Transactions in GIS, 2003, 7(2): 231–241

Research Paper

3D Geographic Reconstruction and Visualization Techniques Applied to Land Resource Management

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Abstract
Optimized land resource management depends on reliable and detailed information describing the spatial distribution of soils, geology, topography, and land use. Soil-landscapes are three-dimensional (3D) systems commonly represented using 2D maps utilizing geographic information systems. Addressing 3D soil-landscape reality is crucial for land resource management in terms of crop growth and transport processes (e.g. nitrate leaching) that are driving soil and water quality. Our objective was to investigate the usefulness of 3D geographic information technology (GIT) applied to land resource management. Our approach is based on 2D and 3D ordinary kriging interpolating surface and subsurface attributes to reconstruct soil-landscapes. We used Virtual Reality Modeling Language, which is a web-based 3D graphics language, to visualize objects (e.g. voxels, polyhedrons) representing soil and landscape attributes. We produced a 3D block model showing the spatial distribution of bulk densities and relief for a site in southern Wisconsin and a 3D stratigraphic model showing the spatial distribution of soil horizons and relief for a site in northern Florida. Emerging GIT was used to develop 3D soil-landscape models describing continuous changes of soil and landscape attributes. Combining multimedia elements (e.g. WWW, 3D visualization, and interactivity) can produce insight that would not arise from use of the elements alone. Three-dimensional scientific visualization is a powerful tool to help us see what is invisible from above the ground.

1 Introduction

An overall goal of land resource management is to optimize the use of land resources and their protection to maintain ecosystem functions for economic, ecological, recreational,

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cultural, aesthetic, and social values. Sustainable management of land resources facilitates preservation of environmental resources without adversely affecting economic profitability and social equity. Ultimately, optimized land resource management depends on reliable and detailed information describing the spatial distribution of soils, geology (parent material), topography, and land use.

Despite major developments in information technologies used to describe land surfaces via airborne and remote satellites pushing spatial resolutions in the sub-meter range, there is a lack of such sensors for subsurface investigations. Traditional soil surveying is conducted with augers and excavated pits, which are labor intensive and costly. Most soil surveys were conducted at a scale of 1:24,000, with some few exceptions at a scale of 1:10,000. The high-resolution digital elevation models (DEM) and land use maps derived from hyperspectral images (e.g. Ikonos images) do not match up well with relatively coarse soil maps.

Characteristics of land resources are that: (1) they vary continuously through three-dimensional (3D) space and through time, (2) they are usually anisotropic, i.e., they exhibit an uneven spatial distribution in geographic space, (3) they are interrelated with other natural resources (e.g. topography, management), and (4) data collection is non-exhaustive where observations and measurements are collected with drills, boreholes or excavated pits limited to specific locations.

Commonly, 2D maps or GIS layers are used to visualize the spatial distribution of soil and landscape patterns (Pennock and Acton 1989, Osher and Buol 1998). Other soil-landscape representations use a $2^1/_2$D design, where soil or land use data are draped over a DEM (Su et al. 1996, Hogan and Laurent 1999) to produce a 3D view. Since this technique describes patterns on 2D landscape surfaces rather than the spatial distribution of subsurface attributes (e.g. soil texture, soil horizons) it fails to address three-dimensional soil-landscape reality. Numerous sketches of soil-landscapes can be found in Soil Survey Reports and other publications (e.g. Dane County Soil Survey; Mickelson 1983). These hypothetical sketches are three-dimensional but neither utilize real data nor interpolation methods. Three-dimensional topographic and subsurface representations are crucial to determine surface runoff, infiltration, drainage, and leaching of nutrients and pesticides.

McSweeney et al. (1994) pointed out that soil-landscapes are 3D systems and should be represented using geographic information technology accordingly. According to the Soil Science Society of America (SSSA) glossary a pedon is described as "a three-dimensional body of soil with lateral dimensions large enough to permit the study of horizon shapes and relations. Its area ranges from 1 to 10 m^2." Burrough and McDonnell (1998) point out that the term "three-dimensional" is usually (and properly) reserved for situations in which an attribute varies continuously through a 3D spatial frame of reference, e.g. soil systems.

