of defining appropriate PSs may be extended to national or smaller scales for more detailed studies of land use planning and scenario analysis. The methodology recommended for doing this has recently been published by FAO (FAO 1996). Case studies are available for Bangladesh (FAO 1988) and Kenya (FAO 1993). However, there is scope for improved calculation of some of the key climatic parameters. The LGP is usually calculated as the period during which precipitation and stored soil moisture exceed half of the potential evapotranspiration, at mean temperatures above 5°C. Bimodal and variable within the year rainfall patterns complicate such calculations. Variation over the years needs to be considered so that the probabilities of LGP can be calculated. Better methods of calculating residual soil moisture are also needed. This can be markedly influenced by such factors as soil type and profile characteristics, rooting depth, crop type, and cropping system (e.g., sole cropping versus intercropping).

Calculation of thermal regimes can be improved by determining heat units available for plant growth and development, as cardinal temperatures for the more important crop species are now known. However, photoperiod effects on crop phenology and partitioning (Summerfield and Roberts 1988 and Wallace et al. 1995) also need to be factored in.

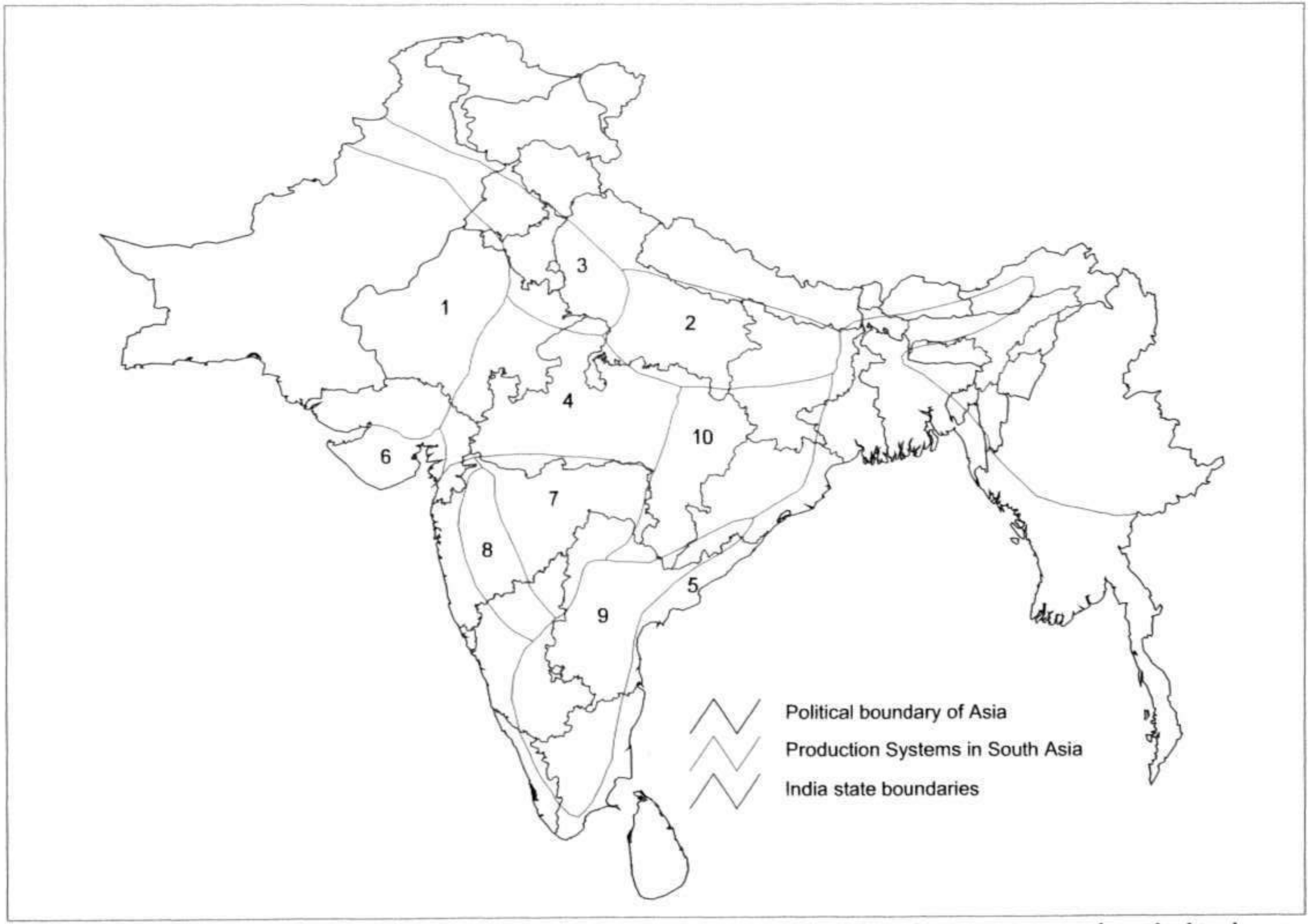


*Figure 1. Depiction of ICRISAT production systems in South Asia. Each numbered production system is described in the text.*

Rather than using a listing of climatic adaptability attributes of crops, as suggested by FAO (1996), there are sufficiently robust crop models available for at least the major crops (Van Evert and Campbell 1994, and McCown et al. 1996). These would assist in matching crops to particular favorable environments and, alternatively, help in identifying crop characteristics that limit their adaptation to particular environments. By comparing modeled potential yields, given the climatic and soil base, with actual yields, say at a district level, yield gap analysis and constraint analysis can be more easily conducted. Such exercises would provide valuable feedback to breeding and agronomic improvement programs.

## Conclusions

Methodology and crop physiological understanding have now advanced to the stage of being able to precisely quantify target environments and examine cropping options within them. Thus, we should be better equipped to undertake constraint analysis and more precisely ascertain research priorities. Use of the tools available, such as GIS, crop models, and G x E analysis techniques, can be adjusted to the appropriate scale, from regional to farm level. It is important that agricultural scientists, particularly those working in threatened production environments (showing signs of unsustainability) should have access to, and use, the tools now generally available to demonstrate how their particular research is being targetted. This is not only for their own guidance but as a basis for future support for their research endeavors.

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# Considerations and Applications of GIS

**P Reich and H Eswaran**[1]

## Introduction

GIS technology provides the means to collect and use geographic data to assist in decision-making for natural resource management. A digital map is generally of much greater value than the same map printed on paper as the digital version can be combined with other sources of data for analyzing information. Before the advent of GIS technology the amount of geographic data that could be analyzed, and the types of analyses that could be performed, were limited. GIS makes it possible to synthesize large amounts of different data, and to manage and retrieve the data in a useful manner. With GIS, different layers of information can be combined and analyzed to better study and understand the complex relationships between the Earth's ecosystems and the effect humans have on them. GIS provides a powerful means for agricultural scientists to better service the general public, farmers, and other land users, in answering their questions and in helping them manage their land in the most sustainable manner.

The purpose of this paper is to provide an overview of GIS, a description of the components, functions, and benefits of using GIS technology. Some examples are included to illustrate the application of GIS technology.

## Components of GIS

GIS enables the user to input, manage, manipulate, analyze, and display geographically referenced data using a computerized system. Each of the necessary components of this system are identified below. GIS is comprised of software, hardware, data, and the users.

1. World Soil Resources, United States Department of Agriculture (USDA)-Soil Conservation Service, PO Box 2890, Washington, DC 20013, USA.

**Reich, P., and Eswaran, H. 1999.** Considerations and applications of GIS. Pages 75-90 *in* GIS analysis of cropping systems: proceedings of an International Workshop on Harmonization of Databases for GIS Analysis of Cropping Systems in the Asia Region, 18-19 Aug 1997, ICRISAT-Patancheru, India (Pande, S., Johansen, C., Lauren, J., and Bantilan, F.T., Jr., eds.). Patancheru 502 324, Andhra Pradesh, India and Ithaca, New York 14853, USA; International Crops Research Institute for the Semi-Arid Tropics and Cornell University.

## Software

There are two types of software: commercial software, and public domain software. Commercial software is protected by copyright, can be expensive, and is updated periodically. Public domain software is not copyrighted and is often available free of charge, though updates may be uncertain.

Currently available commercial GIS software include: Arc/Info (ESRI), IDRISI, Intergraph, Maplnfo, Strings (GeoBased), Synercom, Delta Map (Autometric), ERDAS, AE-GIS (Aeronca), and SPANS (TYDAC). Worldwide, Arc/Info is probably the most popular GIS software package. Examples of public domain GIS software are: AMS/MOSS/MARS/COS, GRASS, and SAGIS.

## Hardware

A typical hardware configuration for a basic GIS should include the following equipment: a 486 166 MHz (or faster) IBM PC computer, with at least a 1 gigabyte (GB) hard disk and 64MB RAM with a VGA color monitor. If map data is to be input, a digitizer with at least a 4-button cursor and a minimum surface area of 36 x 48 inches (91 x 122 cm) is recommended. For data output, a text printer and an E-size (112 x 86 cm) pen or inkjet plotter are needed. A 0.25" tape drive of 150 MB capacity is necessary for managing some of the large databases processed with GIS. Depending on the scale, a typical GIS database including about a dozen data layers may range in size from 20 to 2 000 MB. A CD-ROM drive is also recommended because many large GIS datasets are available on CD media. These are about the minimum requirements for a GIS laboratory to be set up. Computers with 10 GB hard disks have now become common.

## Data

Two types of data are used in GIS—spatial and tabular. Spatial data can be in the form of a map, or as remotely-sensed data such as satellite imagery and aerial photography. Each of these forms must be properly georeferenced (e.g., latitude/longitude, Universal Transverse Mercator (UTM)). Tabular data can be any attribute data that is in some way related to spatial data.

## Users

The most important component of GIS is the user. Users can either be technical or nontechnical. The technical user is the person who has training in the use of GIS software and uses it frequently. The nontechnical user is any other person who may not actually use the software but may use the data output by the GIS; these users are largely interested in the results of the analyses and may have no interest or knowledge of the methods of analysis.

Through user-friendly interfaces to the system, even the nontechnical user can have easy access to GIS analytical capabilities without needing to know detailed software commands. A simple interface can consist of menus and pull-down graphic windows so that all the user has to do is to make some choices and answer a few questions without needing to learn specific commands.

## Functions of GIS

A typical GIS has five major functions: input, manage, manipulate, analyze, and display geographic data. Each of these functions are briefly discussed below.

### Input data

GIS can digitize maps and imagery, and input existing spatial and tabular data. Tabular data is generally typed on a computer using a relational database management system software program. This software allows the data elements to be indexed so that the database can be queried. Maps can be digitized using a vector format in which the actual map points, lines, and polygons are stored as coordinates. Data can also be input in a raster format in which data elements are stored as cells in a grid structure.

#### Digitizing

One of the most important features of GIS is that it allows the input of spatial information using a process known as digitizing. The first step in digitizing is map registration. To register a map, at least four points having known coordinates must be identified and digitized. These points will usually be the four corners of the map sheet which tells the computer where the map is located on the digitizer as well as its real-world coordinates.

Once the map registration is completed, the digitizing of map features can begin. A line is digitized by tracing it from node to node with the digitizer cursor. A node is simply the point where two lines intersect each other. After all of the map features are digitized, the map will probably require some editing. All lines must be properly joined at the nodes. A typical GIS has many commands that make editing quick and easy. After editing, the next step is to label the map. A label is needed so that a feature can be properly associated with its attributes in a tabular database.

The digitizing process is labor-intensive and time-consuming, so it is best to try to find data that already exists. What are the factors that affect the acquisition of existing data? Some of the data will simply not be available, and, depending on the source, existing data can be expensive, especially for satellite imagery. The data may be in a format that is incompatible with the GIS software that is being used. Data content and data quality can also limit the usefulness of existing data.

Data quality is a very important issue concerning data input. When working with multiple map layers in a GIS, the analytical results will only be as good as the least reliable data layer. The phrase "garbage in, garbage out" is an important yardstick here. If the data used as input into a GIS database are full of errors, then any output from it will be useless. The users of maps and reports that are output from GIS must be made aware of the source of the data and its reliability. It is imperative that data quality standards be implemented and maintained at all CIS sites.

### Managing and manipulating data

GIS can store, maintain, distribute, and update spatial data and associated text data. The spatial data must be referenced to a geographic coordinate system, i.e., latitude/ longitude, UTM

Spatial and associated tabular data can be manipulated in a number of ways that make it more useful and manageable. Queries and retrieval of digital map data and tabular resource information are important functions of GIS. Depending on the type of user interface, data can be queried using the Standard Query Language, or a menu-driven system can be used to retrieve map data.

GIS contains frequently used functions to make map generalizations. Functions such as line and polygon thinning (also known as weeding) remove unnecessary points during data capture of a feature. The program keeps only those points that are necessary for the proper representation of a feature. Edge matching is another function that provides a means for joining maps together. Scale and projection changes, distortion removal, and coordinate rotation and translation can be performed within GIS, just as vector and raster conversions. Data is frequently entered using a vector format. Conversion to a raster format facilitates the use of many analytical functions that will be described later. Data can be imported and exported in various formats. For example, data can be exported from GRASS and imported into Arc/Info and vice versa. This means that data can be shared more easily between different systems.

### Analyzing data

Many analytical functions can be performed using grid-cell (raster) data. Measurement and calculation functions involving points, lines, areas, distances, and volumes can be performed with a GIS. Vector (polygon) overlay and dissolve functions are important GIS features that involve the composing of multiple map themes in order to create new map data and the associated tabular data. For example, data layers for soil and land use can be combined resulting in a new map with polygons containing both soil and land use information. Basic arithmetic functions such as addition, subtraction, multiplication, and division can be very useful. Values from different map layers can be used in an equation to create a new map showing the results. This facilitates the use of models based on simple formulas.

GIS can support buffer generation, that involves the creation of new polygons from points, lines, and polygon features stored in the database. If, for example, the location of farm areas within 100 m of a stream that receives pesticide applications needs to be identified, the area could be found using a buffer command in GIS. Digital terrain analysis that involves the computation of a variety of outputs based on digital elevation data is also supported by GIS. Some examples of outputs include:

watershed boundary generation, slope and aspect maps, cross sectional views, and 3-dimensional views.

### Displaying data

GIS can provide hardcopy maps, statistical summaries, modeling solutions, and computer graphic displays for both spatial and tabular data. A typical report summary may list the total area occupied by each soil type.

## Sources of error

There are many possible sources of error that GIS users must understand. Datasets may become obsolete; particularly when dealing with land-use data, the older the data is, the more inaccurate it could become. The area coverage of the map may not be uniform, i.e., the mapper may have mapped at different intensities. The user must be aware of map scale when determining the proper use of a map. For example, site-specific interpretations are inappropriate when using small-scale maps. The user should know the distribution and density of observations used in creating the original map. When converting data from vector to raster format, the size of each grid cell is important; if the grid cell size is too large then details from the original map will be lost. And misuse of logic during analysis can result in the erroneous interpretation of maps. Table 1 identifies possible sources of error that may occur as data are processed through each function of a GIS. Because GIS is such a powerful tool for data manipulation, the opportunities for misuse are great too. An unscrupulous user can produce maps and analytical data that serve his or her purpose while being

**Table 1. Possible sources of error during the processing of GIS data.**

| Function | Sources of error |
|---|---|
| Input | Poor quality of original data<br>Digitizing process<br>Database entry errors |
| Manage | Data update errors<br>Data compression |
| Manipulate | Vector/raster conversion<br>Data interpolation<br>Over-generalization of map data |
| Analyze | Misuse of logic<br>Modeling |
| Display | Improper class intervals<br>Plotted maps may not meet cartographic standards |

completely false. All users can make serious mistakes if the analytical results are not thoroughly verified.

When deciding whether or not to adopt GIS technology, there are a few things that must be taken into account. There should be a long-term commitment with repetitive use of the data, along with significant user training. Hardware and software are expensive, and can become obsolete. There is a choice of using either commercial or public domain software. Commercial software is expensive, but user support is usually good and the software is mostly error free. Public domain software is generally available free of charge but may have less user support and a few errors in the programs.

## Benefits

There are many benefits to be derived from implementing a GIS program. GIS provides greater accuracy for measurements and calculations of lengths and areas on a map. It allows for easy access to large amounts of data, thereby providing timely responses to user inquiries. It is an excellent decision support tool, and it allows for analysis of "what if" scenarios. And lastly, spatial models can be incorporated into GIS for landscape analysis.

## Application of GIS technology

Several journals and books (CAD-TS 1981, Landon 1984, Burrough 1986, and FGISTM 1991) are available on this subject, and the reader should consult them to obtain ideas for application and, more importantly, on how to handle digital information. As in any science, unreliable data must be rejected and should not be used under any circumstance. However, the quality of data may not be known to the GIS specialist and for this reason, it is essential that the data source is acknowledged in the digital products. A second important rule is that a map should not be enlarged from its original scale. If the original map is at a scale of 1:100 000, the final product may be at 1:250 000 or 1:500 000, but never at 1:50 000. If several data layers are being overlaid, the scale of the smallest scale map determines the largest scale of the final GIS product. An example is provided below to illustrate the application of GIS.

### Cimanuk watershed study

The study covered the Cimanuk watershed in West Java, Indonesia. The watershed covers approximately 425 000 ha and has a tropical climate.

The objectives of the study were to evaluate the spatial distribution of constraints to sustainable agriculture, to match soil conditions to crop performance and thereby recommend areas for crops, and to assess land use for the area to aid in land-use policy decisions. The original survey was done in 1976 by the Food and Agriculture Organization (FAO) and the Soil Research Institute of Bogor, Indonesia (Soil Research Institute 1976). The soil map was digitized at 1:100 000 scale; there are a total of 622 polygons with 158 different map units. The following data were provided for each map unit: USDA Soil Taxonomy classification to the subgroup level, slope, depth, texture, coarse fragments, drainage, base saturation, cation exchange capacity, available phosphorus (P), exchangeable potassium (K), and pH.

