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GEOGRAPHIC INFORMATION SYSTEMS AND REMOTE SENSING IN LAND RESOURCES ANALYSIS AND MANGEMENT

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RESUMEN

SISTEMAS DE INFORMACION Y TELEDETECCION EN EL ANALISIS Y GESTION DE LOS RECURSOS DE LA TIERRA

Los sistemas de Información Geográficos (SIGs) son bases de datos computerizados de recursos referenciados a un sistema de coordenadas geográficas y son utilizados para el almacenamiento, manipulación y presentación visual de datos espaciales tales como datos de recursos naturales. SIGs en conjunción con datos provenientes de sensores remotos ofrecen nuevas oportunidades a científicos que trabajan en disciplinas relacionadas con paisajes.

Estos instrumentos pueden ser usados para estudiar la variabilidad espacial y temporal, mejorar la organización e integración de datos, evaluar los problemas con la ayuda de modelos simulados basados en estudios de drenaje de cuencas hidrográficas utilizando tecnologías de SIGs, entender y manejar paisajes como ecosistemas y cuantificar procesos geomorfológicos. Ellos nos permitirán modelar los paisajes del suelo usando métodos cuantitativos y estadísticos para definir las relaciones entre características del paisaje y propiedades de los suelos y hacer predicciones.

Los Sistemas de Posicionamiento Global (SPGs) son instrumentos nuevos para los científicos de suelos (que les permiten determinar las coordenadas geográficas exactas y elevaciones del terreno, en todo el mundo y pueden ser integradas directamente a un Sistema de Información Geográfica. El análisis digital del terreno puede ser usado para caracterizar la topografía superficial en tres dimensiones. De este análisis se pueden derivar los límites de drenaje de cuencas hidrográficas, canales de ríos, límites de áreas contribuyentes y caracterizar la topografía dentro de cada área contribuyente.

Las Bases de datos del terreno obtenidas con fotografías aéreas e imágenes de satélites son cada vez más comunes. Nuevos sistemas de sensores remotos están propuestos como parte del Sistema de Observación de la Tierra por NASA; éstos van a ser complementados con videografía infrarroja y técnicas geofísicas. Los suelos tienen un papel clave en los procesos fluidos y biológicos de la tierra; SIGs y sensores remotos serán un componente importante en el estudio de la ciencia global.

Palabras clave: Sistemas de Información Geográfica. Teledetección. Sistemas de posicionamiento global. Análisis digital del terreno. Videografía infrarroja. Técnicas geofísicas.

SUMMARY

Geographic Information Systems (GISs) are computerized resource databases referenced to a geographic coordinate system and used for the storage, manipulation and display of spatial data such as natural resource data. GISs in conjunction with remotely sensed data offer new opportunities for scientists working in landscape-related disciplines.

These tools can be used to address spatial and temporal variability, better organize and integrate data, assess problems with the aid of watershed-based simulation models that are driven using GIS technologies, understand and manage landscapes as ecosystems, and quantify geomorphic processes. They will allow us to model soil-landscapes using quantitative and statistical methods to define relationships among landscape features and soil properties and make predictions.

Global Positioning Systems (GPSs) are a new tool for soil scientists which will allow the user to collect accurate geographic coordinates and elevations in the field world-wide and can be directly input to a GIS. Digital terrain analysis can be used to three-dimensinally characterize surface topography. It can derive drainage basin boundaries, stream channels, contributing area boundaries and characterize topography within each contributing area.

Terrain databases from aerial photography and satellite imagery are becoming increasingly common. New remote sensing systems are planned as part of NASA's Earth Observing System; these will be complimented by infrared videography and geophysical techniques. Soils serve a key role in the fluid and biological earth processes; GIS and remote sensing will be an important component in the study of global science.

Key words: Geographic Information Systems. Remote sensing. Global positioning systems. Digital terrain analysis. Infrared videography. Geophysical techniques.