To date, few studies have used reconstruction and 3D visualization techniques to portray subsurface attributes at the landscape scale. For example, the Cooperative Research Center for Landscape Evolution and Mineral Exploration constructed a 3D regolith model of the Temora study area in Central New South Wales, Australia (CRCLEME 1999) and a 3D soil horizon model in a Swiss floodplain was created by Mendonça Santos et al. (2000) using a quadratic finite-element method. Sirakow and Muge (2001) developed a prototype 3D Subsurface Objects Reconstruction and Visualization System (3D SORS) in which 2D planes are used to assemble 3D subsurface objects. Even fewer studies have used reconstruction along with virtual reality techniques to portray soil data in 3D space (Barak and Nater 2001, Grunwald et al. 2000). Despite booming 3D information technologies, most of them are developed for the video game industry, movie production and military applications rather than the scientific world.

Scientific visualization techniques such as spatial footprints, transparency, slicing, or virtual holes can be used to view soil-landscapes from the inside-out. New tools are needed to explore high-dimensional data spaces representing soil-landscapes, enabling users to gain insight into the underlying geo-processes. Until quite recently, little attempt has been made to manage geographic information using true 3D or four-dimensional (4D) representations. Innovative research studies demonstrate the development of 3D and/or 4D GIS prototypes, which can manage multi-variate and multi-dimensional datasets and output 3D models, and/or animations (Raper et al. 1998, Doellner and Hinrichs 2000, Edsall et al. 2000, Kreuseler 2000, Morris et al. 2000) and virtual reality applications (Haase et al. 2000). Yet most commercial available GIS softwares are not true multi-dimensional GIS.

To provide a more holistic, multi-dimensional view of soil-landscapes, several issues arise. First, soil attributes and processes in natural environments often vary at granularities ranging from pedons, to hillslopes, watersheds, and regions. This suggests employing a nested hierarchical and object-oriented (OO) approach that integrates over a spectrum of scales. Secondly, soil-landscapes can be represented by many different constituents ranging from categorical (e.g. soil horizons, drainage classes), discrete (e.g. soil texture), and continuous (e.g. bulk density) attributes, which suggest using a multivariate generic model implemented using OO technology. Thirdly, soil attributes are derived from sparse observations and measurements. This suggests using a robust geostatistical method to interpolate attributes in 3D geographic space to create continuous geo-data models portraying soil-landscapes. Fourthly, interactive, computer-generated, 3D representations enrich our perception, which enable clients to comprehend soil-landscapes intuitively and gain insight into complex environmental systems. Therefore, we suggest employing a web-based virtual environment to disseminate models. In this paper, we investigate the usefulness of 3D geographic information technology (GIT) applied to land resource management. Our objective is to integrate conventional techniques to collect and analyze land resource data with emerging 3D GIT.

2 Methodology

2.1 Geo-Data

We will show the versatility of our approach using two different datasets:

Dataset 1: We collected soil and topographic data on a 2.73 ha field located on the University of Wisconsin-Madison Agricultural Research Station West Madison (ARS-WM), southern Wisconsin (Universal Transverse Mercator [UTM] coordinates: lower left corner: E 293,422; N 4,771,230; upper right corner: E 293,732; N 4,771,443). Soils were formed in sandy-loam glacial till overlain by loess and classified as fine-loamy, mixed, mesic Typic Argiudolls (Soil Survey Dane County, WI). We collected soil cores at 77 sampling locations identified with an entropy-based targeted sampling design. Soil cores (4.3-cm diameter plastic tubes) were collected in the field with a hydraulic probe truck. The soil cores were cut at 5-cm depth increments with an electric saw. Each soil sample was analyzed in the laboratory for bulk density. We determined bulk density by oven drying a known volume of soil and presented it on dry weight basis. We used a Trimble 4600 LS differential global positioning system (GPS), single frequency, dual port, with an internal 4600 LS antenna (Trimble 1996) to georeference sampling locations. The GPS unit was also used to conduct a kinematic survey of the study site to derive a DEM with 1-m grid size (vertical resolution error +/− 8 cm). Elevations ranged from 321.3 to 329.6 m above sea level. Climate is temperate humid. Land use was a corn (*Zea mays*) – alfalfa (*Medicago sativa*) rotation.