The maps were digitized using the Geographic Resource Analysis Support System (GRASS, version 4.0) GIS software on a UNIX operating system. The tabular attribute data were entered on a relational database system called INFORMIX, and database queries were made using the Standard Query Language (SQL) in INFORMIX.

First, the soil boundaries were digitized, and the digitized map edited. Each polygon was then labeled with a map unit number from the original maps that related it to the attribute data listed in a table. The tabular attribute data were later entered, using a code, into a INFORMIX database. Coding of the attributes makes it easier to query the data-base, using SQL, and also conserves computer storage space. Table 2 lists the codes used with the corresponding attributes. The database contains a record for each of the 158 map units, and each record has a coded value for each of the different attributes.

The first map that was created showed the USDA Soil Taxonomy classification at the order level (Fig. 1). Maps showing some important soil properties were then created, and included: slope, depth, texture, drainage, pH, and available phosphorus.

It is useful to identify areas where there may be biophysical constraints to implementation of sustainable agriculture. Based on some of the soil properties in the database, a biophysical constraints map was developed. Four biophysical constraint classes were defined: unsustainable, moderate, few, and very few. A map unit was classified as unsustainable if: the slope was steep or very steep, or the depth was shallow, or the coarse fragment was skeletal, or the pH was very acidic or very alkaline (Table 3). The resulting map is shown in Figure 2, and is a good example of how the attributes of different soil properties can be used to create an interpretive map.

In addition to maps, a report was output that lists the total area of each of the soil orders in the watershed (Table 4). Within each order, the total area for each class of the biophysical constraints map is also reported. Maps were then developed showing potentials for growing particular crops. Crop potentials were identified using three classes: high, medium, and low. The two most important soil properties that influence each crop were identified (Table 5) and were used to create the crop potential classes shown in Table 6.

Maps were produced identifying potentials for such traditional crops as paddy rice, upland rice, coconut, banana, and papaya. Maps identifying potentials for nontraditional crops were also made, and included: cocoa, roselle, jute, oil palm, and rubber. One reason for identifying potentials for these nontraditional crops is that they could possibly provide added economic stability to the area while maintaining the sustainability of the land.

## Conclusion

It is important to note that at a scale of 1:100 000 the resulting maps should only be used for making a general assessment. Site-specific interpretations, e.g., for a small farm, are not appropriate using this data. Only with more detailed site information can a reasonable assessment be made for a specific location.

For the above example, the interpretations are theoretical in nature and are based only on the data available. The methods used to make these interpretations were not validated. Future study of this area to gather more data is necessary for a more comprehensive assessment. Crop selection and land-use options are largely determined by the prevailing socioeconomic conditions occurring at a location. Therefore, demographic data is crucial in forming a valid assessment of land-use options and crop potentials.

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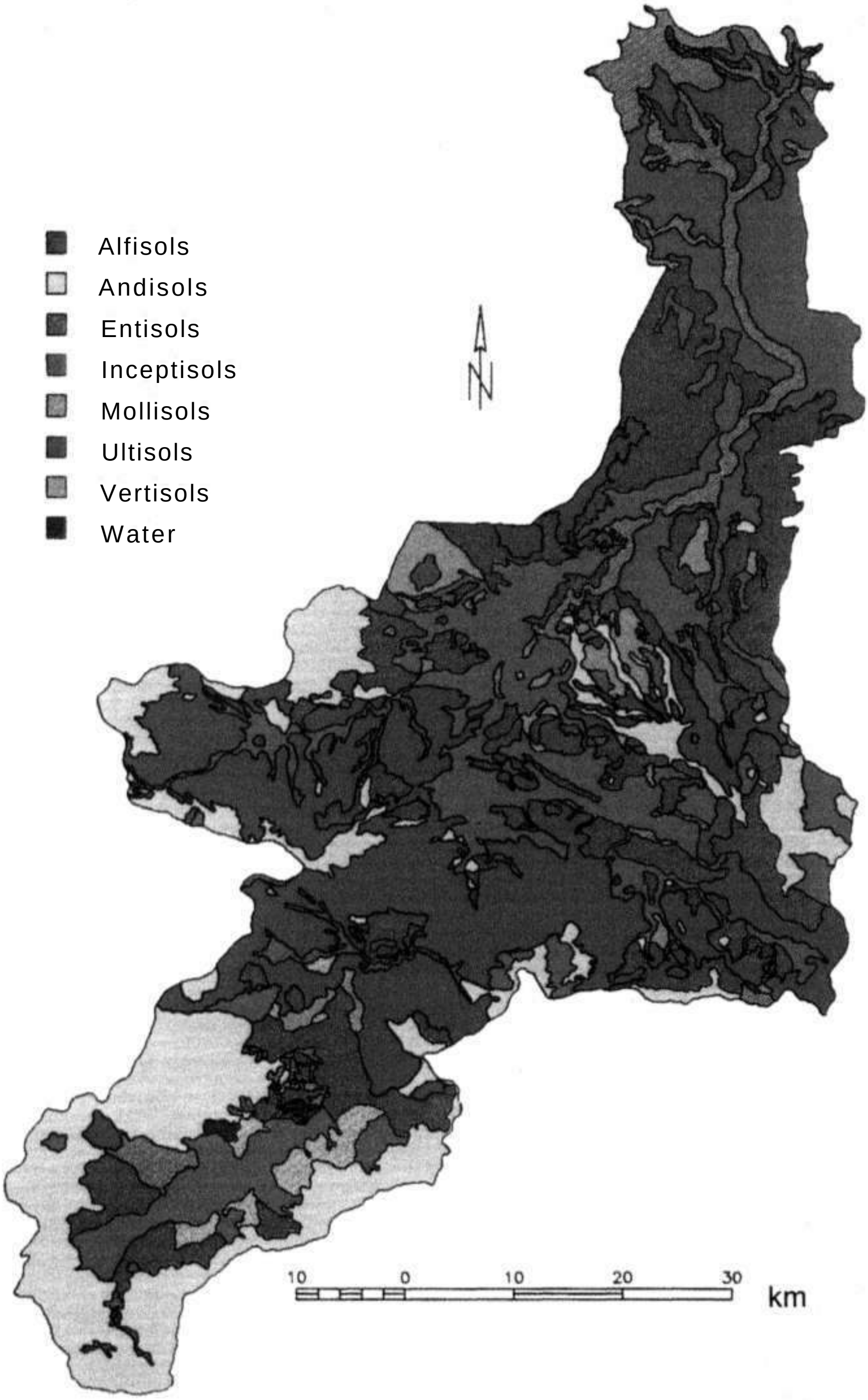


*Figure 1. Soils classified by order (USDA Soil Taxonomy Classification), Cimanuk watershed, West Java, Indonesia. (Source: USDA—Natural Resources Conservation Service, World Soil Resources)*

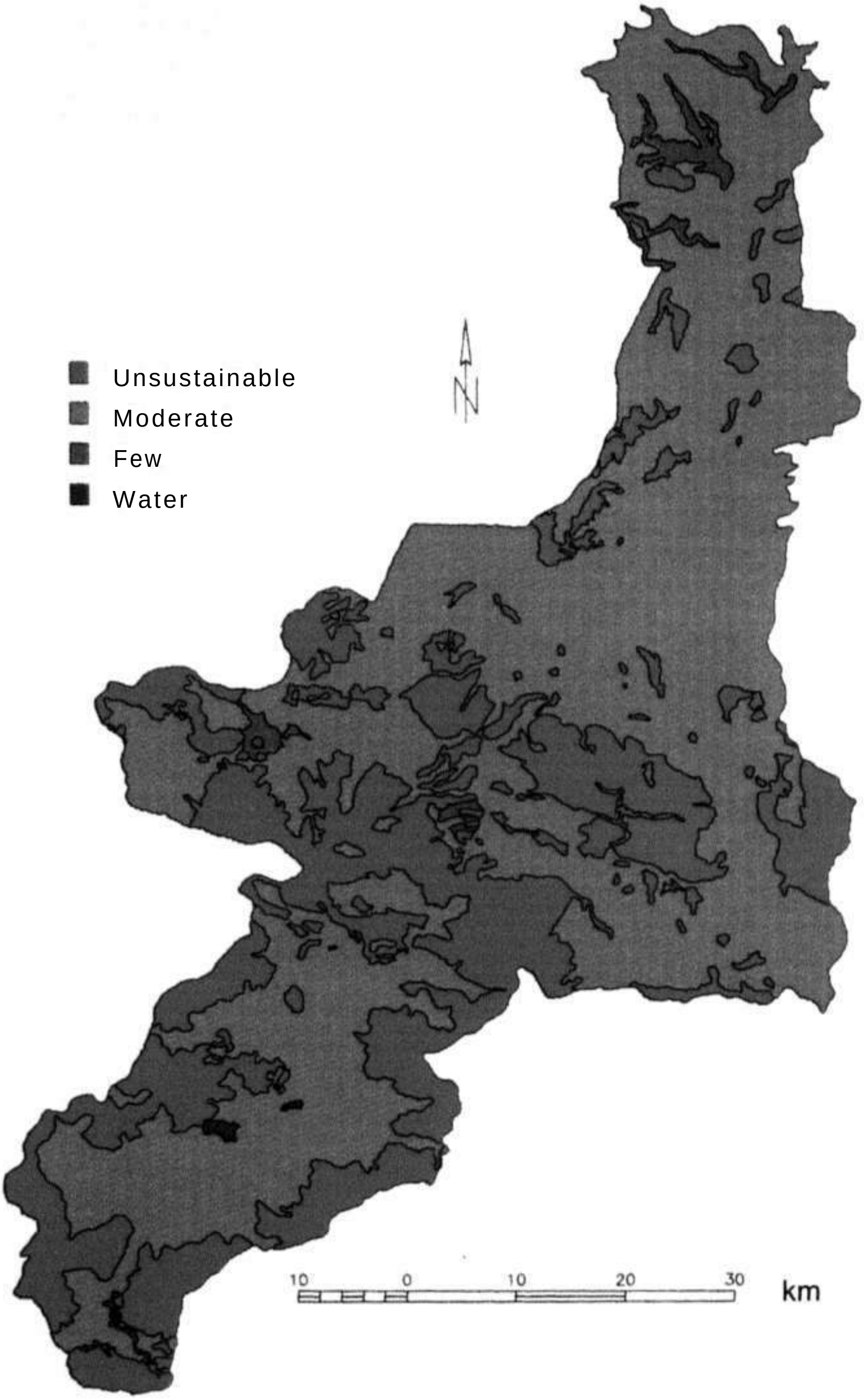


*Figure 2. Biophysical constraints to the implementation of sustainable agriculture, Cimanuk Watershed, West Java, Indonesia. (Source: USDA—Natural Resources Conservation Service, World Resources).*

**Table 2. Tabular database codes and attributes[1].**

| | |
|---|---|
| **Map unit**<br>Numbered 1 to 158 | **Drainage**<br>E = excessive; WE = well to excessive<br>W = well; MW = moderately well<br>SP = somewhat poor; P = poor;<br>VP = very poor |
| **Soil**<br>Four letter code used in the<br>Keys to Soil Taxonomy 1990 and<br>Proposed ICOMAQ Keys 1991 | **Base saturation**<br>L = <35%, low; M = 36-75% medium<br>H = >75% high;<br>ND = no data |
| **Slope**<br>L = 0-5% level<br>ML = 0-15% moderately level<br>GSL = 5-15% gently sloping<br>MSL = 15-35% moderately sloping<br>ST = 35-50% steep; VST = >50% very steep | **CEC (me/100 g soil)**<br>L = < = 10 low<br>M = 11-20 medium<br>H = >20 high<br>ND = no data |
| **Depth**<br>S = 0-50 cm shallow<br>D = >50 cm deep | **Available P (ppm)**<br>VL = <10 very low; L = 10-20 low;<br>ML = 20-40 moderately low;<br>M = 40-60 medium;<br>MH = 60-80 moderately high<br>H = 80-120 high; VH = >120 very high;<br>ND = no data |
| **Texture**<br>S = sand; LS = loamy sand; L = loam;<br>SI = silt; SL = sandy loam;<br>CL = clay loam; SICL = silty clay loam<br>SIL = silt loam; SCL = sandy clay loam<br>C = clay; SIC = silty clay; SC = sandy clay | **Exchangeable K (me/100 g soil)**<br>VL = <0.2 very low; L = 0.2-0.3 low;<br>M = 0.4-0.5 medium<br>H = 0.6-1.0 high<br>VH = >1.0 very high<br>ND = no data |
| **Coarse fragments**<br>S = skeletal<br>G = gravelly<br>N = no fragments | **pH $H_2O$ (1:2.5)**<br>VAC = <4.2 very acid; AC = 4.3-5.2 acid;<br>SAC = 5.3-6.2 slightly acid;<br>N = 6.3-7.2 neutral;<br>SAK = 7.3-8.2 slightly alkaline<br>AK = 8.3-8.7 alkaline;<br>VAK = >8.7 very alkaline; ND = no data |

1. Database query example:

Select map unit if slope = "L" or "GSL" and pH = "SAC" or "N". This query would output all map units that have a slope which is either level or gently sloping, and a slightly acid or neutral pH.

**Table 3. Biophysical constraints to implementation of sustainable agriculture: attributes for each class[1].**

| | |
|---|---|
| **Unsustainable** | slope = ST, VST<br>depth = S<br>coarse fragments = S<br>pH = VAC,VAK |
| **Moderate** | slope = GSL, MSL<br>texture = C, S, LS<br>coarse fragments = G<br>drainage = E, P, VP<br>base saturation = L<br>CEC = L<br>available phosphorus = L, VL<br>exchangeable potassium = L, VL<br>pH = AC, SAK, AK |
| **Few** | slope = ML<br>texture = SL<br>drainage = WE, SP<br>base saturation = M<br>CEC = M<br>available phosphorus = ML<br>pH = SAC |
| **Very few** | slope = L<br>depth = D<br>texture = L, SI, CL, SICL, SIL, SCL, SIC, SC<br>coarse fragments = N<br>drainage = W, MW<br>base saturation = H<br>CEC = H<br>available phosphorus = M, MH, H, VH<br>exchangeable potassium = M, H, VH<br>pH = N |

1. Beginning with 'unsustainable', any category chosen in one class is excluded from all others. The 'very few' class has no categories that were found in the first three classes. See Table 2 for a description of the attribute codes.

**Table 4. Raster map category report[1].**

| Order/constraint class | Area (ha) | Cover (%) Watershed | Cover (%) Order |
|---|---|---|---|
| Alfisols | 84 200 | 20 | 25 |
| Unsustainable | 20 700 | | 25 |
| Moderate | 63 500 | | 75 |
| Andisols | 75 200 | 18 | |
| Unsustainable | 48 700 | | 65 |
| Moderate | 26 500 | | 35 |
| Entisols | 26 200 | 6 | |
| Unsustainable | 1 000 | | 4 |
| Moderate | 20 000 | | 76 |
| Few | 5 200 | | 20 |
| Inceptisols | 110 100 | 27 | |
| Unsustainable | 23 700 | | 22 |
| Moderate | 84 100 | | 76 |
| Few | 2 300 | | 2 |
| Mollisols | 5 600 | 1 | |
| Moderate | 5 600 | | 100 |
| Ultisols | 98 600 | 24 | |
| Unsustainable | 37 600 | | 38 |
| Moderate | 61 000 | | 62 |
| Vertisols | 10 700 | 3 | |
| Moderate | 10 700 | | 100 |
| Water | 500 | <1 | |
| Water | 500 | | 100 |
| Total | 411 100 | 100 | |

1. This table is based on a report output directly from GRASS GIS using a simple report generation command. The area occupied by each soil order is identified along with the area of each constraint class found within each order.

**Table 5. Selected crop requirements.**

Rice (*Oryza sativa*)
Optimum pH 5.5-6.5 dry, 7.0-7.2 flooded
Alluvial soils of river valleys and deltas are usually better suited to rice than lighter soils. Level slope is best.

Banana (*Musa* spp)
Optimum pH 6.5 range 5.5-7.5
Thrive best on free-draining loam, will not tolerate any waterlogging.

Cocoa (*Theobroma cacao*)
Optimum pH 6.5 range 5.5-7.5
Ideal soil consists of aggregated sand, silt, and clay.

Coconut (*Cocos nucifera*)
Need freely draining light soils; and tolerate higher degree of soil salinity than most other crops.

Oil palm (*Elaeis guineensis*)
Requires deep, permeable soils, terrain should have slopes < 8 to 10 degrees unless terracing already exists. Waterlogging is harmful.

Rubber (*Hevea brasiliensis*)
Optimum pH 4.4-5.2
Needs deep, well drained soils.

Jute (*Corchorus* spp.)
Prefers fertile alluvial soils, in lowlands and is usually grown in rotation with rice.

Roselle (*Hibiscus sabdariffa*)
Requires well-drained soils. Grown on uplands.