INTRODUCTION

Current and future pressures on the earth's ecosystem from rapidly increasing population and misuse of land resources will require applying new technologies to maintain a sustainable food and water supply without degrading the environment. The new tools in soil science that can address these issues are geographic information systems (GISs) and remote sensing. We are entering a new era where we will be able to use these tools to address spatial and temporal variability, better organize and integrate scientific data, understand and manage landscapes as ecosystems, quantify geomorphic processes, and model soil - landscapes using qualitative and statistical methods to define relationships. Ground based remote sensing (such as ground penetrating radar and seismic refractometry) and video remote sensing will be integrated with GIS and satellite - acquired remotely sensed data sets. Remote sensing will play an increasingly important role in helping us to monitor environmental and global change. There will be a major remote sensing effort in the mid 1990s, when NASA plans to launch four unmanned space platforms into polar orbit. This will be part of a proposed 15-year international effort to gather satellite data on global environmental trends using NASA's Earth Observing System (EOS).

NEW TOOLS IN SOIL SCIENCE

The use of GISs and remote sensing during the next decade will have tremendous potential for aiding wise land - use decisions. GIS technology allows for the interaction of soil data with other land, climatic and cultural data and remotely sensed data. By examining a wider range of environmental variables than are usually considered in land management decisions, this technology will lead to a better understanding of how landscape systems function and interact. This technology enables scientists and politicians to make decisions with greater sensitivity to environmental quality, more complete exploration of land use options, and greater public participation. It allows mapping of soil and terrain attributes which are the basis for prescribing appropriate management practices and resource protection measures on landscapes. Some techniques that will enhance conventional soil and terrain mapping techniques are GIS tools (including digital elevation modeling and global positioning systems) and remotely sensed data (including color infrared videography and geophysical techniques).

Geographic Information Systems

The four components of GIS software include data collection, storage and retrieval, analysis, and mapping. Data collection entails using line digitizers, scanners and other computer tools to capture and convert information from maps, sensors and field observations to a digital form. GIS software is used to study the relationships between data layers. Analysis techniques include adjacency, proximity, overlay, coincidence, boundary delineation, diversity, majority, minority, averaging, distances and area calculations, etc. A GIS may include generation of simple statistical information concerning the complex spatial relationships between a variety of variables.

Global Positioning Systems

Soil and terrain attribute data can be gathered through maps, field sampling and remote sensing techniques. Soil and terrain patterns are often difficult or impossible to repeatedly locate during subsequent visits to a site. The Global Positioning System (GPS) can be used to accurately and rapidly record and return to an exact location on a landscape. It allows the user to collect accurate geographic coordinates and elevations in the field with precision ranges from several meters to about a centimeter. These data can be collected using a data logger for direct input to a GIS.

Just as early explorers used the light from several stars to calculate their locations, today a GPS receiver can document any location precisely by using electronic signals from a constellation of 21 satellites for precise positioning and navigation 24 hours a day. GPS receivers determine their position by calculating distances to at least four of these satellites by measuring the time required for a radio signal to travel from a satellite to a receiver. Accurate atomic clocks in the satellite are the key to precise measurements.

GPS gives soil mappers and land managers the ability to know precisely where they are at any time. Already, the system is rapidly replacing conventional methods of conducting geodetic surveys. GPS navigation systems, with electronic maps, have been installed in cars and trucks. Crop yield maps could be produced using yield monitors attached to crop harvesters equipped with GPS. Also, electronic sensors of soil attributes could, with a GPS, be used to map some soil conditions as farm implements move through fields. Generating GIS maps that show how fertilizer application rates should be varied throughout a field could be one result.

GPS technology can improve soil mapping procedures by recording the precise location of all points sampled in the process of mapping. This would permit an objective analysis of the spatial variability of soil attributes. Furthermore, since GPS locates in 3-dimensions, it can record precise elevations as well as latitude and longitude as a vehicle moves through a field. This allows for the acquisition of digital elevation data needed for terrain models. Terrain models superimposed on conventional soil survey maps through a GIS may become the basis for future detailed soil maps for precise soil - specific land management.