Dataset 2: We assembled soil and topographic data for a 41.4-ha site in Alachua County, Florida (Projection: Albers Equal Area Conic – lower left coordinates: E 567,819.7; N 625,912.9; upper right corner: E 568,996.9; N 625,935.2) (Plate 8). This County is part of the Central Florida Ridge and it has four major geologic formations at or near the surface – the Ocala Group, the Hawthorn Formation, the Alachua Formation, and Plio-Pleistocene Terrace Deposits. According to the Soil Survey of Alachua County, Florida, the following Soil Series were found on the site: Lochloosa (loamy, siliceous, semiactive, hyperthermic Aquic Arenic Paleudults), Pomona (sandy, siliceous, hyperthermic Ultic Alaquods), Monteocha (sandy, siliceous, hyperthermic Ultic Alaquods), Plummer (loamy, siliceous, subactive, thermic Grossarenic Paleaquults), Millhopper (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults), and Tavares (hyperthermic, uncoated Typic Quartzipsamments). The Tavares Series consists of nearly level to gently sloping, moderately well drained soils that formed in thick beds of sandy marine deposits. Commonly, these soils are on slight ridges in the flatwoods. The Millhopper Series consists of nearly level to sloping moderately well drained soils that formed in thick beds of sandy and loamy marine sediment. The Lochloosa Series consists of nearly level to sloping, somewhat poorly drained soils that formed in thick beds of loamy marine deposits. Both Millhopper and Lochloosa Series occur in slightly convex areas of the flatwoods. The Plummer, Pomona, and Monteocha Series consists of nearly level, poorly drained soils that formed in thick beds of sandy and loamy marine sediments. These soils are nearly level and are in the broad areas of the flatwoods. Monteocha occurs in ponds and shallow depressional areas in the flatwoods. A sequence of water table depths and durations for the six different Soil Series are shown in Figure 1. Mean annual precipitation for Alachua County was 1,346 mm (1951–1980). Land use was river/lake swamp (50%), residential low density (20%), hardwood conifer mix (28%), and mixed scrub-shrub wetland (2%) (data source: land use cover 1995 – St. Johns Water Management District, Florida).

2.2 *Reconstruction*

Reconstruction of soil-landscapes was implemented in Virtual Reality Modeling Language (VRML) (Ames et al. 1997, Lemay et al. 1999), which is a 3D object-oriented graphics language. Object-oriented programming models real-world objects with software counterparts and encapsulates data (attributes) and methods (behavior, communication, and interaction) into objects. Attributes such as geometry (shape, size), content (value), and appearance characterize objects. Objects interact with each other and with their environment, i.e., they exhibit behavior (e.g. algorithms to calculate percolation or

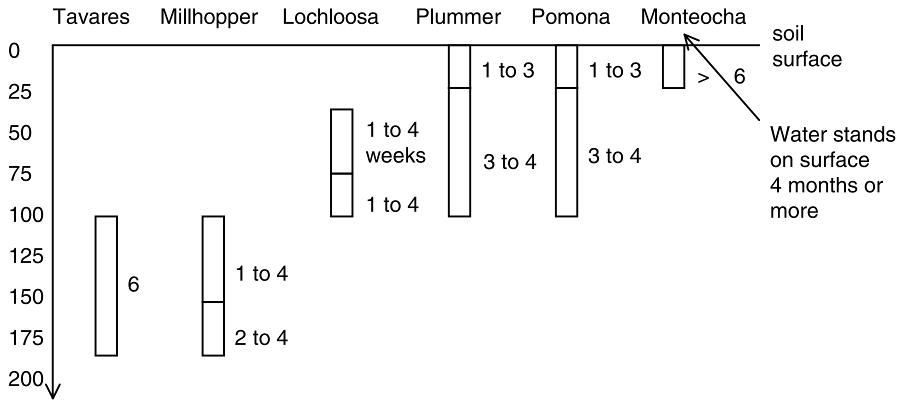

Figure 1 Average water table depth below soil surface for Soil Series on site 2. Numbers indicate duration in months