**Table 6. Crop potentials: attributes for select crops[1].**

| Crop | Attribute | Potentials Low | Medium | High |
|---|---|---|---|---|
| Rice (paddy) | Slope | MSL | ML, GSL | L |
| | pH | AK, VAK | SAK, VAC | N, AC, SAC |
| Rice (upland) | Slope | ML | GSL | MSL |
| | pH | AK, VAK | SAK, VAC | N, AC, SAC |
| Banana and Papaya | Slope | L | MSL | GSL |
| | pH | VAC,AK,VAK | AC, SAK | SAC, N |
| Cocoa | Slope | L | GSL | MSL |
| | Drainage | SP, P, VP | E, MW | WE,W |
| Coconut | Slope | ML, MSL | GSL | L |
| | Texture | Sandy | Clayey | Loamy |
| Oil palm | Drainage | E, P, VP | WE, SP | W, MW |
| | pH | VAC, SAK, AK, VAK | AC, N | SAC |
| Rubber | Drainage | MW, SP, P, VP | W | E, WE |
| | pH | N, SAK, AK, VAK | VAC, SAC | AC |
| Jute | Drainage | MW, SP, P, VP | E | WE,W |
| | Slope | MSL | ML, GSL | L |
| Roselle | Drainage | MW | WE, W | E |
| | Texture | Sandy | Clayey | Loamy |

1. Categories with a slope >35% were not included. See Table 2 for a description of the attribute codes.

# Crop Distribution Mapping: Applications and Techniques for Broad-scale Analysis of Crop Geography

**G Hyman**[1]

This paper describes the International Center for Tropical Agriculture's (CIAT) project to map the broad-scale distribution of agricultural crops in mainland Latin America. The data collection and pre-processing stages of data development are described. Techniques for estimating distributions within administrative divisions are considered. The utility of remote sensing information is evaluated and some basic applications of crop distribution information are discussed.

## The CIAT crop production database

Maps of crop distribution are critical for commodity studies, agroecological modeling, and numerous environmental applications. Perhaps the most basic need is to know how many hectares have been cultivated, where the cultivation has occurred, and how much food has been harvested. As part of CIAT's goal of analyzing land-use patterns and dynamics, we have developed a database of crop production for Latin America. The information in this database, important for many CIAT activities and for those of our partners, has numerous uses for agricultural research. Agroecological modeling can help to determine if farmers are growing the most appropriate crops for the given biophysical environment. The crop distributions help modeling of climatic and other environmental changes and their effects on agriculture. For example, the modeling of expected changes in crop distribution caused by global warming requires accurate maps of the current spatial extent of crops. Crop distributions will be critical for continental-scale land degradation research. The georeferenced digital data allows us to make the link between environmental degradation and agriculture. For CGIAR scientists and our NARS partners, crop distribution mapping can help guide our crop improvement programs by aiding breeders to understand the relationships between crops and the environmental constraints in which they are grown.

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In the past, CIAT has developed digital maps of crop distributions and densities for Latin America, Africa, and Asia, focusing on the CIAT commodities. In 1996, as part of the Ecoregional Project for Latin America, we initiated a program to improve our contacts with crop data providers, update our previous crop distribution maps, map new crops, and automate the process for future updates. This year our focus has been on database development and automated mapping of crop distributions.

CIAT has obtained the most recent crop distribution data at the best available geographic resolution for the 21 mainland Latin American countries. Table 1 shows the date of our most recent crop data, the number of crops we hold data for, the collection method, and the administrative level of the information. The range of dates of the information points out only one difficulty of merging data from individual countries across a broad region. The geographic detail of the data also varies. For example, Honduras recently completed a relatively detailed agricultural census; in contrast, Costa Rica's last census was in 1984. Their current data are available only at the national level. Many countries provide sample data rather than census data. The sample data are derived by accepted international standards and may actually be better than the census data due to the difficulties of carrying out a complete census. Nevertheless, all the information must be carefully studied to assess its comparability from one country to the next. We are investigating data quality problems in our efforts to reduce errors and provide metadata. We have linked over 75% of the tabular crop data to the third-level administrative division maps. So far our efforts have focused on the principal crops of the region and those of particular interest to the CGIAR system. However, this project has purposely sought to look at the broad range of crops in order to take a more comprehensive view of the agricultural sector in Latin America. From the "Number of crops" column in Table 1, it may be noted that we have gone far beyond our previous focus on CGIAR mandate crops.

## Raster modeling for geographic analysis and improving crop distributions within administrative units

The vector data structure of the CIAT crop database is optimum for handling the large amounts of crop data collected but is deficient for many purposes. While it can store information for the administrative unit, it cannot display the distribution of crops within the unit. In the past, our methods to locate distribution within administrative units have relied on the subjective interpretation of the map technician. To estimate the distribution, the technician uses his knowledge of the crop environments and map interpretation skills. The method is quite useful and will produce accurate maps for the scale of the project. However, this manual method has two important limitations. First, the subjectivity of the work may limit the data for purposes of comparison, especially if different technicians work on the same map or if time series maps are used. Secondly, the technique is time-consuming and therefore limited by the human resources that can be assigned to do the work.

An even more critical limitation of the vector format is its insufficiency for modeling purposes. Perhaps as much as 90% of spatial analysis and modeling is carried

**Table 1. CIAT crop distribution database[1].**

| Country | Administrative level | Year | Number of crops | Collection method |
|---|---|---|---|---|
| Belize | Department | 1994 | 42 | Census |
| Costa Rica | Country | 1993-95 | 14 | Sample |
| El Savador | Region | 1994 | 7 | Sample |
| Guatemala | Department | 1989-95 | 6 | Sample |
| Honduras | Municipality | 1993 | 63 | Census |
| Mexico | Municipality | 1991 | 78 | Census |
| Nicaragua | Department | 1995 | 9 | Sample |
| Panama | Municipality | 1990-91 | 17 | Census |
| Argentina | Department | 1991 | 6 | Census |
| Bolivia | Municipality | 1987-95 | 20 | Sample |
| Brazil | Municipality | 1993 | 62 | Census |
| Chile | Department | 1979-94 | 40 | Sample |
| Colombia | Department | 1993 | 26 | Sample |
| Ecuador | Region | 1991-93 | 93 | Sample |
| Guyana | Commune | 1993-94 | 19 | Census |
| French Guyana | District | 1994 | 9 | Census |
| Paraguay | Department | 1995 | 35 | Sample |
| Peru | District | 1993 | 229 | Sample |
| Surinam | Municipality | 1990-91 | 44 | Census |
| Uruguay | Department | 1993 | 61 | Census |
| Venezuela | Federal District | 1984-85 | 25 | Sample |

1. Note that CIAT has taken a much more comprehensive approach to agricultural land use analysis by collecting data for a large number of crops. This is a significant advance over previous work when only core commodities of CIAT were studied.

out using raster data structures. We have thus recognized the importance of redistributing the vector data to a raster format. We carried out some preliminary work on this in 1996 and developed the first modeling results this year. This type of conversion has not been attempted for agricultural crops. However, Deichmann (1996) has developed vector to raster redistribution models for population data as part of the UNEP/CGIAR initiative on the use of GIS in agricultural research. We are using a similar approach, tailoring the work to crops instead of population.

Our first efforts to improve crop distribution information within administrative units have focused on the use of a continental scale land cover map and an accessibility map. The continental land cover map was developed by the United States Geological Survey (USGS) in conjunction with the United Nations Environment Programme (UNEP) Global Resources Information Data (GRID) project. The source data is from Advanced Very High Resolution Radiometer (AVHRR) satellite imagery at 1 km spatial resolution—appropriate to continental scale analysis. In 1996, CIAT provided some of our crop and land cover datasets to USGS for verification purposes. We continue to work with USGS in their efforts to improve the quality of these data.

To better estimate the distribution of crops within an administrative unit, we used accessibility information on the assumption that crops are more likely to be cultivated in conjunction with the road networks that allow transport to storage facilities and markets. This very basic assumption has a rich history in geographic literature (Chisholm 1979) and we employ it here as a first approximation with the expectation of refining our methods in the future. The accessibility map was developed using a cost-distance approach. The map utilizes the Digital Chart of the World (DCW) road network and map of populated places (Defense Mapping Agency 1994). Towns with human population of 10 000 or more are assumed to have maximum accessibility and represented by individual grid cells on the digital map. For all roads and trails, a travel velocity is assumed. The roads are organized in a hierarchy so that highways and paved roads are assigned greater velocities than dirt roads or trails. Areas at great distance to populated places are less accessible than areas nearby towns. For each grid cell, the time that it takes to reach a town is calculated using distance and cost functions. These tools are widely available in standard GIS software packages (e.g., IDRISI, GRID-Arc/Info). The resulting map gives us an index of accessibility for the study area.

The vector to raster conversion of the crop data is carried through in two phases. First, all areas in forest from the USGS land cover map are assumed to have no cropland, effectively masking these areas out during future processing. Second, the total crop area is redistributed within the administrative unit based on the accessibility index. The accessibility index is transformed into a municipality level potential surface by dividing the value at each grid cell by the sum of the indices within each municipality. This is a simple way of weighting areas according to their ease of access to urban areas. The weighted potential surface is then combined with the crop data to estimate the distribution within municipalities. The method still falls short of the results obtained by the individual technician making subjective judgements about where crops are cultivated. Next year, our group will refine this process to include such ancillary data as elevation and climate. We expect to obtain results equal to those of our previous methodology, while overcoming the problem of subjectivity and at the same time automating the process.

## Applications

The processing described above has been automated and developed with a graphical interface that allows a user to select a country and a crop for mapping (Klass 1997). The programs are then run, making a new point dataset for display and further analysis. Users can choose the thresholds for displaying the density of crop production. This interface effort has only just begun and will be refined in the future along with the methodology. Any of the crop data shown in Table 1 can now be processed to produce maps. The map of maize distribution, together with a similar map of wheat distributions, are CIAT's first maize and wheat maps ever (Hyman 1997). Maize experts at CIMMYT are evaluating the map and its associated data. They have high expectations for using this information for crop improvement and economic analyses of their core crops.

For studies of the whitefly virus, we have mapped the distribution of beans in relation to the known occurrence of bean golden mosaic virus (BGMV). This is a simple application with potentially huge benefits. Researchers working on BGMV can now define critical areas of bean production that are being affected by the virus, as well as those areas that should be protected from future infestation. Once the production and virus data is related to the physical and human geography of bean growing regions, whitefly researchers can better understand the behavior of the virus, especially with respect to its spatial diffusion.

The crop and livestock mapping efforts are slated to become key datasets for several collaborative projects already under way. The crop production dataset will be used as a variable in the CIAT-UNEP indicators project. CIAT will use the data for a study of crop distributions of Latin America, an investigation along the lines of some of the classical agricultural regionalization work carried out for North America.

One of the most important aspects of our crop and livestock database efforts is institutionalization of the work. We will be able to analyze agricultural land use in a timely manner, at greater frequencies, and with an expanded view of the crops of Latin America.

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# Use of Remote Sensing in Distribution of Environment and Crop Distribution

**L Venkataratnam[1]**

## Introduction

Precise information on various natural resources—soils, water, crops, forest, geology, and climate—on their degradation/depletion and contamination is essential for an environmentally balanced development. India has varying conditions of climate, soils, flora, and fauna, diversified agricultural practices, and land-use patterns. Due to unscientific exploitation of various resources, environmental problems like land degradation, drought, floods, deforestation, and decrease in productivity levels are on the rise. Lack of reliable information on natural resources from a reliable database has also contributed to the aggravation of the problems. Therefore, for better environmental management, there is a need to prepare natural resources inventories, study various environmental problems scientifically, and prepare action plans for sustainable development of natural resources.

## Development of remote sensing technology

The application of remote sensing technology in the study of natural resources has resulted in the development of methodologies for mapping and monitoring natural resources in a cost-effective manner. This is due to the fact that remote sensing satellites have a synoptic view, cover the same area at regular intervals, collect data in multispectral channels of the electromagnetic spectrum, and data generated can be analyzed on computers at a faster rate. Besides, remote sensing satellites provide more reliable and precise baseline information on crops, soils, and water resources than conventional surveys.

The application of spaceborne remotely sensed data for natural resources inventory began with the launch of the first Earth Resources Technology Satellite (ERTS-1)/Landsat-1 in the 1970s. Landsat-TM (Thematic Mapper), Systeme Probataire d'Observation de la Terre (SPOT), and Indian Remote Sensing Satellites

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(IRS) with better spatial and spectral resolution form the subsequent generation of satellites that enabled mapping and monitoring of various resources more efficiently. Systematic application of spaceborne remote sensing data in mapping various resources enabled development of operational methodologies to map and monitor salt-affected soils, eroded soils, waterlogged areas, environmental changes due to mining, deforestation, drought, floods, etc.

## Assessment and monitoring of natural resources

Remotely sensed data are being regularly utilized in generating information on various resources and also in monitoring the land degradation and environmental hazards. In the following sections, the application of remotely sensed data in soil resources, degraded lands, land use/land cover, environmental hazards, and crops is discussed.

## Remote sensing of soils

Systematic application of spaceborne remote sensing data in soil resources mapping enabled development of operational methodologies to map soils on a routine basis. Visual interpretation of satellite data from various satellites like Landsat-Multispectral Scanning System (MSS), TM, IRS, and SPOT, based on photoelements and ancillary data is a common method in the preparation of soil maps at various scales. Operational methodologies were developed at the National Remote Sensing Agency (NRSA), Hyderabad, India, to prepare soil maps at 1:250 000 and 1:50 000 scales in various agroclimatic regions of the country (NRSA and AISLUS 1986; NRSA 1995, 1996). A soil map for the entire country at 1:500 000 scale is being published by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur. In 1995, the Department of Space took up soil mapping under the project 'Integrated Mission of Sustainable Development' on a 1:50 000 scale using IRS LISS (Linear Image Self-Scanning Sensor)-II data.

Limited work has been reported in the literature on soil mapping using digital analysis techniques. Reliance on digital techniques is increasing in order to handle voluminous data inflow and to meet the increasing demands for planning. The utility of GIS in soil resources evaluation is also increasing. Major GIS applications in soil resources study are land capability classification, land irrigability classification, water management for crops, watershed management, crop suitability assessment, and generation of sustainable action plans (NRSA 1996, Sharda et al. 1993).

## Mapping and monitoring of degraded lands

Remotely sensed data has been utilized to study the nature, distribution, and magnitude of problems in various classes of degraded lands, namely eroded lands, salt-affected soils, shifting cultivation areas, waterlogged areas, ravinous lands, etc.

NRSA, using remotely sensed data from Landsat MSS, TM, and IRS LISS-I/LISS-II sensors, mapped and monitored the areas under erosion and shifting cultivation in parts of Tripura (NRSA 1990). In the study area, nil to slight, moderate, and severe to very severe erosion classes were mapped along with areas under shifting cultivation at 1:250 000 scale. At 1:50 000 scale, the above-mentioned soil erosion classes could be mapped as pure units and small areas that could not be mapped at 1:250 000 scale (due to scale limitation) could also be detected. Besides current *jhum* (shifting cultivation) lands, abandoned *jhum* areas could also be identified and mapped. Computer-aided digital analysis was attempted for the same test site. Nil to slight, moderate to severe erosion classes, and *jhum* lands could be classified in Tripura because digital analysis depends solely on spectral response of classes. The monitoring of eroded and shifting cultivation areas in the study area using Landsat MSS data of 15 Apr 1978, and Landsat TM data of 26 Mar 1986, revealed that the area under nil to slight erosion class decreased from 19.46% in 1978 to 5.62% in 1986. The area under moderate erosion has increased from 30.94 to 36.97% during the same period. A similar upward trend was found in the severe to very severe category during an 8-year period. The area under shifting cultivation increased from 5.13% in 1978 to 6.54% in 1986.

NRSA in association with NBSS&LUP (Nagpur), All India Soil and Land Use Survey (New Delhi), and other central and state government organizations, prepared salt-affected soil maps for the entire country at 1:250 000 scale using Landsat TM/IRS imagery. This has been made possible due to the clear manifestation of salt-affected soils on False Color Composite (FCCs) of satellite data from bright to dull white tones within the background of normal soils supporting good crops. The maps showing salt-affected soils at 1:50 000 scale have been prepared for limited areas. Digital techniques were also used to study the salt-affected soils (Venkataratnam and Rao 1977, Venkataratnam and Ravi Sankar 1992).

Both visual and digital methods of analysis are used for monitoring the salt-affected soils. Venkataratnam (1983, 1984) used the multitemporal data of Landsat to monitor the salt-affected soils vis-a-vis reclamatory efforts taken up by the state government authorities for parts of Punjab and Haryana States. The salt-affected soils were monitored in the Mainpuri district of Uttar Pradesh using Landsat MSS data of 1975 and Landsat TM data of 1986 (Rao et al., in press). The degraded lands (salt-affected and waterlogged areas) occurring in the Sharada Sahayak Command area were studied at NRSA from 1975 to 1993, using satellite imagery of every 5 years available from Landsat MSS, TM, and IRS sensors. Similar efforts are being made in other major command areas.

Spaceborne multispectral data have also been utilized in mapping and monitoring of waterlogged/wetlands/marshy areas because waterlogged areas appear in different shades of bluish green or greenish blue patches on satellite data with smooth texture.

## Land use/land cover inventory

Information on land use/land cover is essential to identify such land utilization aspects as cropping pattern, fallow land, forests, grazing lands, wastelands, surface water bodies, etc. Remotely sensed data from TM, IRS, and SPOT are being used to map land use and land cover at micro and macro levels. In India, land use and land cover of all the 447 districts, distributed across 15 agroclimatic zones have been mapped on a 1:250 000 scale. For some selected areas, maps of 1:50 000 scale were also prepared. The satellite data were also used for monitoring the land use/cover changes over a temporal scale to enable implementation of timely measures to arrest degradation and conserve valuable land resources. Satellite data enables mapping of surface water in tanks, lakes, reservoirs, and depressions. Heavily silted tanks could be identified for prioritizing soil conservation in the upstream areas.

## Assessment of environmental hazards

Satellite data from various sensors are employed to assess the impact of mining, deforestation, forest fires, and aquaculture on the surrounding environment. These data are also used in assessing natural disasters like drought, damage due to floods and earthquakes, etc.

Mining can cause severe ecological implications if proper planning and management strategies are not adopted. Remotely sensed data were found to be extremely useful in assessing the environmental impact of mining. In a study of the iron ore mining at Kudremukh in southern India (Anonymous 1990) using satellite data of the pre-mining phase (1973, 1976) and the mining phase (1985, 1989), environmental changes as a result of the mining activity have been mapped. The total forest area of 74.27 $km^2$ in 1973 decreased by 10.8% by 1989, while the grasslands area of 97.94 $km^2$ in 1973 increased by 2.8% during the same period.