Digital Terrain Analysis

Digital terrain analysis is the investigation of, primarily, topography by means of computers and computerized representations of the topography. The usual representation of the data is a digital elevation model (DEM) which is a spatial arrangement of the elevations, ie. a GIS file. DEMs provide the fundamental information set necessary to describe and model landscape geometry that is important in any process model involving surface, subsurface and near-surface phenomena. Exploiting DEMs produces a variety of secondary landscape parameters important in global applications ranging from hydrology and microclimatology to regional tectonics. Manual techniques to gather similar parameters are time consuming and costly and subsequently limit their use to fewer and smaller study areas as compared to areas studied using DEMs.

Sources of DEM data can be stereoscopic pairs of aerial photographas or satellite images, topographic maps, conventinal surveying data, GPS data, or any other source of elevation values. It can be input to a computer manually, with a digitizing tablet or scanner, or with various computer algorithms which can automatically derive a DEM from one or more of the previously mentioned sources. DEMs can be processed with a variety of algorithms to compute terrain attributes such as slope gradients, aspects, ridges, valleys, landscape curvature etc. DEMs can be used to three dimensionally characterize surface topography within a drainage basin. Techniques are available to derive basin boundaries, stream channels, contributing area boundaries and to characterize topography within each area (Gardner *et al.*, 1990).

Although exploitation of existing DEMs can achieve many secondary information products, relatively few areas of the world have high resolution data. New satellite-based remote sensing systems, such as the French SPOT (Chevrel *et al.*, 1981) satellite, provide products that can be used to produce high-resolution DEMs anywhere in the world that approach U. S. A. National Map Accuracy Standards at 1:24.000 scale. Accuracies have been reported of 15 meters vertical and 10 meters horizontal (Vincent *et al.*, 1988).

Remote Sensing

New remote sensing instruments will be suppliying vast amounts of data to scientists. The obsevational techology of these remote sensing systems coupled with the computational power to analyze the data may be the most powerful technique for monitoring environmental problems and changes on a global scale.

Most of the remote sensing for the NASA EOS project will be done by the Moderate-Resolution Imaging Spectrometer (MODIS), which will image the atmosphere, ocean, and land in visible and infrared wavelengths with resolutions of up to one-half kilometer. This system will be complimented with the High-Resolution Imaging Spectrometer (HIRIS), which will provide 30-meter resolution over 192 spectral bands. There are also satellites, such as the European Space Agency's ERS-1 satellite, that various countries throughout the world are planning to launch.

Two relatively new remote sensing tools useful in land resource analysis and management are infrared (IR) videography (Pfordresher, 1988) and geophysical techniques. IR videography records the electromagnetic response in the 900 nm range which is best suited for soil/vegetative cover (Lintz and Simonett, 1976). The data are recorded on video cassette tapes allowing real-time access, ready and inexpensive duplication, field monitoring of data as it is collected, and quantification by digital image analysis. Two geophysical techniques discussed here are ground penetrating radar (GPR) and seismic refractometry (SR). Both techniques remotely sense below-ground features such as soils and geology.

Infrared Videography

Use of video IR imagery to assess differential plant response to soil and pathogenic constraints is in its infancy. This is partly because this technology is rapidly improving and only now reaching a point of commercial distribution. This technique is being tested to identify plant response to highly variable local soil conditions in surface mine reclaimed areas of the U. S. and in the Sahel region of West Africa.

This tool has potential agronomic applications that are yet untested. Still-camera IR imagery has been used to determine areal extent and distribution of Fe-chlorosis in grain sorghum, Co-deficiencies and nematode infestations in peanuts, root rot-infestations in cotton and peach orchards, and salinity constraints on winter vegetables. It has also been used to assess the extent of insect damage to citrus leaves before these damages could be observed by the unaided eye (Escobar. *et al.*, 1983). Still-camera IR has the disadvantages that images can not be readily processed by computerized image analysis and often the images are not geometrically rectifiable. Also, still-camera IR images must be processed before being viewed, whereas video imagery can be viewed immediately.