erosion), communicate with other objects (e.g. routing of soil particles from one object to an adjacent object), and interact with users (e.g. a mouse click triggers the rotation of an object). Object-oriented programming takes advantage of class relationships; where objects of a certain class share the same characteristics, attribute types, and operations. It also takes advantage of inheritance relationships where newly created classes of objects inherit characteristics of existing classes yet contain unique characteristics of their own. These characteristics make object-oriented code portable and increase the flexibility of changing code. We used an object-oriented approach geo-referencing each object. Models implemented in VRML are portable across platforms and deliverable across the Internet. Within the VRML-capable web-browser, the user can interact with objects, e.g. move around these VRML worlds, scale and rotate objects, and view virtual worlds from different viewpoints, e.g. bird's eye view or immersive world view where the user moves through a landscape (Fairbairn and Parsley 1997, Moore et al. 1999).

Input data for site 1 comprised X, Y, and Z (depth)-coordinates, elevations (E), and soil attribute values (bulk densities). Plate 9 lists the steps we used to create a 3D block model based on the voxel geo-data model. A multi-dimensional variogram identified a symmetrical spherical variogram surface describing the spatial structure of bulk densities. We used 3D ordinary kriging that is an innovative 3D weighted interpolation method to interpolate attributes in the horizontal and vertical dimension simultaneously (EVS-PRO, Environmental Visualization System; CTech Development Corporation, Huntington Beach, CA).

To process data for site 2, we downloaded the soil GIS layer for Alachua County from the Soil Survey Geographic Database (SSURGO) web page at http://www.ftw.nrcs.usda.gov/ssur_data.html and imported it into ArcView 3.2 GIS (Environmental Systems Research Institute, Inc., Redlands, CA). We matched attributes to polygons of the GIS layer via the common variable *Muid* (map unit ID). We downloaded topographic data, 5-foot USGS contour lines from the Florida Geographic Data Library (FGDL) web site at http://www.fgdl.org/. A point data layer with 100 points was created in shapefile format. The geo-referenced points and topographic data were exported in ASCII format. We used the Soil Series descriptions from the NRCS Official Soil Series

Description database at http://www.statlab.iastate.edu/soils/osd/ to add soil profile information to the point locations. We imported the ASCII file into EVS-PRO software and used 2D ordinary kriging in the horizontal plane and linear interpolation in the vertical plane to create face geometry of soil layers. The output product was a stratigraphic model representing soil horizons as polyhedrons (volume objects). The *IndexedFaceSet* VRML class was employed to render polyhedrons. A point-arc geographic data model was used to create *IndexedFaceSets*. The *Normal* VRML class specified a list of normal vectors calculated from the face coordinates of objects. This normal indicates the direction the entire polygon faces. Plate 10 describes steps we used to create the 3D soil-layer model.

The accuracy of our reconstruction methodology was verified with a soil-landscape dataset covering a 2.73 ha site in southern Wisconsin by Grunwald et al. (2001b).

2.3 Visualization

Our models visualize the three-dimensional spatial distribution of soil and topographic attributes. Colors were used to specify the appearance of objects utilizing the *Shape*, *Color*, and *Appearance* VRML class. Soil attributes were portrayed using the red-green-blue (RGB) color specification system and topographic attributes were portrayed on the z-axis. The VRML capable web-browser automatically computes shading to augment the 3D appearance of objects. Users can specify reflection and diffusivity parameters.