Recently, in one of the studies at NRSA, the areas under prawn cultivation along the coastal areas of Krishna and Guntur districts of Andhra Pradesh were monitored from 1973 to 1994. It was observed that although the prawn cultivation areas started initially in barren/salt-affected areas, these areas are being extended into prime rice fields and mangrove areas (Venkataratnam et al. 1997).

The satellite-derived vegetation index (VI), which is sensitive to vegetation stress, is used to monitor drought conditions on near real-time basis, helping decision makers to initiate strategies for mid-season corrections and other agronomic measures. The National Agricultural Drought Assessment and Monitoring System (N-ADAMS) has been developed for fortnightly assessment of drought in India. Every year, floods in major rivers are being monitored using remote sensing data to assess the damage due to floods and to identify risk zones.

## Crop studies

An accurate and timely crop production forecasting system is an essential element in strengthening the country's food security and distribution system. Remote sensing data can provide information on: 1. spatial distribution of crops and their areas, 2. crop condition assessment, and 3. crop yield prediction. The area's estimation procedure broadly consists of identifying representative sites of various crops/land cover classes on the image generation of signatures for different classes and classifying the image using training area statistics. Total enumeration or sampling techniques are employed to derive crop area statistics, depending upon the extent of the study area.

These procedures have been successfully operationalized under the Crop Acreage and Production Estimation (CAPE) project for crops like paddy, sorghum, soybean, wheat, groundnut, rapeseed-mustard, cotton, and jute/mesta (SAC 1990, Venkataratnam et al. 1993). The remote sensing technology proved its utility in monocropped areas of large, contiguous and homogenous nature. Pilot studies are being conducted using high resolution IRS-1C data under multiple cropping situations.

The condition of the crop is affected by such factors as supply of water and nutrients, insect pest attack, disease outbreak, and weather conditions. These stresses cause physiological changes that alter the optical and thermal properties of leaves and bring about changes in canopy geometry and reflectance/emission. Condition assessment warrants multispectral satellite data at regular intervals. The National Oceanic and Atmospheric Administration (NOAA)/Advanced Very High Resolution Radiometer (AVHRR), and Indian Remote Sensing (IRS)-Wide imaging and Field Sensors (WiFS) are being used to assess the crop condition at regional level, whereas the finer spatial resolution satellite data (TM, IRS-LISS-II/III) are being used at district and sub-district level. Condition assessment is normally done by computing vegetation indices on grid cell basis (SAC 1990).

Yield is influenced by a large number of factors such as crop genotype, soil characteristics, cultural practices, weather conditions, biotic influences like weeds, diseases, and pests. Spectral data of a crop is the integrated manifestation of the effects of all these factors. The two approaches generally available for yield modeling are: 1. relating remote sensing data or derived parameters directly to yield, and 2. relating to such biometric parameters as leaf area index, biomass, etc., that in turn, serve as input parameters for yield models. Efforts are being made to develop yield and spectral index relationships using spaceborne spectral indices such as the normalized difference vegetation index (NDVI).

## Conclusion

Remotely sensed data have been successfully used on an operational basis in not only preparing the natural resources inventory but also in assessing land degradation and other environmental hazards. The information generated both by conventional methods and remote sensing techniques is being used to create databases in GIS environment for performing integrated analyses to generate sustainable action plans, environment management plans, etc. Efforts are being made to use remotely sensed data from IRS-1C/ID satellites to map various resources at 1:12 500/1:10 000 scales for micro-level planning.

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# Interfacing GIS and Crop Simulation Models

**A D Hartkamp, J W White,[1] and G Hoogenboom[2]**

GIS facilitates the management and analysis of spatial data. GIS can also represent variation over time using time-series data from remote sensing or similar sources (Marble 1984). This approach can document historical trends but is less useful for evaluating different management scenarios or for extrapolating trends into the future. Crop simulation models can describe processes over time but usually produce outputs for specific sites. Thus, there is a logical interest in placing the site-specific output of models in a spatial context by interfacing GIS with models. Examples of possible applications of an interfaced GIS-model system include:

- prioritizing regions for potential impact of such new agronomic practices as direct sowing of wheat after rice.
- identifying rice-wheat production regions where nitrogen leaching may be especially high.
- evaluating the possible role of grain legumes in improving soil fertility or soil organic matter.

This paper considers issues related to terminology strategies, and limitations for interfacing GIS and models, with emphasis on agricultural research.

A 'model' is a simplified representation of a real-world situation. We focus on process-based simulation models, as opposed to rule-based (logical) and empirical (regression) models (Burrough 1996a).

In GIS applications to environmental problems, the term 'modeling' also appears frequently. 'Spatial modeling' refers to the use of such techniques as reclassification, overlaying, and interpretation that are used to produce summary maps (Yakuup 1993). 'Environmental modeling' includes techniques ranging from interpolating climate data to the use of data models and remote sensing. Most of these are computer-based tools rather than models per se, but environmental modeling also includes such process-based models as those used for groundwater flow and the fate of contaminants (Maslia et al 1994).

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## Strategies for interfacing

There are two fundamental issues in interfacing GIS with models. The first is the level at which the software systems are combined. Are files passed manually from one system to the other or, at the other extreme, are GIS and model functions programmed in a single software language as a unified system? This is essentially a problem of software development and management. Three systems based on the same simulation model, but interfaced at differing levels, should produce identical outputs. The second issue is the logical structure of the interface. This includes whether the model simulates all polygons or grid cells and whether dynamic attributes of one map unit affect attributes of other units.

## Level of interfacing

'Interfacing' is used to describe the overall concept of combining use of GIS with models. Three types of interfaces can be recognized:

- Simple linkages use GIS to display simulation results, usually with some form of spatial interpolation. More complex linkages use maps or a combination of these to process the data to produce a database containing inputs for a model. Linking usually requires little software modification. Simple transfer of files in ASCII or a common binary file format is sufficient. An example of a linked system is the Spatial Analysis Tool of DSSAT3.1 (Thornton et al. 1997).
- Combining also involves processing data in a GIS and displaying model results, but the model is configured with interactive tools of the GIS, and data are exchanged automatically (Burrough 1996a). Use is made of macro languages of the GIS or other programming languages (Tim 1996). Several process-based models have been combined with GIS (Table 1).
- Integration implies incorporating one system in the other. Either a model is embedded in a GIS, or a simple GIS (or GIS procedures) is included in a modeling system. There are few examples of process-based models integrated with GIS (Tim 1996). More often, integrated systems use simplified models. Examples include RAISON (Lam and Swayne 1991, Lam et al. 1996) and EGIS (Deckers 1993).

All levels of interfacing require knowledge of GIS, modeling, and programming. To simplify programming and subsequent use of interfaced systems, there is a clear need for modular systems that support standards for inputs and outputs, so that models and GIS may be interchanged easily. An example of this approach is in the DSSAT/ICASA file standards (Ritchie 1995) that have been used to link models with GIS in the Spatial Analysis Tool (Thornton et al. 1997) and to combine models and GIS in the AEGIS and AEGISWIN systems (Engel and Jones 1996; Engel et al. In press).

Table 1. Examples of models interfaced with GIS packages.

| Tool/Model | GIS system | Focus | Interface type[1] | DF[2] | Reference |
|---|---|---|---|---|---|
| AEGIS | PC Arc/Info | Regional land use planning | C | P | Calixte et al. (1992) Hoogenboorn et al. (1993) |
| AEGIS | Arc/Info | Regional land use planning | C | P | Lal et al. (1993) |
| AEGIS/WIN (DSSAT3) | ArcView | Precision farming | C | P | Engel and Jones (1996) Engel et al. (1997) |
| AGNPS | VirGIS | Cropland management and pollution | L | P? | Hession et al (1989) |
| AGNPS | ERDAS | Hydrology/pollution | C | R? | Olivieri et al. (1991) |
| AGNPS | GRASS | Watershed erosion/nutrient movement | ? | R | Engel et al. (1993) |
| AGNPS | Arc/Info | Water quality/pollution | C | P | Tim and Jolly (1994) |
| ANSWERS | GRASS | Watershed erosion/deposition | ? | R | Rewerts and Engel (1991) Srinivasan and Engel (1991) |
| CMLS | Arc/Info | Hydrology | L | P | Zhang et al. (1990) |
| CMLS | Arc/Info | Groundwater/herbicide fate | C | P | Wilson et al. (1993) |
| CMLS | ? | Pesticide fate | ? | ? | Foussereau et al. (1993) |
| DSSAT | IDRISI[3] | Crop management modeling, | L/C | R | Thornton et al. (1997) |
| EGIS (MODFLOW) | swGIS | Hydrology/pollution | I | ? | Deckers (1993) |
| GLEAMS | Arc/Info | Hydrology, groundwater | L? | P | Stallings et al. (1992) |
| GOA | Arc/Info | Land suitability evaluation | L | R | Brisson et al. (1992) |
| GISMO (EPIC) | GRASS | Erosion; climate variability/sensitivity | L/C | R | Martin and Neiman (1996) Goddard et al. (1996) |
| FLOWCONC | Arc/Info | Pesticide/herbicide fate | L/C | P | Lucke et al (1995) |
| MODFLOW | ? | Groundwater flow | ? | ? | Hinaman(1993) |
| PLANTGRO | Arc/Info | Forest production planning | L | P | Pawitan (1996) |
| RAISON | ? | Environmental modeling | I | ? | Lam and Swayne (1991) |
| RUSLE | ? | Erosion | I | ? | Blaszczynki (1992) |
| STREAMS | ? | Hydrology/erosion | ? | ? | Oslin et al. (1988) |
| SPUR | ERDAS | Watershed hydrology | ? | R | Sasowsky and Gardner (1991) |
| SWAT | GRASS | Watershed hydrology, water quality | L | R | Srinivasan and Arnold (1994) |
| SWAT | ArcView | Watershed hydrology, water quality | L/C | R/P | Stallings (pers.comm. 1996) |
| USTED (CLUE) | IDRISI? | Land use planning | C | R | Stoorvogel (1995) |
| USLE | MAP | Regional sediment load | L | R | Hession and Shanholtz (1988) |
| USLE | ? | Regional soil erosion | L | P | Ventura et al. (1988) |
| WOFOST | Arc/Info | Crop production potential/ land use planning | L | R | van Laanen et al. (1992) |
| ? | ? | Hydrology | I? | ? | Stuart and Stocks (1993) |

1. Interface type: L = linking; C = combining; I = integrating.
2. DF = data format; P = polygon, R = raster.
3. Idrisi-based, but handles Surfer and Arc/Info grid files in ASCII format.

## Interface structure

The appropriate structure for interfacing GIS and models varies with the research problem. Factors that affect the interface structure include whether map units can be assumed to act independently of one another, the complexity and scale of the processes being simulated, the format and type of input data, software systems available and in some instances, preferences within disciplines (Stoorvogel 1995, Tim 1996; Burrough 1996b).

### Interactions among map units

Map units are said to interact when values of units affect one another. Examples include water runoff, soil erosion, microclimate, and pest or disease dynamics. Two problems that must be faced are in which order should map units be evaluated and how should transfers among map units be allocated. For runoff, the order of evaluation can be structured along lines of flow down slopes or drainages, and flow to adjacent units can be partitioned based on slopes.

### Scale and complexity

The spatial coverage of a problem can vary from a subplot level up to a global level. Temporal scales can be in seconds to days or years. Related scales affecting the interfacing strategy include: measurement scale, original map and GIS scale, data manipulation scale, modeling scale, natural scale of the phenomenon, and scale of application (Burrough 1996b). The necessary map scale is often predefined. For regional studies, maps of scales between 1:100 000 and 1:250 000 are often used, whereas for farm-level applications, maps of scales of 1:1000 and 1:2500 are more appropriate (Garrity and Singh 1991).

The appropriate scale for the model is often less clear. In this context, the term 'scale' has three components: space, complexity, and time (Penning de Vries 1996). The spatial scale is often confined to the scale at which model parameters are collected. The level of model complexity involves the detail used in describing processes in terms of their physiological complexity and subsequent mathematical representation in the model. When applying models at regional level or larger, there is a tendency to emphasize simplification. However, Leenhardt et al. (1995) concluded that for soil and water variability, this is not theoretically justified. For equal experimental effort, simple approaches allow a greater spatial sampling density, but this is at the cost of the sphere of validity of the results.

### Nature of the spatial data for inputs

If point data for weather or soils show large variation in space, the data can be interpolated using such methods as kriging, co-kriging or thin plate splines. The choice of method is affected by spatial distribution of the data. The decision whether to manage data in a raster (grid) or vector (polygon) structure is often considered a critical step in developing GIS applications. However, incompatibilities between these structures have largely been overcome (e.g., the Spatial Analyst of ArcView), and GIS and models may be interfaced using both data structures.

### Model runs in relation to type and size of spatial unit

When the number of map units is large, various strategies may be taken. For interactive evaluation of scenarios, a 'point-and-shoot' interface can be used to simulate single or small sets of units. Alternatively, a subset of units can be evaluated. With the Monte Carlo method, a subset of units are chosen at random. Various forms of spatial analysis can be used to group units by similarity of model inputs (e.g., soil type). In a modified Monte Carlo analysis, units are pre-stratified to ensure that different regions are represented in proportion to their importance. For example, variable numbers of runs might be executed for different regions according to their relative importance as production areas or of their soil types. More runs may be executed for border cells to reduce edge effects.

## Example of GIS and model interfaces

Applications of interfaces of GIS and modeling have included agroecological characterization and zonation, scenario modeling, and impact assessment (ex ante as well as ex post), precision farming, spatial yield prediction, climate sensitivity/ variability studies, and regional risk analysis (Bouman 1993, Hoogenboom et al. 1993, Lal et al. 1993, Bouman et al. 1994, Petersen et al. 1995, Stoorvogel 1995, Mamillapalli et al. 1996, and Stockle 1996).

We will illustrate a simple application of GIS and modeling using the CERES wheat model to simulate variation in wheat yields and nitrogen leaching for a hypothetical region in Punjab, assuming a single set of weather conditions and cropping practices. The soil map recognized 14 different soil types, varying in surface nitrogen content and moisture retention parameters (drained upper and lower limits). This information was used to specify 14 field types in the model control file. CERES wheat was run for each field type for 3 years of weather data. The regions of highest grain yields (Fig. 1) corresponded to the regions with the lowest total nitrogen leaching over the season (Fig. 2).

## Challenges for the future

### Data sources

Crop simulation models are often criticized for the large requirements of input data. This has lead to the promotion of 'minimum datasets' such as those promoted by ICASA (Ritchie 1995), but these requirements often prove difficult to satisfy even for single locations. Availability of data can be restricted by concerns over data ownership (Kam 1996), but increasingly, data collected by government agencies are considered public goods (Bauer 1996).

## Error analysis

Spatial data have identifiable sources of error, including measurement, digitizing, interpolation, and manipulation. Besides effects of errors in inputs, simulation results may contain errors due to incomplete understanding of processes, deliberate simplifications in sub-models, or errors in programming. Conventional error propagation theory can assess the quality of modeling results only if they are influenced by random errors. For data used as model input from a GIS, error due to measurement and entry are usually random. However, some techniques used in GIS, such as logic models (e.g., suitability classes), contain systematic error of unknown magnitude to which error propagation theory is unsuitable (Drummond 1987). Burrough (1996b) recognized this problem and developed error propagation rules for several GIS procedures.

Other attempts at error analysis for GIS have used probability modeling, but this has proved problematic because of the diversity of spatial data processing procedures and the rigorous requirements of probabilistic data gathering. In a GIS, two major classes of error and uncertainty are positional error (digitizing, georeferencing) and thematic uncertainty and error. For spatial variability, fuzzy surfaces are used for uncertainty analysis, and for error analysis, Monte Carlo methods (Davis and Keller 1996) are used. For modeling, validation and Monte Carlo type uncertainty analysis can help determine error.

In interfacing GIS and models, data resolution and model organization are often changed, and error can increase because of aggregation effects. De Roo et ah (1989) found that modeling with the GIS-interfaced version of the model predicted 46% more runoff and 36% more erosion than with the original model. There is insufficient understanding of how aggregation and up- and down-scaling influence error propagation. Hill et al. (1996) estimated error using Monte Carlo type iterative processes for a range of model parameters, grid resolutions, and value estimates, where the rules of Burrough (1996b) were not applicable.

## Complexity of systems and interfaces

Although increased availability of computer-based tools improved the capabilities for analysis, there is no guarantee that increased analytical capability will improve science. Each computer-based tool is developed with its own conventions, procedures, and limitations, and linking them at a technical level does not guarantee understanding or useful prediction (Burrough 1996b). A growing problem is understanding how to structure the interface to address a given research objective. Engel et al. (In press) sought to produce an interface that demands less GIS knowledge of the crop modeler. However, when modeling and GIS become too easy, the need for calibration, validation, and investigation may be neglected (Burrough 1996a). In addition, interpretation of results is influenced by the user's knowledge of the system.