Geophysical Techniques

Olson and Doolittle (1985) have described two geophysical techniques ground penetrating radar (GPR) and seismeic refractometry (SR). GPS is an impulse radar system in which short electromagnetic pulses are radiated into the ground from a transmitting antenna. Each pulse consists of a spectra of frequencies that is distributed around the central frequency of the antenna. Whenever a pulse strikes an interface separating layers of differing electrical properties, a part of the pulse's energy is reflected back to the receiving antenna. The received, reflected waveforms are displayed on a graphic recorder or are taped for future playback of recording (Olson and Doolittle, 1985).

Seismic refraction uses a technique developed for earthquake seismology. Elastic waves that are propagated by percussion at the surface move out from this point source in equidistant wavefronts until they strike an interface. At the interface the velocity of the compressional waves change. Megaphones, placed at the surface, detect returning ray velocities of direct and refracted wavefronts. Using Snell's Law it is possible to determine the depth of different sediment or rock interfaces by calculating ray velocities of sediment or rock layers and respective critical distances between the megaphones placed in a straight line at the surface. Compressional waves have much higher ray velocities than surface waves. Average velocities range from 500 $m\ s^{-1}$ for unsaturated sandy soils to > 6000 $m\ s^{-1}$ for limestone rock.

REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM APPLICATIONS. GIS Applications

Soil Landscape Modeling

Soil scientists rely on associations between soil properties and landscape features that are learned through successive point, field observations (Arnold, 1988) forming a mental soil-landscape model. Recent research projects have explored the use of multivariate statistical analysis to define soil-landscape relationships followed by the application of these models to GIS databases to generate predictive soil property maps (Bell, *et al.*, 1988, Kyoo-seock, *et al.*, 1988). The model predicts soil property classes for each grid cell based on the combination of landscape features. Typical sources of landscape information include multispectral data from satellite sensor, DEMs, and geologic, hydrologic, and climatic information interpreted or modeled from other data sources.

Soil-landscape modeling as a technique for soil property mapping has two main advantages. First, it provides a common methodology appropriate for use with computerized, spatial data bases to produce standardized soils information at local scales. Secondly, assuming suitable models are developed, soil-landscape relationships can be mapped consistently, rapidly, and at less cost compared to ground survey tecniques.

GIS and GPS Applications for Precision Farming

GIS and GPS technologies offer opportunities to use environmentally sensitive, precision farming methods ("soil-specific farming" or "farming soils, not fields.") (Nielsen, *et al.*, 1990; Petersen, 1991). This may mark the beginning of an era in which the genetic potentials of plants and animals, including those originating from advances in biotechnology, can be precisely matched with soils and microclimates in the field allowing farm enterprises to be profitable, environmentally benign, and sustainable. GIS, GPS and remote sensing technologies facilitate accurate mapping, monitoring and management of non-uniform soil landscapes. Uniform management (e. g. uniform fertilizer application) is wasteful and a potential source of groundwater contamination. Fortunately, there are new opportunities for replacing uniform management with variable management (Abelson, 1990; Carr, *et al.*, 1991; Larsen, *et al.*, 1989; Luellen, 1985; Peck, 1990).

Computers in GPS-equipped agricultural implements, in conjunction with GIS soil maps, can control the application of fertilizer, herbicides, tillage depth and seeding rates as prescribed for each soil management map unit. A GIS for precisión farming would include data layers that represent topography (slope gradient, aspect, and catchment areas), drainage patterns, soil type, crop yield, soil pH, soil texture, plant nutrient status, and soil organic matter content, records of previous management treatments, microclimate, and other variables. Ultimately, GPS or similar positioning systems will help operators drive so precisely that skips and overlaps in applications of agricultural chemicals will be virtually aliminated resulting in economic and environmental benefits by decreasing fertilizer and herbicide usage, and, therefore, nonpoint-source pollution of surface and groundwater.