2.4 Architecture

Currently, a server hosts our HTML-coded interface to facilitate access to VRML soil-landscape models. Models are accessible either with web-browsers (e.g. Netscape Communicator, Microsoft Internet Explorer) equipped with VRML-capable plug-ins (e.g. Blaxxun Contact plug-in available at http://www.blaxxun.com/services/support/download/install.shtml; Cortona plug-in by Parallelgraphics at http://www.parallelgraphics.com/products/cortona/ or with stand-alone software such as GLView 3D available at http://home.snafu.de/hg/). Viewers capable of interpreting VRML syntax have been coded in a number of computer languages for numerous operating systems. By design, the computational effort of 3D calculations is shifted from the server to the client to reduce bandwidth requirements. Many VRML viewers are further optimized to utilize the high-end gaming capabilities of 3D video cards (e.g. OpenGL or Direct3D drivers) thereby transferring some of the computational load from the client CPU central processing unit to the video card RAM (random access memory). Legend and metadata enhance the information content disseminated to end-users. Information transfer is by intention primarily in one direction, from the virtual model (server) to the user (client), to inhibit manipulation of reconstructed soil-landscapes by clients.

3 Results

3.1 Site 1

In Figure 2, bulk density, elevation, and depth are plotted in a 3D scatter diagram. Visual interpretation suggested a trend surface with small bulk densities at shallow depths and high elevations, and large bulk densities at deeper depths and lower elevations.

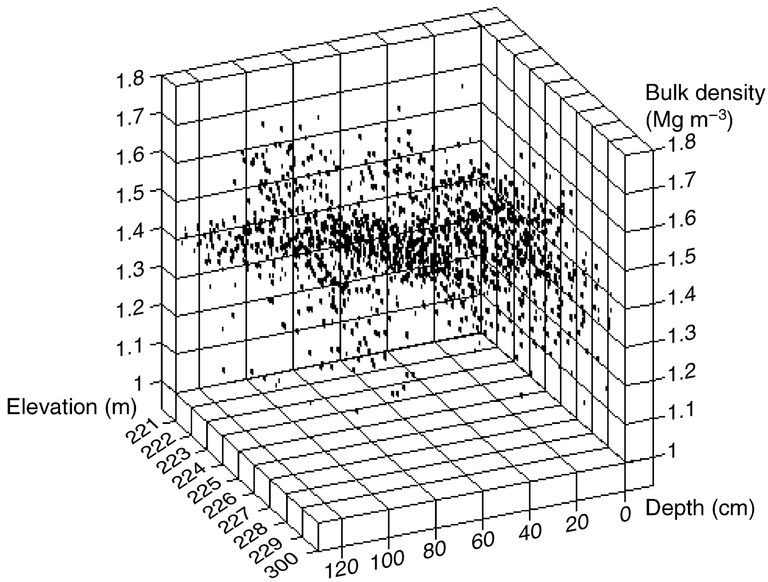

Figure 2 Scatter diagram showing the relationship between bulk density, elevation, and depth on site 1 (n: 1831)

Table 1 Pearson Correlation Coefficients (data records [n]: 1831)

	Bulk density (Mg m^{-3})	**Elevation (m)**	**Depth (cm)**
Bulk density (Mg m^{-3})	1	0.407**	0.332**
Elevation (m)		1	−0.141*
Depth (cm)			1

** Correlation significant at the 0.01 level (2-tailed).

Significant correlations were found between bulk density and elevation as well as between bulk density and depth (Table 1).

We developed a predictive model that describes the relationship between bulk densities measured at specific depths and elevations on the soil surface:

$$E = 0.307 * (BD * Z) \tag{1}$$

where BD is the bulk density (Mg m^{-3}), E is the elevation (m), and Z is the depth (cm). This model produced a coefficient of determination (R^2) of 0.685, standard error of the estimate of 67.682, F value of 3,975.72, and was significant at the 0.0001 level of significance. The F statistic is the mean square regression divided by the mean square residual and serves to test how well the regression model fits the data.