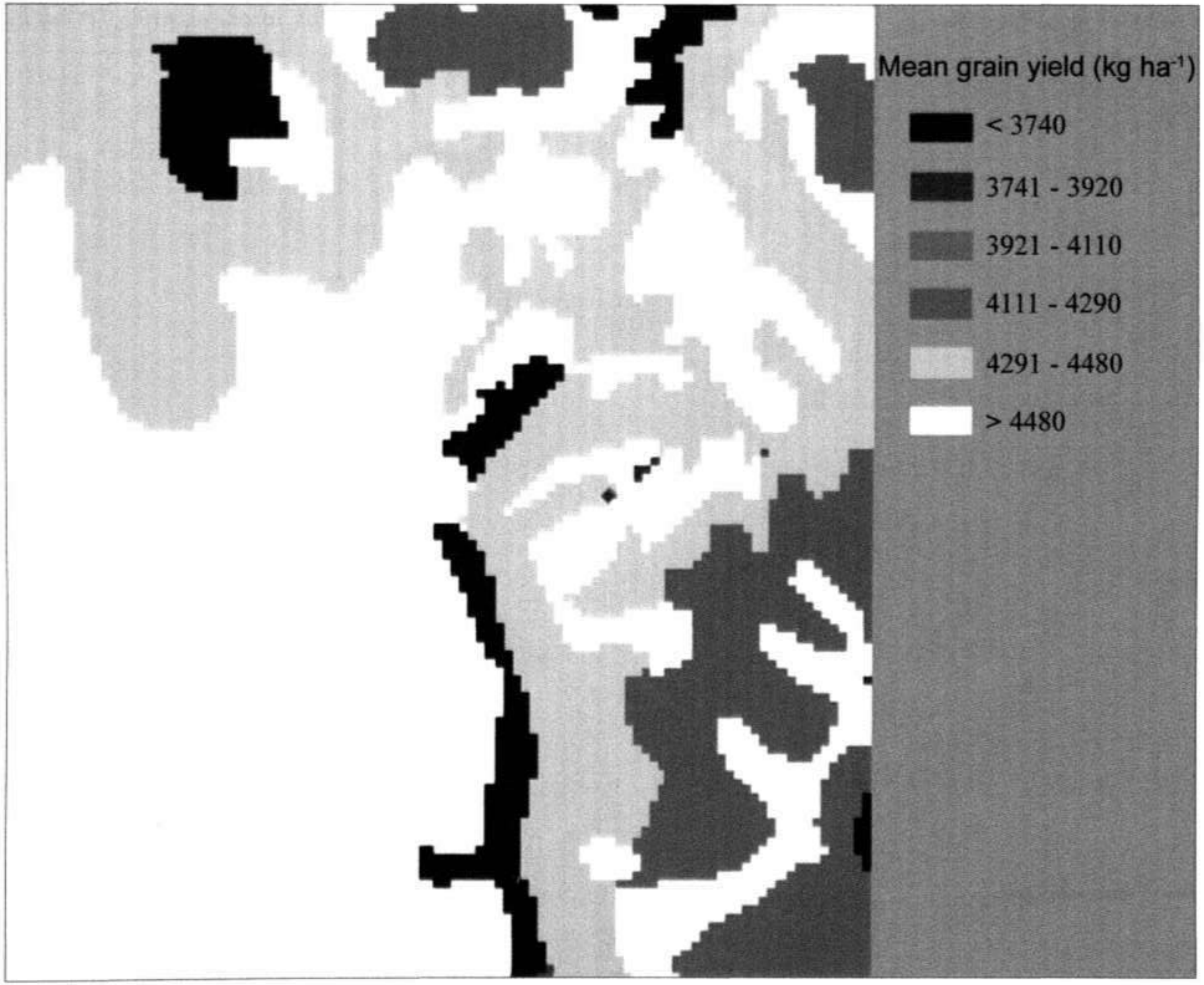


*Figure 1. Simulated grain yield over 3 years for a wheat crop in a hypothetical region in Punjab.*

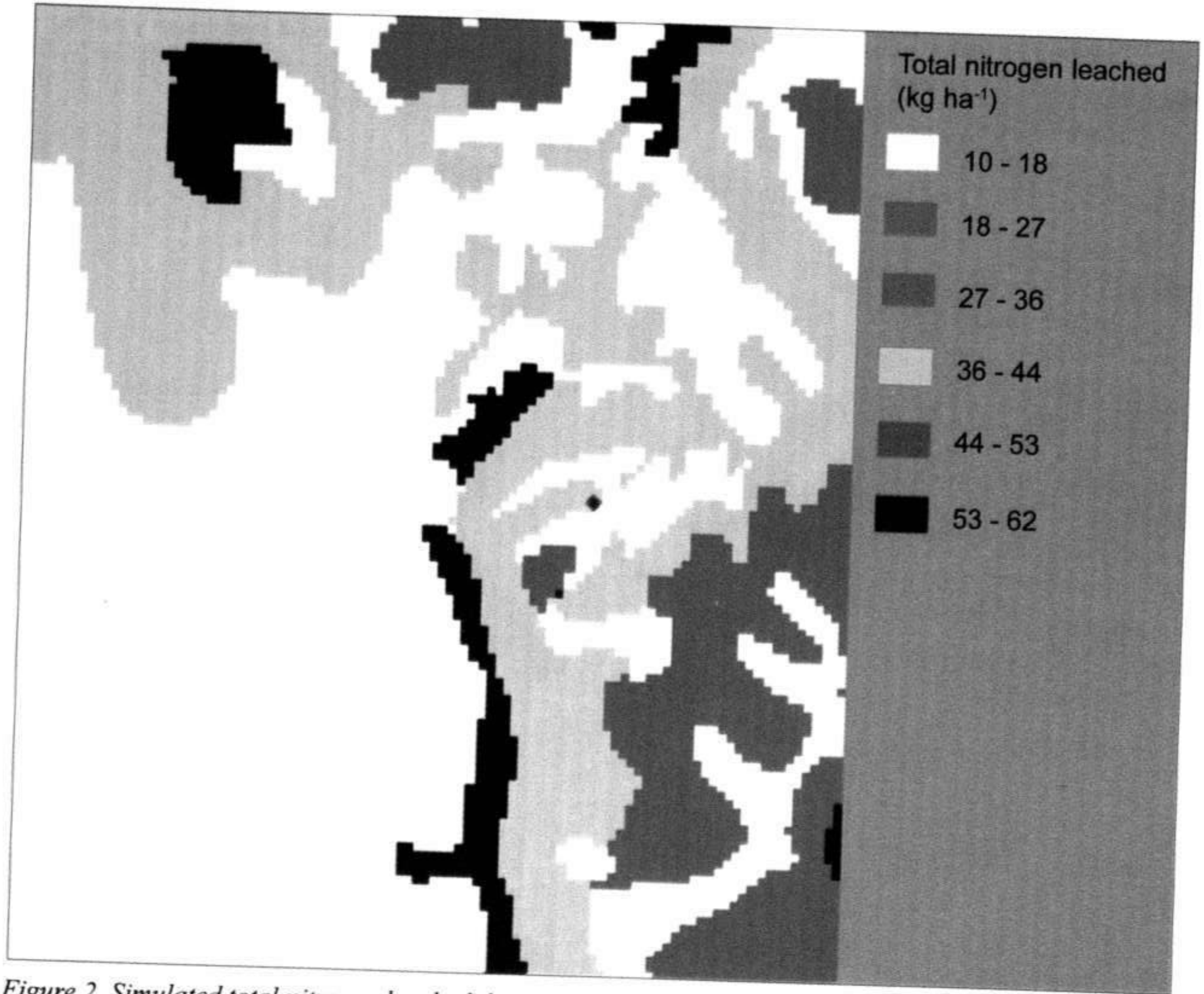


*Figure 2. Simulated total nitrogen leached during the wheat crop over 3 years for a hypothetical region in Punjab.*

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# Application of Statistics in GIS

**S Chandra**[1]

## Introduction

GIS can be defined as systems for input, storage, analysis, and output of geographically referenced data (Maguire et al. 1991) that normally also involve a temporal dimension. These systems are extensively used as software toolboxes for: 1. integration of geographic data emanating from a multitude of sources, 2. implementation of spatial data analysis techniques (Fotheringham and Rogerson 1994), and 3. display of geographic data in maps and similar other forms.

Geographic data, which GIS deals with, are essentially spatial in nature with a tendency for the nearby geographic points to be correlated in their values. A temporal dimension is added to the problem when the same geographic points are observed over time. For each geographic point over time, a number of characteristics such as rainfall, minimum and maximum temperature, and crops grown may be observed. The GIS data, then, in essence, become *spatio-temporal multivariate data* that may emanate from a multitude of sources—land-use records, weather records, and remote sensing. These data can come in many different formats: tabular data, graphical data, maps, and digital images. These widely different features of GIS data give rise mostly to an extremely large dataset.

Variation is an intrinsic property of any set of biological and physical data, GIS data being no exception. GIS data, being spatio-temporal and multivariate in nature, are expected to be subject to a relatively larger scale of variation. The total variation in any dataset is usually expected to comprise a systematic component and a random component. What we look for is that part of the variation which is systematic and exhibits some clearly discernible patterns that only help us to take practical actions. The major task in dealing with GIS data, like in any other data, is how effectively and accurately to describe, analyze, and summarize this wide variation and thereby to be able to separate the systematic part from the random part of variation. To be able to accomplish this task, the use of appropriate statistical tools becomes necessary.

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Application of statistics in GIS is a relatively new area. A modest attempt is made here to stipulate the use of some available statistical tools to deal with GIS data. Applications of spatial statistical methods and of multivariate statistical methods are discussed in this paper. This is not intended to be an exhaustive presentation. In this paper an attempt has been made to further expand some of the ideas presented in a paper by Diggle (1996) that can be referred to for further references and details.

## Spatial statistical methods

Spatial statistics represents a collection of statistical methods that explicitly account for the position of the geographic locations in the analysis of geographic data. Variation in geographically referenced spatial data could be broadly classified into three categories: continuous spatial variation (CSV), discrete spatial variation (DSV), and spatial point patterns (SPP).

*Continuous spatial variation* (CSV) represents a spatial phenomenon wherein a (random) variable of interest, say $Y(x)$, can in principle be conceived to be obtainable at any location $x$ within a typically 2-dimensional, geographic region. The variable $Y(x)$ may itself be either continuous, discrete, or categorical. Examples are: continuous—amount $Y(x)$ of soil nitrogen at location $x$ within a field; discrete—number $Y(x)$ of organisms of a particular species found in a soil core sample centred at location $x$; categorical—presence or absence $Y(x)$ of a plant disease at location $x$. The CSV models, commonly known as kriging models, were originally developed for use in the mining industry and have more recently been used in soil science.

*Discrete spatial variation* (DSV) represents situations wherein a random variable of interest, say $Y_i$, is associated with each of a finite or countably infinite set of fixed geographical locations $x_i$; for example, the height $Y_i$ of an individual tree at location $x_i$ in a plantation. A fundamental difference here, in relation to CSV, is that the phenomenon of interest exists only at *the* particular set of locations $x_i$ under consideration. However, a DSV model could be applied to a CSV situation provided this can more effectively address the relevant practical question. An example of this is the *spatial analysis of agricultural field trials* with small plots. Here, the location of each plot is *assumed* to be represented by a single point in a 2-dimensional space, and the plot yields are analyzed with reference to these *notional* locations, though the real picture is that the yield Y from the i-th plot comes from the entire plot area representing a continuous space rather than a single point. In a similar vein, the *remotely sensed images* of a land area are routinely presented as a set of values in each of a number of small areal elements, called *pixels,* which are then treated, as an approximation, as a rectangular grid of points as in the case of an agricultural field trial. The DSV model has also been used in geographical epidemiology for production of disease atlases.

In the case of *spatial point patterns* (SPP), the locations $x_i$, $i = 1,2,\ldots,$ themselves constitute the data. For example, locations of trees in a naturally regenerated forest. Such data are assumed to be generated by some underlying stochastic (random) point process. The SPP models were developed by foresters and ecologists in the context of field sampling for plant communities observed in situ.

## Modeling continuous spatial variation

Let the underlying spatial variation in a 2-dimensional geographic space be represented by S(x), more succinctly represented as $\{S(x):x \in R^2\}$, where $R^2$ represents the 2-dimemsional geographic space within which the geographic points x lie. To develop a model, we assume that the spatial variation $\{S(x):x \in R^2\}$ is a stationary Gaussian (i.e., normal) stochastic process with mean zero, variance $\sigma^2$, and spatial correlation structure p(d). = corr{S(x),S(x-d)}. This spatial correlation structure implies that the correlation between data at geographic point x and at any other geographic point (x-d), d distance apart from point x, is, irrespective of its directional placement, a function only ofthe geographical distance d between the two points.

We collect a sample of n observations $y_i$ (i=1,...,n) from the n geographical locations x. (i=1,...,n), and assume that any individual observation $y_i$ is described by the model (call it the CSV model)

$$Y_i = \mu(x_i) + S(x_i) + Z_i \qquad i = 1,\ldots,n \qquad (1)$$

where $\mu(x_i)$ is the average value (called 'expected value' in statistics) at point $x_i$ ofthe spatially varying phenomenon of interest, $\mu(x_i) + S(x_i)$ represents its actual value, and $Z_i$ are measurement errors assumed to be mutually independent Gaussian random variables with mean zero and variance $\tau^2$. As an example, S(x) may describe the spatial variation in the true amount of soil nitrogen, $Z_i$ the random errors (similar to experimental error in a designed experiment) introduced in determining soil nitrogen in the laboratory.

Depending on the situation at hand, one can take for $\mu(x)$ a constant average value

$$\mu(x) = \mu \qquad \text{for all } x \qquad (2)$$

or represent M(X) by a regression equation

$$\mu(x) \quad \Sigma \beta_j z_j(x) \qquad j = 1,\ldots,p \qquad (3)$$

with $z_j(x)$ being suitably defined geographically referenced explanatory variables.

### Application of CSV model

The CSV model (1) can be applied to address many practical problems, some of which are briefly discussed below. These applications fall under two broad categories: 1. spatial prediction problems, and 2. estimation problems.

a. An example of a spatial prediction problem is to predict the realization of S(x) at an arbitrary geographic point x, as shown in (d) below, on the basis of the n available observed data points $y=(y_1,\ldots,y_n)$. Here, it is usual to specify a very simple model for $\mu(x)$, either a constant as in (2) or a simple polynomial trend surface similar to (3). The ultimate objective is to use the predicted values of S(x) to reconstruct an unobserved continuous spatial surface from the n observed data points $(x_i,y_i)$.

b. Sometimes, interest may lie in the model parameters involved in $\mu(x)$ as in (3), with the stochastic process $S(x)$ being of secondary interest. For example, Zimmerman and Harville (1991) used this approach to analyze agricultural field trials. They incorporated the treatment effects and any concomitant variable information into a regression model through $\mu(x)$, and used $S(x)$ to account for the residual unexplained spatial variation in response.

c. Of special interest to a soil scientist may be the determination of the underlying spatial correlation structure $\rho(d)$. This can be done with the help of the variogram. For any stationary process, say $Y(x)$, the (semi-)variogram is defined as

$$V(d) = (1/2)\ E\{[Y(x) - Y(x-d)]^2\}$$
$$= (1/2)\ \mathrm{var}\{Y(x) - Y(x-d)\} \qquad (4)$$

where the symbol E stands for the 'average' value of the squared difference within the flower brackets, and var stands for variance. Burgess and Webster (1980) present a good discussion of many theoretical variograms, including the frequently used spherical variogram. The values of $V_{ij}=(1/2)(Y_i-Y_j)^2$ are first calculated. An empirical variogram is constructed as a scatter-plot of points $(d_{ij},V_{ij})$, where $d_{ij} = |x_i-x_j|$ represents the physical distance between the geographic points $x_i$ and $x$. It can be shown that $E(V_{ij})=V(d_{ij})$, and, under the assumptions of CSV model (1), $V(d) = \tau^2+\sigma^2\{1-\rho(d)\}$. The shape of the empirical variogram can, therefore, be used to estimate an approximate parametric form of $p(d)$ and to get initial estimates of $\tau^2$ and $\sigma^2$, and for any parameters in the chosen model for $\rho(d)$. The visual impression of the empirical variogram, however, could be quite misleading. This is because the sampling distribution of $V_{ij}$, being $\chi^2$ under the Gaussian assumptions, is highly skewed. A more practical approach, therefore, is to classify the total range of the interpoint distances d. into a number of discrete classes, compute the class midpoints $d_k$, and compute the averages $V_k$ from the $n_k$ values of $V_{ij}$ whose corresponding $d_{ij}$ fall into the k-th class. The empirical variogram is then constructed from the scatter-plot of points $(d_k,V_k)$. Another potential approach, rather than simple averaging within discrete classes, is to use a more sophisticated nonparametric smoother. After a parametric model for $\rho(d)$ has been chosen, the model parameters can be estimated either using the weighted least squares (Cressie 1991), or using restricted maximum likelihood (REML) (Laslett 1994).

d. Once a model has been fitted, as in (c) above, it can be used to predict the values of $S(x)$ at unobserved geographic locations x. This is called kriging. The predicted value, say $s(x)$, of $S(x)$ at the unobserved location x can be computed as

$$s(x) = \mu + g'(\tau^2 I + \sigma^2 R)^{-1}(Y-\mu 1) \qquad (5)$$

where $Y=(Y_1,\ldots,Y_n)'$; g is a vector with i-th element $\sigma^2\rho(|x-x_i|)$; I is a unit matrix having 1's on its diagonal and 0's elsewhere; R is the spatial correlation matrix with ij-th element $r(|x_i-x_j|)$; and 1 is a vector each of whose element is 1. Under the Gaussian assumption of model (1), the predictor (5) is $E\{S(X)|Y\}$ which minimizes the mean squared error of prediction (MSEP) $E\{[s(x)-S(x)]^2\}$.

In simple kriging, substitution of the estimated values of parameters $\mu$ $\tau^2 \sigma^2$, and $\rho$ in (5) delivers the predicted value s(x) at the unobserved location x. In ordinary kriging, explicit allowance is made for estimation of $\mu$. In universal kriging, the constant $\mu$ is replaced by a regression model.

## Modeling discrete spatial variation

Suppose that random variables $Y_i$ are observed at a sequence of regularly spaced geographic locations $x_i$. We need a model to describe the joint distribution of the $Y_i$ that, in a sensible way, incorporates the spatial dependence amongst the $Y_i$.