Stream Network and Drainage Basin Delineation

Digital elevation models (DEMs) make it possible to process large volumes of topographic data. Algorithms to delineate strems and drainage basins or watersheds from DEMs have been available for a long time and continue to be produced (Mark, 1983; Jensen, 1985; Jensen and Dominique, 1988; Morris and Heerdegen, 1988; Gardner *et al.*, 1990).

Although there are a variety, albeit similar, methods for stream and drainage basin delineation, one of them (Gardner *et al.*, 1990) will be described briefly here to illustrate one approach. The algorithms use slope aspects derived from the DEM and a specified outlet to determine which areas point toward the outlet. Surrounding areas are recursively searched until all areas which drain toward the outlet are defined, determining the basin or watershed. The stream is delineated by tracing flow paths from the drainage divide or watershed boundary to the outlet. This potentially shows areas of concentrations of soil water, and, hence, poor drainage areas or localized erosión. Since shallow subsurface flow generally mimics surface flow paths (excluding flow though macropores), the paths of lateral soil solution movement could be traced. This should aid investigations, especially modeling, of soil genesis processes.

Geomorphometrics from DEMs

Geomorphometrics, or measurements of the shape or form of the earth, have been measured manually by geomorphologists for decades (Horton, 1945). Only recently have DEMs been exploited for geomorphological studies (Franklin, 1987; Morris and Heerdegen, 1988; Gardner *et al.*, 1990). DEMs convert the extraction of geomorphometrics from an extremely labor intensive process to a practical tool for landscape analysis.

Geomorphometrics which can be calculated from DEMs are numerous (Gardner, *et al.*, 1990), but some which may be relevant to soils investigations include basin slope, basin relief, ruggedness, drainage density, and stream frequency. Connors *et al.*, (1988) demonstrated how DEMs can be used to measure the LS factors (subbasin lengths and slopes) of the Universal Soil Loss Equation (USLE).

Remote Sensing Applications

GIS and Remote Sensing Applications to Hydrologic Models

As digital soils data and DEMs have become available there is an increasing use of this data as input to computer models. One example is surface hydrology models, where several investigators have linked GISs with these models (Potter *et al.*, 1986; Evans and Miller, 1988; Moore *et al.*, 1988; De Roo *et al.*, 1989; Sasowsky and Gardner, 1991). Ease of linkage between a GIS and a model depends upon the nature of both the GIS and the model.

Remotely sensed data have been used as input for surface hydrology models for a long time, especially in the form of land cover classification from imagery (Jackson *et al.*, 1977; Engman, 1981; Groves and Ragan, 1983; Rango *et al.*, 1983; Alexander and Rao, 1985). Remotely sensed data has the advantage of being an areal average while traditional input to models is point measurements which are then used to represent areal averages over portions of the watersheds. Remotely sensed data is a unique measurement of spectral response to the combined affects of soil type, soil moisture, vegetation cover, and surface roughness, some of the same characteristics that control surface hydrology. Because of the digital form of remotely sensed data, it is also readily input to models. Furthermore, in areas where ground truth data are limited, remotely sensed data may be the only data available.

Color Videography for Monitoring Vegetation Cover

Color videography is collected with an IR camera, portable video cassette recorder, portable color monitor, computer graphics card, sofware, and a microcomputer (Pfordresher *et al.*, 1989). The camera is mounted in the cameraport of an aircraft and flown at altitudes ranging from 440 to 650 m producing resolution ranges from 0.9 m to 1.8 m per pixel with a field view of about 15 ha. Data are recorded on standard 17.7 mm VHS videotapes using a 4-head video cassette recorder. Analog images are then digitized with computer sofware. A digital image processing is used for classification and calibration of reflectance values with ground truthing.

In a computer-enhanced video image of a surface mine reclaimed area with variable ground cover, darker areas represent dense stands of healthy vegetation, whereas progressively lighter areas represent sparse vegetation and white areas are barren. Barren areas and sparse vegetation indicate soil conditions that are restrictive to plant growth. Infrared videography has also been used in quantifying the percentage of farmers millet fields that are non-productive in Niger, West Africa (Pfordresher *et al.*, 1989).