One approach, due to Whittle (1954, 1963) is to use, based on the linear time-series models of Box and Jenkins (1970), the spatial autoregressive models. An example of such models is the following first-order simultaneous autoregressive model

$$Y_i = \alpha (Y_{i-1} + Y_{i+1}) + Z_i \quad (6)$$

where $Z_i$ is assumed to be a sequence of mutually independent normally (Gaussian) distributed random variables with mean zero.

Another approach, due to Bartlett (1971), is to use a first-order conditional spatial autoregression model wherein the conditional distribution of each $Y_i$, given the realized values $y_i$ of all other $Y_j$, is normal with mean $\alpha (Y_{i-1} + Y_{i+1})$ and a constant variance. Besag (1974) provides a systematic account of methods of estimation for the conditional spatial models to describe discrete spatial variation.

Papers by Wilkinson et al. (1983), Besag and Kempton (1986), and Williams (1986) discuss the application of these models in the context of adjusting the inferences from agricultural field trials to take account of spatial correlation among nearby field plots. A number of statistical computing software are now available to undertake these spatial analyses for agricultural field trials. Some of these are TWO-D, SAFE, NNDES, NNANAL. Recently, these models have also found application in epidemiology, specifically in the production of disease atlases (e.g., Besag et al. 1991; Clayton and Bernardinelli 1992).

## Modeling spatial point patterns

Nearly all available models to describe spatial point patterns (SPP) assume, explicitly or implicitly, that the points in question form a partial realization of a homogeneous planar Poisson process. This is the accepted standard of complete spatial randomness (CSR). Specific problems addressed using these models are development of tests for departure from CSR, and estimators for the intensity or mean number of points per unit area. Discussed below are three types of models corresponding to the manner in which the data are collected. Diggle (1981) presents graphical methods to analyze SPPs.

### Quadrat counts

Points may be sampled in situ by recording the number of points in each of a set of randomly picked Up sampling quadrats. This situation is known as random quadrat sampling. Alternatively, contiguous quadrat sampling may be made. In both cases, two properties are used in the modeling process. One is that, for a homogenous planar Poisson process, the number of points in any predetermined spatial region follows a Poisson distribution with mean proportional to the area of the spatial region: Second, the counts in disjoint regions are assumed to be independent. Greig-Smith (1952) presents an account of these two sampling situations for application in plant ecology.

For the random quadrat sampling situation, the resulting set of quadrat counts, under CSR, forms an independent random sample from a Poisson distribution with mean $\lambda \mid A \mid$, where $\mid A \mid$ is the area of an individual quadrat and $\lambda$ is the mean number of points per unit area (called intensity). For observed counts $y_1,\ldots,y_n$, an estimator, say L, for $\lambda$ is

$$L = \{1/(n\mid A\mid)\}\Sigma y_i \qquad i = 1,\ldots,n \tag{7}$$

L in (7) is a consistent estimator for the true intensity whether or not CSR holds. A commonly used test-statistic to test departure from CSR is the index of dispersion I defined as

$$I = s^2/m(y) \tag{8}$$

where $s^2$ and m(y) are the variance and the mean of the sampled quadrat counts respectively. Provided that m(y) is at least I, the statistical significance of I can be tested using the fact that, under CSR, (n-1)I follows a $\chi^2$ distribution with (n-1) degrees of freedom.

The contiguous quadrat count data arise when a study region is divided into a regular grid of square or rectangular quadrats. If CSR holds, the resulting quadrat counts still possess the same Poisson distribution properties as in the case of random quadrat sampling. However, the systematic spatial structure permits more deeper analyses if CSR hypothesis is rejected (Greig-Smith 1979).

### Distance methods

The distance methods, using in situ measurements, were developed as alternatives to random quadrat sampling to estimate the intensity of a point pattern and to test departure from CSR. In this method, each quadrat is replaced by a sampling *point,* say P. The distances of the neighboring points are measured from P. Suppose $X_k$ is the distance from P to the k-th nearest point in a Poisson process of intensity $\lambda$. Then

$$Y_k \quad 2\pi\lambda(X^2_k - X^2_{k-1}) \quad (\text{with} \quad X_0 = 0) \quad k = I,\ldots,n \tag{9}$$

are mutually independent $\chi^2$ variates each with 2 degrees of freedom. As suggested by Holgate (1965a, b), $Y_1$ and $Y_2$ can be used as tests of CSR. The rationale therefor is that $Y_2$ will tend to be stochastically smaller than $Y_1$ in a spatially aggregated pattern, and stochastically larger in a regular pattern (Diggle 1983, Chapter 3).

### Mapped patterns

Observations collected in situ, either using quadrat sampling or distance methods, have limited capacity for statistical analysis. Data in the form a mapped pattern, i.e., a complete set of n points $x_i$ $(i=1,\dots,n)$ in a designated spatial region, have a greater potential for fitting and validating explicit stochastic spatial models other than the homogenous Poisson process. Ripley (1977), under the assumption that the data constitute a partial realization of a stationary isotropic spatial point process, proposed the use of K-function which is defined as

$$K(s) = \lambda^{-1} E(p) \tag{10}$$

where p is the 'number of further points within distance s of an arbitrary point of the spatial region'. K(s) can be estimated from the cumulative distribution of distances between all pairs of points with a correction for edge effects. Let the observations be $x_i$ $(i=1,\dots,n)$ corresponding to locations of all n points in a planar region A. For each point $x_i$, the observed number of points within distance s of $X_i$ can be represented as

$$\sum_{(j\neq i)} I(\|x_i-x_j\|\leq s) \qquad j\neq i = 1,\dots, n$$

where I(.) denotes the indicator function, and $\|x_i-x_j\|$ is the Euclidean distance between points $x_i$ and $x_j$. An estimator, say k(s), of $\hat{K}(s)$ can be obtained as

$$k(s) = (|A|/n^2) \sum_{i}\sum_{i\neq j} I(\|x_i-x_j\|\leq s) \qquad i=1,\dots,n \tag{12}$$

The estimator k(s) in (12) is subject to a considerable negative bias as points outside A are not observed. This edge effect bias can be substantially reduced by using estimators having the general form

$$k(s) = (|A|/n^2) \sum_{I}\sum_{i\neq j} \phi_s(x_i,x_j) \qquad i=1,\dots,n \tag{13}$$

for some suitably chosen function $\phi_s(x_i,x_j)$. A widely used form of $\phi_s(x_i,x_j)$, as proposed by Ripley (1977), is the following

$$\phi_s(x_i,x_j) = w(x_i,x_j)^{-1} I(\|x_i-x_j\|\leq s) \tag{14}$$

where $W(X_i,X_j)$ is the proportion of the circumference of the circle with centre $x_i$ and radius $\|x_i-x_j\|$ which is contained in the planar region A.

Under the null hypothesis of CSR

$$K(s) = \pi s^2 \tag{15}$$

which provides a benchmark for assessing the underlying spatial structure. For a spatial point process with aggregated pattern, $K(s) > \pi s^2$ for all positive s. For a spatial point process with regular pattern, $K(s) < \pi s^2$. The K-function is now widely used as a standard technique in the analysis of spatial point patterns, including the multivariate patterns wherein the points are two or more qualitatively different types (Lotwick and Silverman 1982).

## Multivariate statistical methods

When P different characteristics are observed on each of a large number N of different objects, as usually is the case with GIS data, this gives rise to a large data matrix of order N x P, having N rows and P columns. An example is of data on minimum and maximum temperature, rainfall, wind speed, and day length, collected for each of 450 geographic locations within some specified geographic region. This gives us a data matrix of the order of 450 x 5, with N = 450 rows and P = 5 columns. In a given situation, P may be even of the order of 15 or 20. Some of the aspects related to handling such a large data matrix are:

a. To summarize the N x P multivariate structure through an appropriate 2-dimensional representation with maximum possible retention of the original variation in data. Only then is it possible to more clearly comprehend the broad features of the data.

b. To classify the N locations into a few, say n = 4, homogenous groups based on the values of their P characteristics. This may be required for the purpose of stratification of the given geographic region into a few homogenous subregions. This information is also a vital input for designing an efficient and cost-effective sampling strategy for future research and development studies in the given geographic region.

c. To group the P characteristics (variables) into a few, say p (< P), cognate groups. This information may be very useful to get rid of redundant and costly variables in future research and development work, and thereby considerably reduce the costs.

A large number of multivariate techniques are available to address the above problems. Some of the more commonly used are the Principal Component Analysis (PCA), Principal Coordinate Analysis (PCOA), Biplot, and a number of Cluster Analysis Techniques. The PCA and PCOA are dimension reduction techniques, and can be implemented using the GENSTAT and SAS software programs. The software GEBEI and MATMODEL are particularly useful for PCA. The Biplot, a graphical tool to geometrically see the structure in the N x P matrix, can be constructed using either the GEBEI or the GENSTAT software. Biplot particularly is an effective way to look into the relationships among the N objects, among the P variables, and the inter-relationships among N objects and P variables. Cluster analysis attempts to classify the given N objects and/or P varables into homogenous/cognate groups. Cluster analysis, in its many different forms, can be carried out using the SAS, GENSTAT, and GEBEI software.

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# Real-life Problems in Developing a Land-use Plan Using Computerized Systems

**A K Maji and M Velayutham**[1]

## Introduction

All over the world, agricultural production systems are changing in response to social demands and ecological conditions. The role of scientists involved in land-use planning studies is also changing to meet present day challenges. Land-use planning exercises encompass a multidisciplinary approach to assess multidimensional and complex features of land, water, climate, and biotic factors for appropriate assessment of the productivity of lands. Inappropriate use of these resources leads to various types of degradation and ecological imbalances, and ultimately affects the social framework. Scientific assessment of land resources is, therefore, essential to overcome the problems of degradation, and to ascertain sustainable use of the natural resources. The assessment or evaluation of these resources depends on a strong information-base established through systematic and objective-specific survey work, incorporation of farmers' experiences, and secondary data sources. The data thus generated can help in interpreting the feasibility of land use for various purposes like site selection for developmental planning, soil management, crop management, prime land preservation, and potential population supporting capacity assessment. However, datasets generated for such activities are very large and managing them manually is very difficult. Today's powerful computer systems have made it possible to handle with relative ease the complex data management and analyses involved.

## Computers in land evaluation

The modern era of land evaluation began with the publication of "A Framework for Land Evaluation" by the Food and Agriculture Organization (FAO 1976), and it was felt necessary to have a computerized system for land evaluation. The first attempt in this direction was made by Wood and Dent (1983) in Indonesia. Thereafter, many

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countries attempted to develop computerized interpretation systems based on their individual needs. MicroLEIS (De la Rosa et al. 1992) is one such program. The Automated Land Evaluation System (ALES) developed by Rossiter (1990) can be used to implement provincial, country, and regional land evaluation. AGIS-based land evaluation system, Integrated Land and Water Management Information System (ILWIS), has been developed at the International Institute for Aerospace Survey and Earth Sciences (ITC), The Netherlands (Meijerink et al. 1988). Map analysis based land evaluation can be accomplished using GIS (Burrough 1986). IDRISI, developed at Clarke's University, USA (Eastman 1990), provides various tools useful for analysis of data for land-use planning.

## Data for land evaluation/land-use planning

Problems can be encountered at any stage of land assessment studies—from the initial stage of data collection, to the final decision-making and the representation of data in GIS outputs. In India, in most cases, the data sources are *tehsil/taluka/block/* district level administrations, where the data are collected with different objectives and purposes. These data may not be the same as those desired by land-use planners and/or may not reflect the real situation (particularly, in the case of socioeconomic data). The quality of data primarily depends on the source of the data, that are ultimately used in the land evaluation/land use planning exercises.

### Spatial reference of the data

Data pertaining to locations are generally represented as point data, but in soil maps a representative polygon may include some vital information relevant to diagnostic parameters for a suitable land-use plan. One of the difficulties encountered is that data for an entire area is not available, leading to partial coverage. Such partial data only allow extrapolation of the decision to unrepresented areas, that may or may not be useful.

### Operational faults in data collection

Collection of data on natural resources, socioeconomic features, and cropping systems are generally carried out at different administrative levels. The village-level database remains at the *block/tehsil* office where major gaps in the database can exist. As data follows the hierarchical structure from.village to *tehsil* to district, etc., the volume of data grows enormously, and managing and arranging them in a suitable database management system becomes tedious and error prone. Sometimes, data are collected by persons not having full understanding/competence in the subject. Thus the procedure for the collection of data is very important as it forms the very basic element of any GIS analysis.

## Unit of the data

In India, the land measurement; yield measurement, socioeconomic and other parameters are reported at varying units of measurement. In some advanced farming areas, the metric system has been adopted, but most of the rural database is reported in local units of measurement. So, the additional task of data conversion to a standard level is necessary to ensure compatibility of data.

## Temporal variability of data

Sometimes the data collection period varies due to a lengthy data collection procedure or less manpower involvement. The present administrative system or the fact that the data needed for analysis are old in nature are other contributory factors. Old data generally represent the condition at the time of collection of data but the real situation and attribute value of the data changes over time. Such a situation in particular occurs in the case of land-use data.

## Scale limitations

Scale of mapping is an important aspect in representing data. A small-scale map contains much coarser data than a large-scale map. In GIS, database maps of two different scales always pose problems of edge matching, registration, etc. The problem is again compounded when there is even a slight variation in the registration co-ordinates or latitudes and longitudes.

## Land-use requirements

In land evaluation studies, the land quality is matched with land-use requirements (LURs) of a particular crop. It has been observed that land-use requirements for different crops are not available for specific cropping systems in India, and in major cases, studies are conducted based on the criteria developed by FAO (1976). In such cases, the results obtained may not fit well with the real situation. This emphasizes the need to have LURs based on local case studies and experimentation. In this direction, NBSS&LUP, through a workshop and subsequent studies, have developed LURs for five crops (NBSS&LUP 1993).

## Economic suitability evaluation

Economic suitability evaluation along with physical suitability of land parcels has been recommended in many fora. Economic suitability classes are based on the socioeconomic features of the farmers of the area concerned, and depend on several factors:

- capacity of the farmers to provide input in terms of fertilizer, irrigation, pest control, postharvest operation, etc.

- market price, marketing opportunity, transport infrastructure, storage facility, etc.
- satisfaction level of the farmer on economic returns, that may vary from farmer to farmer.

The above factors must therefore be considered before conducting any economic suitability evaluation and its acceptability by the farming sector.

### Crop suitability models

India is a country of diverse climatic conditions, physiographic variation, and soil environments. The crop adaptability, cropping system, and management practices have wide variation; Under these circumstances, a single crop model will not be sufficient to fulfil the needs of the country. Therefore, it is envisaged to have crop models based on agroecological zones both for irrigated and rainfed environments, keeping in view the local crops and food preferences.

## Data format

Various GIS packages are currently being used, some are vector-based, and others raster-based. The first problem that arises is data compatibility between the different systems. However, conversion packages are now available that help overcome this problem to a large extent.

Incompatibility between packages is another issue. Therefore, interdisciplinary work, like the one being discussed here on rice-wheat systems research, needs a uniform software platform to avoid difficulties of data transfer and analysis.

## Knowledge interface

In the domain of spatial analysis and its use, the interface of various disciplines and expertise are needed. In land-use planning implementation, the policymakers and implementing authorities need to interact and discuss the scientific findings. On the other hand, GIS experts need to understand the views of land-use planning scientists even though they represent diverse fields of specialization. The computer professionals in GIS are required to provide realistic solutions to the concepts of soil scientists/ land-use planners. In many cases, the latter group of scientists feel inadequate to attempt computer applications by themselves.

Therefore, unless data sources are authentic and spatially referenced, they may lead to confusing results. Very often, different agencies report their data using locator varied units which hinder smooth data handling. Timely use of data is also important to the decision-makers as old data depict a picture that differs from current reality. However, old data are useful in predicting temporal changes as in case of studies on land-use/land cover changes of an area.

## Conclusion

The problems discussed here are the outcome of working experience in the fields of land evaluation and land-use planning using computerized systems. The major cause for such problems can be attributed to improve understanding of the system and communication gaps along the chain of specialized work areas involved, from data collection to processing to output. If suitable precautions are taken at various steps, these problems can be minimized or eradicated. The interdisciplinary mode of activity is necessary to achieve results in an accurate format.

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# Towards More Sufficient Use of GIS Analysis by the CGIAR System and its Partners

S Chator[1]

## Introduction

In 1994, as a fragile peace returned to Rwanda, eight centers in the CGIAR system worked with nongovernmental organizations (NGOs) and national research systems to multiply and disseminate the seed of suitably adapted, improved crop varieties. Placed in the hands of returning farmers, the seed helped kick-start the rural economy, speeding the recovery of food production. The Seeds of Hope Project, as it was called, has since become well-known outside the CGIAR as a landmark project marking the evolution of a new model of technology transfer in Africa—a model that is proving effective in bringing the benefits of research to some of the world's poorest people.

What is perhaps less well appreciated—at least outside the CGIAR system—is the crucial role geographical analysis played in the project's success. At several centers, including the Centro International de Agricultura Tropical (CIAT), maps of the distribution of relevant crops in neighboring countries were used to identify the areas where seed adapted to Rwanda's diverse environments could be found. The maps were generated on computer, using data that had previously been collected for other research purposes.

The Seeds of Hope Project is thus a potent example of how GIS can be applied to benefit, not just researchers and planners, but the ultimate target group of the CGIAR's research—resource-poor farmers. The Project is also a measure of the progress made over the past decade in developing and refining the tools of geographical analysis. During the Ethiopian famine of 1984/85, neither the tools nor the necessary information had been generated. As a result, much of the seed aid distributed at that time was poorly targeted.

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## Geographic information systems

GIS systems can become a useful tool whenever information has a spatial dimension that would be easier to understand in a visual form. Their advantages over conventional map making are several: they allow the job to be done much faster; they allow different sorts of information to be integrated and overlaid easily; and they are more flexible and accessible to users. With GIS, individual users can, for example, update a map rapidly in response to new information.

GIS is a means to an end rather than an end in itself. It is also just one part—often quite a small one—of the overall analytical process required for effective research and development, in combination with other tools and techniques, notably modeling.

### What is a GIS?

The words "Geographic Information System" can be interpreted in two ways and confusing the two ideas in administrative work has caused much consternation. In the restricted sense, a GIS is a suite of computer routines that help manipulate georeferenced data. In this sense, Arc/Info, ILWIS, IDRISI, and ERDAS are examples of GIS; many others exist.

It is when using the term in a broader sense, in phrases like "we are putting up a GIS for the department of x in country y", that the confusion is likely to occur. For over 10 years now, it has been bruited that GIS is a solution looking for a problem. In many cases, a lot of money was invested in GIS software (restricted sense) and staff training, only to find that lack of georeferenced data frustrated the endeavor. A wealth of detailed information is available on world agriculture but converting this information to georeferenced form implies a high cost.

In this paper, GIS is interpreted in the broad sense—the software and the data. Only when we can explain the costs and infrastructure involved, will we be able to inform administrators without incurring future disappointment.

GIS is used in agricultural and environmental research and development in four basic ways:

- *to diagnostically help research planning.* For example, the International Livestock Research Centre (ILRI), Nairobi, Kenya, used GIS to map the known and probable distribution of the tick species that cause theileriosis. This will be useful in identifying zones at varying degrees of risk from the disease and defining appropriate control strategies. CIAT's 1990 strategic planning exercise relied heavily on the use of GIS to define priority agroecological zones in tropical America.

- *to target research products accurately to areas where users will find them relevant and acceptable.* Under the Asian Rice-based Farming Systems Network (ARFSN), based at the International Rice Research Institute (IRRI), Manila, Philippines, national scientists used IRRI's GIS to identify the adoption domain of dry seeding of rice and new rice varieties in the Philippines. The Seeds of Hope Project, mentioned above, provides another example.

- *to assess the impact of research or development, either ex ante or ex post.* This is a particularly powerful set of applications, as the integrative capacity of GIS can be used to predict how a whole farming system or an ecology is likely to evolve in response to different policy or technology interventions. An example is the collaborative project between the International Food Policy Research Institute (IFPRI), CIAT, and the Brazilian National Research Institute. The project's scientists are attempting to forecast local changes in land use and the degree to which farmers in Brazil will switch to soybean from other crops in response to changes in input and output prices and the release of new crop varieties.
- *to further research, used as a pure (strategic) tool.* For example, OAT has used its GIS together with statistical techniques and genetic markers to map the genetic diversity of beans and other crops. The results help breeders to locate likely sources of desirable traits and provide useful guidance for future germplasm collection.

GIS can be used in support of all of the CGIAR system's major objectives: increased agricultural productivity, better protected environments, improved conservation of genetic diversity, better policy-making, and more equitable sharing of the benefits of research. GIS systems have already proved their value as a tool to support commodity research. They are also increasingly used to tackle the complex issues in natural resource management research. Recent applications in this field are legion—ranging from assessing erosion risks on sloping land, through predicting the effects of climate change on crop distribution, to managing coral reefs.

Its user-friendliness makes GIS a tool of great potential in empowering local people to improve the management of local resources. This is likely to be a major growth area in the future. Both International Water Management Institute (IWMI) and OAT have launched projects that aim to explore this potential at the watershed level.

Many CGIAR Centers now make effective use of an in-house GIS capacity. But there is room for improvement in the efficiency with which the CGIAR system as a whole uses its collective GIS capacity. These efficiency gains are the subject of this paper.

## GIS and the CGIAR — a brief historic overview

CGIAR Centers have for long been interested in using modern information technology in agricultural research. Their exposure to GIS dates back to 1986, when a workshop on characterizing, classifying, and mapping of agricultural environments was held in Rome, organized by the CGIAR and the Food and Agriculture Organization (FAO). Several experts attended the workshop from organizations outside the CGIAR that were already using GIS. Their inputs sowed the seeds for the CGIAR Centers' growing involvement in their use in subsequent years.

For two reasons, the development of CGIAR's capacity in GIS has mostly occurred in an ad hoc manner. First, in the late 1980s, few Centers could afford the considerable investments then required to build a sophisticated GIS capacity. This led individual Centers to invest as and when they could, to meet specific needs. Second, because no mechanism existed that allowed them to do so, the Centers did not seek complementarity, either in their GIS investments or in the specialized GIS services and products they offer.

The phase of incremental, ad hoc development lasted into the early 1990s. Since then, more powerful software has become available, with easier access to a wider range of databases. A few among them like CIAT, have made more substantial investments in both hardware and software, while the other Centers have made little or no investment. So the gap between centers with a "strong" or "weak" capacity in GIS has, if anything, grown during the 1990s (Table 1).

**Table 1. Investment in staff, hardware and software by the CGIAR Centers[1].**

| CGIAR Center | Staff | Hardware | Software |
|---|---|---|---|
| CIAT | **** | **** | *** |
| CIMMYT | *** | ** | * |
| CIP | *** | * | - |
| ICARDA | ** | ** | * |
| ICLARM | * | - | - |
| ICRAF | *** | ** | * |
| ICRISAT | *** | ** | * |
| IFPRI | * | - | - |
| IIMI | ** | * | - |
| IITA | * | * | - |
| ILRI | *** | ** | * |
| IPGRI | - | - | - |
| IRRI | *** | *** | ** |
| ISNAR | * | - | - |
| WARDA | *** | * | - |

1. Data obtained from an informal email survey and reinterpreted to cost range in US$ by P.G. Jones.
– > 10 000
* 10 000 - 50 000
** 50000 - 100000
*** 100 000 - 250 000
**** < 250 000

## UNEP/GRID phase

In 1991, a group of Center Deputy Directors decided to seek a more concerted follow-up to the 1986 meeting. They submitted a project proposal to the Government of Norway to convene a second workshop, held in 1992 at Arendal. The choice of Arendal reflected the fact that this northern Norwegian town is the location of one of the GRID centers.

At the Arendal workshop, later known as Arendal I, the Norwegian Government offered to fund a project to promote cooperation among the CGIAR Centers and with UNEP/GRID centers on GIS-related issues. The project, entitled "UNEP and CGIAR Cooperation on Data, Capacity Building and Networking Needs for the Use of Geographical Information Systems in Agricultural Research", was to be coordinated in Arendal and to run initially for a 2-year period.

In 1996, the Norwegian Government agreed to fund a second phase, on condition that collaboration among the Centers become self-sustaining by the end of the project, in April 1998. The project has several achievements to its credit. It has increased awareness, both among CGIAR stakeholders and at the Centers themselves, of the power of GIS and the broad range of GIS applications now possible in both commodity and natural resource management research. Interested Centers have been visited and their GIS-related requirements assessed, as a basis for planning future collaboration. Funds have been given for several mini-projects to complete databases and make them available to users. Information on existing databases has been compiled and will shortly be made available in catalogue form. Two further workshops hosted in Arendal have provided opportunities to exchange experiences and improve coordination.

The project has also developed an effective multi-tier approach to obtaining funding that is well suited to the complexity of GIS research and to the need to explore future research directions with a wide range of potential partners. As a first step, small amounts of seed money are granted to implement clearly defined tasks. These tasks are necessary steps in the preparation of larger project proposals that can be later submitted, either to the project or to other potential donors. This approach is currently being used to develop a project on poverty mapping and the proposal for the development of a global crop and livestock database.

The project's most significant achievement was to demonstrate that sizeable efficiency gains can be achieved through global or inter-center collaboration. Sustaining the Arendal process, in one form or another, is vital if the CGIAR system and its stakeholders are to continue to capture these gains.

## Poverty mapping: a shared objective requiring global collaboration

All the CGIAR Centers share a goal to alleviate poverty. To focus their efforts, they need accurate data on where poverty occurs. Such data would also aid the CGIAR's Technical Advisory Committee (TAC) and donors in allocating research resources.

Poverty mapping, however, is much more than an exercise in GIS analysis. Measuring poverty itself is difficult and raises many methodological problems. A joint effort to compare methods and develop a standard approach is needed, before mapping goes ahead.

In a mini-project supported by GRID-Arendal, a consultant is being appointed to conduct a literature review and write a position paper on this subject, to seek experts willing to take part in a workshop, and to identify potential national partners. Under the project, CIAT scientists will also seek funds for, and organize, the workshop itself The outcome of the workshop should be a project proposal to donors to fund a multi-center effort on poverty mapping—with a coherent methodology spelled out in the project document.

## Advantages of collaboration

### Capacity building

While most CGIAR Centers need a capacity to analyze and use relevant data generated through GIS applications, not all require the facilities and expertise necessary to generate data. Systematic collaboration would allow some Centers to be service providers and others service users. In other words, Centers that have not invested in building a strong core of GIS expertise would be able to capture some of the benefits of such investments made by other Centers.

Similar arguments apply to the building of capacity at national level. First, not all parts of national systems, and perhaps not every national system within a subregion, would need to make large-scale investments in GIS expertise and equipment. Second, collaboration would ensure coordination and hence coherence in developing and providing training materials and opportunities to national programs and other partners. This would avoid the competition between Centers that so bedevilled the promotion of the farming systems approach to research during the 1980s. It was not uncommon for national programs at that time to complain that five Centers were "on their doorsteps", each preaching its own version of the farming systems' "gospel". It is vital that the same fate does not befall the introduction of GIS at national level.

Systematic collaboration would allow the development of a coherent global training strategy that would rationalize access to different levels of skills. Basic training, for example, could be devolved to strong national or regional institutes, while specific centers could meet more specialized needs.

### Methodology development

As a relatively new tool, GIS frequently presents its users with methodological problems. Often, it takes a significant input of time and other resources to develop and test solutions to these problems. In many cases, considerable savings could accrue through joint efforts to identify needs and opportunities in methodology development, leading to an inter-center or global workplan allocating such research to one or two partners, or to a lead Center with a comparative advantage in tackling the problem in question.

Methodological problems often occur when GIS is used in conjunction with models to predict future trends in land use or in the adoption of new technology. The difficulties arise because such economic variables as market prices cannot easily be matched to GIS coverages. For example, in the joint project between IFPRI, CIAT, and Brazil, outlined above, data on the elasticity of supply for soybean are available at state level in Brazil but not by region within the state, complicating the task of disaggregation. Under an inter-center collaborative arrangement, IFPRI could be asked to take the lead in solving this problem, sharing its finding with other Centers.

A further set of methodological problems concerns the introduction of GIS as a management tool for local communities. This is an area of great potential, in which little has yet been achieved. The issues are partly technical—what functions are needed, what level of sophistication is suitable?—but also social—who in the local community should have access, and who should have overall responsibility? Again, designating a lead Center to coordinate work on these issues and share the answers with others could bring considerable savings.

## Building and sharing databases

Many critical gaps in existing datasets need to be filled. In addition, datasets can be "married" to increase their relevance to a broader range of users. Collaboration in this area brings efficiency gains both through economies of scale and by avoiding the duplication of efforts.

A Center that is already building a database covering its own mandate commodities can, at little extra cost, include data on the commodities of other Centers. For example, under a project funded by the Inter-American Development Bank (IDB), CIAT is currently mapping the distribution of important crops and livestock species in Latin America. The data on crops will be shared with the Centro International de la Papa (CIP), the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT), and other interested Centers such as the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), which as a result will be spared the expense of undertaking this effort themselves. Livestock data will be shared with ILRI. Meanwhile, ILRI is compiling data on livestock in Africa. A collaborative project planned jointly with other centers and national partners would allow ILRI's database to include important African crops, making the results available both to other African and to the Latin American centers. Possibly, ICRISAT and the International Center for Agricultural Research in the Dry Areas (ICARDA) could undertake similar exercises in West Asia-North Africa and in the rest of Asia. The end result could be a snowballing effect, leading to a single global database shared by all interested Centers. Global collaboration would also allow projects to be undertaken that are relevant to the whole CGIAR system, not just one or a few Centers.

## Documentation on databases

Metadata, or in other words information about databases—who holds them, what they contain, how reliable they are, and so on—can be more easily assembled and disseminated through a collaborative arrangement. The initiative in developing metadata launched under the Arendal project needs to be continued after the project has ended.

## Possible modes of operation

Various options for sustaining GIS-related collaboration within the CGIAR system and with its partners have been suggested. They include:

- launching a system-wide initiative devoted solely to GIS use
- associating the development of GIS use with that of the ecoregional approach
- seeking support of the United Nations Environment Programme (UNEP) for a new project, based in Nairobi or elsewhere
- adding GIS use to an existing system-wide initiative

This paper restricts itself to a brief discussion of each of these options, without making a recommendation.

### Launching a System-wide initiative devoted solely to GIS use

The System-wide initiative, leading to the System-wide program, is a relatively new concept within the CGIAR system. It may represent a significant future development path for the system, especially if further rationalization and/or downsizing occurs.

Although high start-up and transaction costs are frequently mentioned as the major disadvantages of this mode of operation, they can be minimized. In the case of a GIS-related initiative, start-up costs would be reduced because a network is already operational. Transaction costs could be lowered by such measures as timing Steering Committee meetings to coincide with working scientific meetings or system-wide meetings (International Centers Week (ICW), Mid-Term Meetings (MTM)—a practice the Arendal project has already successfully adopted—and using e-mail and the Integrated Voice Data Network (IVDN) systems, instead of travel, to reduce consultation and participation costs.

Launching a System-wide initiative would require strong donor support. A leadership function would be required at some point in the system, possibly in the form of a secretariat rotated between participating Centers. The secretariat, consisting of a principal scientist and a technician, would be responsible for such activities as promoting database exchange, serving as a clearing house for training requests, and organizing annual scientific meetings. Such a System-wide initiative devoted solely to GIS use would make the greatest impact and savings of those reviewed.

### Associating the development of GIS use with that of the ecoregional approach

Under this option, ecoregional centers would take the lead in developing GIS-related activities for their mandate region and commodities, while seeking to undertake low-cost complementary activities that would benefit other regions.

There are strong synergies between this type of approach and the use of GIS. A recent proposal for an ecoregional approach to research in tropical America, for instance, specifically envisages developing a "regional analytical capacity for prioritizing, targeting, and extrapolating research results" and developing land-use databases and associated models to this end. This option permits clarity in the allocation of tasks, allowing lead centers to specialize in GIS issues and activities relevant to their region. It also helps clarify relationships with national partners: these would always know which center should be their first "port of call" for GIS-related needs.

This option is the most "natural", in the sense of building on existing trends in the evolution of the CGIAR system. Several of the activities mentioned above, including poverty mapping and compiling global databases on the distribution of crops and livestock, would fit well within this approach.

Disadvantages include the temptation to let collaboration simply "evolve", without providing strong overall leadership across the CGIAR system as a whole, and without setting aside any additional funding to identify priorities and ensure coherence. For this reason, this option, like those involving a System-wide initiative, would require a Secretariat (or a Steering Committee) at CGIAR system level. Again, this could be attached to a specific Center or rotated between Centers, and need not add a new layer of bureaucracy at system or CG Secretariat level.

### Seeking UNEP support for a new project

Based at UNEP's Nairobi headquarters, such a project would have the advantages of building on UNEP's experience in operating the GRID system, with which it would enjoy close links. On the other hand, funding difficulties and the short life cycle of projects might make this option difficult to launch and to sustain.

As the Norwegian Government has already ruled out a further extension of the Arendal process, the continuation of the current networking arrangement has not been listed as an option. However, under each of the above options, the possible role of Arendal in providing continuing support would need to be considered.

### Adding GIS use to an existing System-wide initiative

Attaching GIS-related activities to an existing System-wide initiative has the advantage of being relatively quick to implement. It would save an even greater proportion of the start-up costs.

However, the myriad applications of GIS in both commodity and resource management research, and policy-making, make it difficult to select a relevant, existing, System-wide initiative to host a GIS component. Given that the system increasingly emphasizes natural resource management, the soils, water and nutrients management initiative is a possible candidate. But care would have to be taken to ensure that commodity research interests did not become the "poor cousin" in such an arrangement. Similar arguments would apply if GIS-related concerns were included under the system-wide initiative on information for germplasm research (System-wide Information Network for Genetic Resources [SINGER]) or any other system-wide program.

## Conclusion

It is vital for all stakeholders in the CGIAR system not to lose the momentum gained through the Arendal project. There is a real opportunity to turn GIS into a highly effective tool for meeting the system's objectives more efficiently. Realizing that opportunity depends critically on choosing the right way forward, strong leadership will be required to embark upon it and to demonstrate its value to stakeholders.

# Concluding Session

## Development of Recommendations

# Development of Recommendations on Harmonization

Participants assembled into five groups to develop recommendations under the major topics of consideration. It was intended to propose procedures whereby databases and outputs could be readily exchanged, and there would be minimal duplication of effort. It was also intended to establish the status quo and further efforts needed to achieve a suitable output on constraints and opportunities of legumes in rice- and wheat-based cropping systems. This would be treated as an example of using GIS in cropping systems analysis. Group-wise recommendations are summarized below:

## A. Current Software Options

*F T Bantilan (Group Convenor), A K Maji, S P Pandey, and H B Nayakekorala*

The group primarily recommended a "small and simple" approach in choosing appropriate GIS hardware/software. The needs of the institution or consortium, and possibilities for data and expertise sharing should be emphasized.