Ground Penetrating Radar and Seismic Refraction of Soils

Olson and Doolittle (1985) have compared the efficiencies of GPR and SR for remotely sensed bedrock cavities, water tables, restrictive diagnostic horizons, lithological contacts, faults, bedding planes, roots, rocks and surficial geological deposits. According to Olson and Doolittle (1985), GPR has the advantages of: continuous, high resolution, interprettive imagery to 2-3 m; ability to resolve water tables in coarse textured materials; identification of depth and lateral extent of select horizonation, roots and rocks; and speed if easy access is available. They state its disadvantages as: depth limitations of 7 m; depth restriction by shales and clay; inability to resolve water table in moderately-fine-textured materials; inability to identify bedrock if blanketed by thick alluvium; and need for good ground control for calibration.

The GPR has been especially helpful to the Florida, U. S. A. soil survey program in quantifying spatial distribution of Arenic and Grossarenic Paleudults and Quartzipsamments. The position of the Bt (argillic) horizon underlying coarse sands is represented by dark positive and negative pulse polarities and reverberated signal. The depth to the argillic horizon is highly variable and is the feature which separates major soils of the area.

The advantages of SR are: easy identification of physical composition and water table (Perched and permanent); penetration to 10's of meters and independence of bedrock depth determination and overburden thickness (Olson and Doolittle, 1985). They state its disadvantages as: it is time consuming for short, lateral crossections; profile lines must be overlapped; soil profile characteristics are not identified; and it requires good ground control for calibration.

Both GPR and SR have limitations, but when coupled with ground truthing and elevation control, they significantly reduce the labor intensive traditional methods to establish soil/geomorphic relationships.

FUTURE NEEDS AND TRENDS

The growing availability and capability of GIS and remote sensing technology is bringing about rapid changes in conducting natural resource analysis and management. As with any rapidly evolving scientific or technological field, the development of the tool is only a step ahead of the applications. Future research will need to concentrate on a number of key issues if the use of GIS technology is to reach its full potential.

GISs coupled with remote sensing are new tools for the scientific community. These tools are allowing us to quantitatively describe landforms and landscape ecology. We are able to assess problems by linking GISs to physical process models. New and/or improved models need to be developed to fully take advantage of the spatial nature of the data provided by the GIS and remotely sensed data. The development of these new models will rely heavily on spatial statistical analysis techniques to quantify accuracy of the input parameters and model output. Three dimensional scene simulation visualization of complex scientific phenomena, and animation capabilities in together with remote sensing and image processing technologies will have an enormous impact on the ability of scientists to study environmental problems and monitor global changes.

Recent research with three-dimensional GIS is largely a result of graphical hardware advances. Another innovation is the linkage of expert systems with GISs and the incorporation of artificial intelligence techniques in an effort to develop intelligent GISs.

Several aspects of database development will need additional focus. The whole issue of database integrity must be addressed. The assessment and quantification of the accuracy of the data layers constituting a GIS is an area which needs more study. In the rush to use the GIS technology, relatively little attention has been given to the various sources of error inherent in the development of the databases. If the results of the modeling with data from GIS are to be used, error and sensitivity analyses on the models and databases will be required. These studies will establish the accuracy of the data supplied by the GIS to the modeling community. As new data capture and collection processes evolve (automatic digitization, new remote sensors etc.), the issue of data standards and quality will continue to grow. Ultimately, a comprehensive set of standards for GIS databases will need to be implemented to insure data integrity and compatibility throughout the user community. As GIS becomes more entrenched in the day-to-day management of our natural resources, the above issues concerning database accuracy and integrity as well as the development of new models based on spatial data will become critical to the success of policy implementation.

Spatial statistical analysis techniques (e. g., geostatistics, spatial autocorrelation, fractal geometry), which have been developed and applied in other areas, show promise for addressing the spatial resolution and sampling requirements for GIS development and implementation. GPS can assure accurate locating of field data collection and georeferencing. GIS and remote sensing technologies will be common tools for solving global problems in land resources analysis and management.

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