- A minimum software platform was considered as:

PC *Arc/Info*

- for digitization, generation of coverages, overlay, plotting, display
- for vector data structures
- widely used; expertise is therefore available

PC *ArcView 3.x*

- for database query, display, plotting for coverages already generated by PC Arc/Info
- very user-friendly Windows interface
- for vector data structures
- widely used; expertise is therefore available

*IDRISI for Windows* (option for dealing with raster data structures)

- cheap and user friendly
- includes capabilities in image processing of remotely-sensed data
- widely used; expertise is therefore available

*RDBMS - dBase IV, FoxPro, Access*

- cheap and widely used

- A minimum hardware option was considered as:
  - Pentium computer with CD-ROM reader
  - AO digitizer
  - AO plotter, for plotting maps A4 size
  - Color Desk/Inkjet printer, For quick color prints of A4 maps
  - GPS, for georeferencing survey data
  - CD-ROM writer (optional), for archiving voluminous data

## B. Agricultural Production Databases

*I P Abrol (Group Convenor), C Johansen, Y S Chauhan, and Masood Ali*

It was reiterated that sound and comprehensive agricultural databases are necessary in order to understand existing situations and trends, understand constraints to production, and define extrapolation domains for improved technologies. Data are required not only on area, production, and yield of individual crops, but also on cropping systems and patterns, and on such inputs as fertilizer, pesticides, and irrigation.

In Bangladesh, India, Nepal, and Pakistan, individual crop data are normally available to district level on an annual basis, published in the relevant statistical yearbooks. These yearbooks may also contain some agricultural input data, such as inputs of inorganic fertilizers. However, data are not normally available on crop varieties (or names of hybrids), forages, green manures, cropping systems, organic manures, etc. This information needs to be gathered from alternative sources, including specific surveys.

Crop statistics in yearbooks are already in the public domain but they need to be digitized to be made more accessible and interpretable. Data sources need to be clearly acknowledged in all outputs. National databases need to be cross-referenced with well-established databases, like those of FAO.

Where reported data appear suspect for any reason, some ground-truthing is advised. There needs to be much greater feedback and interaction between data generators and data users. For example, information on varieties used in a region would considerably enhance the value of crop statistics; this would permit tracking of adoption of new varieties. Planners need to be made aware of the outputs now possible from sound databases, so that they would also be encouraged to promote sound data collection and tabulation. In order to better understand reasons for low yields in farmers' fields, information on biotic and abiotic stress factors needs to be systematically recorded. Simple scoring methods should be used (e.g., no, low, moderate or severe yield loss due to the stress).

## C. Combining Remote Sensing and GIS

*L Venkataratnam (Group Convenor), U K Deb, S Pande, and B K Khandpal*

Remote sensing is clearly an important tool to provide fresh and retrospective information on soils, land evaluation, land degradation, crop distribution, and, potentially, stresses affecting crops. It can effectively be combined with conventional technologies (e.g., ground surveys) and other more recently developed tools (e.g., GIS).

In India, remote sensing data from various sensors like Landsat TM and Indian Remote Sensing (IRS) satellites are being used to prepare soil and land degradation maps of various scales. Forms of land degradation such as salinity and alkalinity are relatively easy to pinpoint. Satellite data have been used particularly in India and Latin America to provide data on geographical distribution of crops. However, because of frequent cloud cover during normal growing (i.e., rainy) seasons, it is necessary to use microwave data (SAR) for this purpose. Research is under way to adapt satellite spectral data for use in crop yield modeling studies (i.e., application not yet validated).

Maps can be prepared at various scales depending upon the objectives of the study. Initially, soil maps were prepared at scales of 1:250 000 using Landsat MSS data, but, with the improvement of data resolution, maps of 1; 50 000 scale can be produced. With the availability of such high resolution data as IRS 1C panchromatic at 5.8 m resolution, the mapping scale could be reduced to 1:12 500. However, for preparing broader scale maps of larger areas depicting either soil or crop distribution, IRS WiFS data at 180 m resolution will suffice.

Remote sensing data is available in digital form and can be used as an input layer to GIS. However, the software used for both remote sensing and GIS need to be compatible (e.g., ERDAS/Arclnfo) and have adequate storage capacity, data portability, be user-friendly and available at a reasonable cost. Use of GIS in combination with remote sensing enhances decision-making in three ways:

- process identification to enable comparison of different acquisitions through time
- identification of agricultural (and other) development problems
- evaluation of possible technical interventions for conservation/reclamation measures.

There is scope for further methodology development in combining remote sensing and GIS for use in crop-soil-water management studies and mapping/monitoring of soil and land degradation processes.

## D. Progress in Database Development for Analyzing Legumes in Rice- and Wheat-based Cropping Systems

*S M Virmani (Group Convenor), D N R Paul, G S Sidhu, P Tulachan, A Ramakrishna, and P K Joshi*

The group discussed progress made so far in assembling the necessary data to analyze constraints and opportunities of legumes in rice- and wheat-based cropping systems of the Indo-Gangetic Plain. This information would be presented as country chapters at the workshop on this topic in October 1997. This was considered as an overall case study in applying GIS techniques to cropping systems analysis. The discussion mainly referred to the Indo-Gangetic Plain of India, but knowledge available for Bangladesh, Nepal, and Pakistan was also updated.

District boundary maps are available for all countries, but boundaries have changed in some countries over years. For example, in India it was decided to use the 1991 boundary status for the base map and adjust subsequent crop production parameters to those boundaries. A similar situation applies in Bangladesh.

For all four countries, there appears to be adequate data on such environmental factors as soils, rainfall, physiography, and length of growing period (as per FAO derivation).

District-wise data for the major legumes are also available, up to the mid-1990s. For India, this includes chickpea, pigeonpea, groundnut, blackgram, mungbean, lentil, soybean, and pea. Similarly, district-wise data are available on rice and wheat area, production, and yield. However, reliable and comprehensive data on forage and green manure legumes are not available, to the knowledge of the group.

District-wise data on abiotic and biotic (e.g., diseases, insect pests, nematodes, weeds) are not available in a comprehensive manner. Only very broad ratings can be given, based on sporadic surveys and anecdotal reports. But sufficient expert information should be available to give ratings according to the format in the book *Adaptation of Chickpea in the West Asia North Africa Region*[1] — i.e. absence, and low, moderate and high incidence of the constraint. The group emphasized the need to establish a methodology for systematic quantification, across space and time, of abiotic and biotic constraints.

In conclusion, the group considered that sufficient data were already available, or potentially accessible, to conduct a GIS-based analysis of constraints and opportunities for legumes in the Indo-Gangetic Plain region.

1. Saxena, N.P., Saxena, M.C., Johansen, C., Virmani, S.M., and Harris, H. (eds.). Adaptation of chickpea in the West Asia North Africa Region. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics; and PO Box 5466, Aleppo, Syria: International Center for Agricultural Research in the Dry Areas. 270 pp. ISBN 92-9066-336-7. Order code BOE 022.

## E. Options for GIS Outputs

*S P Kam (Group Convenor), G Hyman, Kamal Sah, and B Bajracharya*

Although attractive and informative GIS outputs can be displayed on-screen, this group focused on how to convert the digital format to hardcopy or other outputs. GIS datasets, map layers, and attributes are usually left in digital form. Only processed results, in the form of interpretive maps, graphs or tables require hardcopy output as working copies or of publication quality.

Digital products would normally be in the form of CD-ROMs, or could be put on the Internet or World Wide Web. Use of diskettes would be minimal due to the voluminous data storage requirements. File formats would comprise datasets and/or graphics files. Advantages and disadvantages of available software are summarized in the table below:

| *Software* | *Advantages* | *Disadvantages* |
|---|---|---|
| PC Arc/Info (specifically Arcplot) | More cartographic options than ArcView. Cannot deal with grids. | Command mode; not so user-friendly—could be standardized with macro programs. |
| ArcView | Cartographic production quality; not satisfactory for publication quality. | |
| MapInfor | Very good cartographic functionality. Internal linkage in Microsoft Excel. | Less popular software. |
| Arc/Info for Windows NT (future) | Can handle grid output. | |

The type of hardcopy products would depend on the target users. Cartographic quality is an important consideration if formal publication is considered. Necessary equipment includes a color inkjet plotter, with adequate buffer size, and a slide making facility. A film writer would be very expensive.

Some issues that need consideration in generating output are sensitivity of data, clearance of source agencies, the need for standardization (format standardization, acknowledgment, source citation, units of reporting, etc.), and cartographic issues (symbology, colors, black/white hatching).

The group recommended that ICRISAT acquires a dedicated unit for presentation of map output from GIS with the requisite skilled staff. Such skills should include training in cartographic principles.

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# Product names

Presented below is a list of product (and company) names referred to in the various papers of these proceedings. They are either registered trademarks or trademarks of their respective owners. The use of trade names in these proceedings does not constitute endorsement of or discrimination against any product by Cornell University or by ICRISAT.

Access (Microsoft Corporation, USA)

AEGIS/WIN (IBSNET) (Agricultural and Environmental Geographic Information Systems for Windows (AEGIS/WIN)

AIX Operating System (Hewlett Packard Company)

ANUSPLINE (Australian National University, Australia)

Arc/Info, ArcView, ArcExplorer (Environmental Systems Research Institute (ESRI), Redlands, California, USA)

Colorado (Hewlett Packard Company)

dBASE IV (Borland International, USA)

DELL, DELL GXPro (Dell Computer Corporation, USA)

DeltaMap (Autometric)

MS DOS (Microsoft Corporation, USA)

DSSAT (IBSNAT, University of Honolulu, Hawaii, USA)

ERDAS (Earth Resources Data Analysis Systems), ERDAS Imagine (ERDAS Inc, Atlanta, Georgia, USA)

Epson LQ-510 (Seiko Epson Corporation, Japan)

ER Mapper (Earth Resource Mapping Pvt. Ltd., San Diego, California, USA)

Exabyte (Exabyte Corporation)

Exceed (for X-Window emulation) (Productivity through Software Inc. (PtS))

FoxPro (Microsoft Corporation, USA)

Gateway 2000 (Gateway 2000 Inc., USA)

GEBEI (GEnotype By Environment Interaction (University of Queensland, Australia)

GENSTAT (Rothamsted, UK)

Arc/Info - GRID (Environmental Systems Research Institute (ESRI), Redlands, California, USA)

GTCO Rollup (GTCO Corporation)

GTOPO30 DEM (EROS Data Centre, USGS, USA)

HP DesignJet 650C, HP LaserJet 5P (Hewlett Packard Company)

IBM RISC System/6000 (International Business Machines, USA)

IDRISI (Graduate School of Geography, Clark University, Massachusetts, USA)

ILWIS (Integrated Land and Water Information System) (International Institute for Aerospace Survey and Earth Sciences, ITC, Enschede, The Netherlands)

Intergraph (Huntsyille, Alabama, USA)

Iomega Jaz, Iomega Zip (Iomega Corporation, Utah, USA)

Maplnfo (Maplnfo Corporation, Troy, New York, USA)

MapObjects, MapObjects LT (Environmental Systems Research Institute (ESRI), Redlands, California, USA)

MATMODEL (Microcomputer Power, Ithaca, New York, USA)

Microsoft Office 97, Microsoft Office 95 (Microsoft Corporation, USA)

PAMAP (PAMAP Technologies Corporation, Canada)

Pentium Pro (Intel Corporation, USA)

SAS (SAS Institute, Cary, North Carolina, USA)

SPANS Explorer (Intra Tydac Inc., Ontario, Canada)

Spatial Analyst and Network Analyst (Extensions of ArcView) (Environmental Systems Research Institute (ESRI), Redlands, California, USA)

Strings (GeoBased)

SUN, SUN Ultra2, SUN Sparc5, SUN Sparc 10 (Sun Micro Systems)

Surfer (Golden Software Inc, Colorado, USA)

Synercomm (New Berlin, Wisconsin, USA)

Trimble GPS , Pathfinder Pro, GeoExplorer (Trimble Navigation, California, USA)

UNIX (SUN / Bell Laboratories)

Visual Basic (Microsoft Corporation, USA)

Windows NT, Windows 95 (Microsoft Corporation, USA)

## About Cornell University

Cornell University, located in upstate New York, USA, includes 13 colleges and schools. The university's 13 510 undergraduates and 5 970 graduate and professional students come from all 50 States of the USA and more than a 100 countries. Cornell is an Ivy League university and also the land-grant institution for New York State, committed to the three functions of the land-grant system in America: teaching, research, and extension. As such it is a unique combination of public and private divisions. Interdisciplinary study and research are Cornell hallmarks, as is attention to undergraduate education. The university's 2 340 faculty members are active teachers as well as researchers. State and Federal government agencies, industries, and foundations and other non-profit organizations are all potential sources of research support. Stemming from the university's land-grant role are Cornell Cooperative Extension (an education-outreach program for New York State residents) and the notion that the fruits of Cornell research should extend into the public domain.

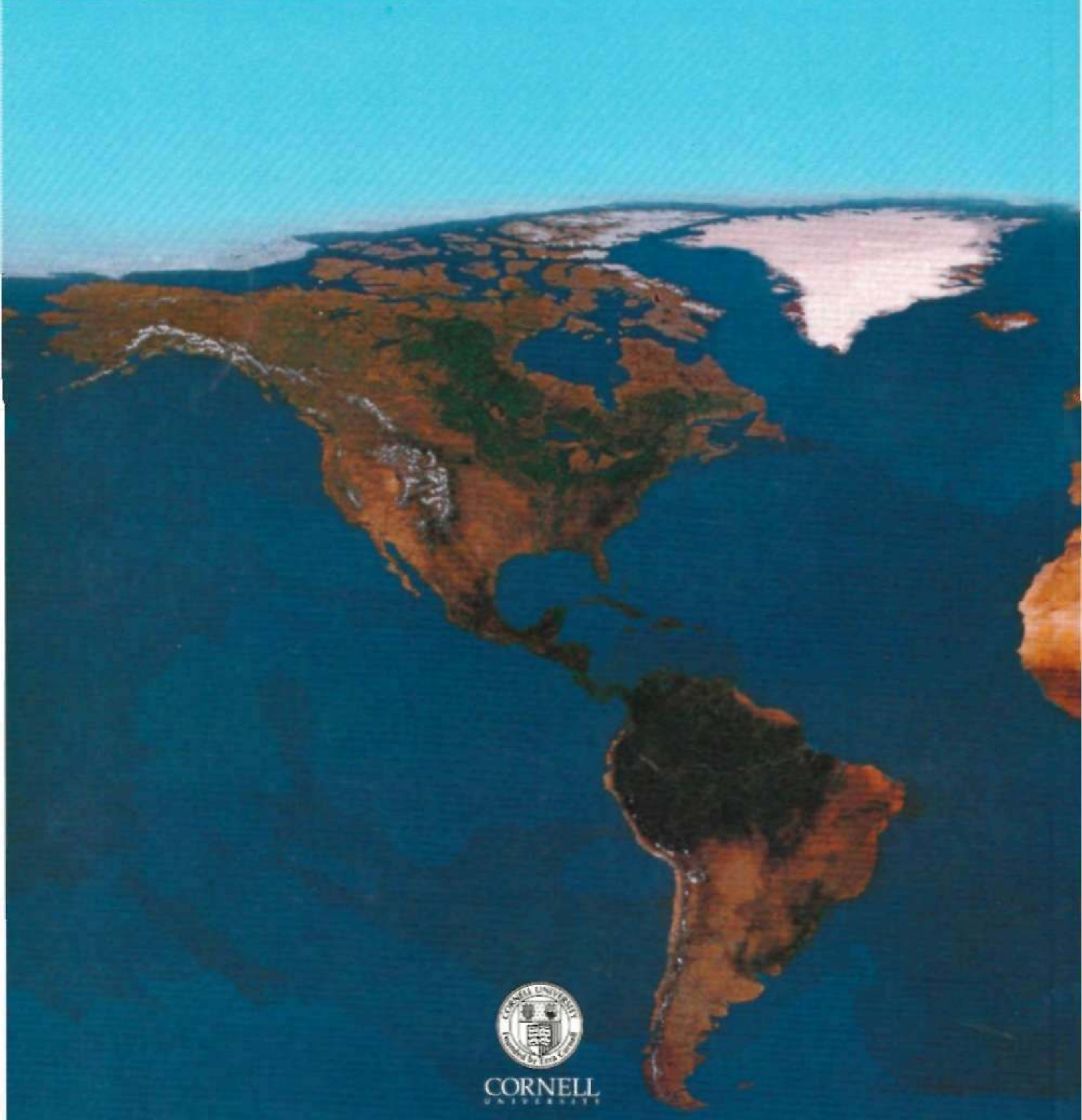
Cornell University has been a leader in the arena of international agricultural and rural development for much of this century. The Department of Soil, Crop, and Atmospheric Sciences (SCAS) has had a long and distinguished history at Cornell. Studies in soil and crop science at Cornell have existed from the early days of the university. Today SCAS has over 30 faculty members who teach over 50 courses. The SCAS mission is to develop research teaching, and extension programs that will provide pragmatic solutions to agricultural and environmental problems, produce an educated populace, and advance the understanding of basic natural processes. The research program of the Department is one of the largest in the College.

## About ICRISAT

The semi-arid tropics (SAT) encompasses parts of 48 developing countries including most of India, parts of southeast Asia, a swathe across sub-Saharan Africa, much of southern and eastern Africa, and parts of Latin America. Many of these countries are among the poorest in the world. Approximately one-sixth of the world's population lives in the SAT, which is typified by unpredictable weather, limited and erratic rainfall, and nutrient-poor soils.

ICRISAT's mandate crops are sorghum, pearl millet, finger millet, chickpea, pigeonpea, and groundnut; these six crops are vital to life for the ever-increasing populations of the semi-arid tropics. ICRISAT's mission is to conduct research which can lead to enhanced sustainable production of these crops and to improved management of the limited natural resources of the SAT. ICRISAT communicates information on technologies as they are developed through workshops, networks, training, library services, and publishing.

ICRISAT was established in 1972. It is one of 16 nonprofit, research and training centers funded through the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is an informal association of approximately 50 public and private sector donors; it is co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), and the World Bank.

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