Equation 1 suggests that there is a rather strong linear relationship between elevation and bulk density measured at specific depths. Following Equation 1, bulk densities can be therefore predicted using topographic data. It was shown by Grunwald et al. (2001a) that in southern Wisconsin bulk density is also closely related to soil materials such as glacial till and reworked loess. Commonly, large bulk densities ($\geq$ 1.6 Mg m^{-3}) were associated with sandy-loam glacial till and medium bulk densities ($\geq$ 1.3 and < 1.6 Mg m^{-3}) were found in loess material. Glacial till and loess differ also in a variety of characteristics such as texture, water holding capacity, structure, porosity, drainage, adsorptivity, and leaching of agrichemicals.

The spatial distribution of bulk density in 3D geographic space is shown in Plate 11. Isomorphing was used to visualize bulk densities exceeding specific thresholds. Such a spatial footprint visualization technique is capable of highlighting geographic locations showing large bulk densities. Such a 3D scientific visualization technique is superior to traditional 2D representations visualizing the relationship between bulk densities at specific depths and topographic landscape positions.

Integrating conventional factorial soil-landscape modeling with GIT is a valuable asset for land resource management at the landscape scale. Factorial soil-landscape modeling was utilized to identify a relationship between topography and bulk density measured at specific depths. This predictive model uses an easy to measure variable (topography) to predict a variable (bulk density at specific depths) that is more labor intensive and costly to collect. Geographic information technology was used to reconstruct and visualize the spatial distribution of bulk density in 3D geographic space. The spatial footprint technique identified geographic locations with large bulk densities.

3.2 Site 2

The spatial distribution of soil horizons on site 2 is shown in Plate 12. The spatial footprint visualization technique was used to show the spatial distribution of each horizon starting with the bottom horizon C up to the top A horizon. Compared with the soil map shown in Figure 1, there is greater clarity about the occurrence of soil horizons at a specific geographic location and landscape position. For example, layer BE occurs only on a very small part of site 2. We used a scientific visualization technique, peeling-off layer by layer. The 3D representation is beneficial to show the spatial distribution of each layer in 3D space.

This stratigraphic model was created with readily available soil and topographic data. Since this soil-landscape model integrates a variety of distributed data from different sources (databases), it shows the potential to create 3D soil-landscape representations. High quality and high-resolution soil and landscape data could be used to enhance the information content. However, in this paper we focus on the GIT applied to land resource management.

On site 2 it is critical to understand the relationship between water table depth / duration and the distribution of soils to manage these land resources. The 3D soil-landscape model is beneficial to visualize the interrelationship between land resources and topography. Horizons with lower case letter 'g' indicate strong gleying and the occurrence of redoximorphic features caused by reduction of iron in stagnant, saturated conditions (Plate 12). Of interest is the occurrence of two different E horizons at different depths in soils classified as Monteocha Soil Series (lower landscape position). The horizon sequence A-E-Bh-BC-E'-Btg-Cg indicates an eluviated E horizon formed in association with a Btg horizon, and a Bh horizon that has subsequently formed within the E horizon (bisequal soils). The Bh horizon is illuviated with organic matter. In contrast, the horizon sequence of Tavares occurring on upslope landscape positions is A-C with sand texture throughout the soil profile. Though strongly acid at lower depths only very few redoximorphic features were found indicating less impact by high water table.

The model enables the user to target geographic locations for future land use by taking into account readily available resource data. Optimized use of land resources on this site can be guided by current environmental conditions (e.g. indicators such as g; occurrence of redoximorphic features) superimposed on potential development. For example, future expansion of residential areas can be better evaluated using the 3D soil-landscape model. Without understanding the spatial distribution of soils, such an endeavor is speculative.

Reconstructed soil-landscape models for site 1 and 2 are accessible at: http://grunwald.ifas.ufl.edu. These models are interactive, enabling users to zoom, rotate, scale, and drag models. Interactivity enhances the involvement of users to intuitively gain insight into these soil-landscapes.

4 Discussion and Conclusions

The results presented illustrate the capabilities of an object-oriented and multi-dimensional approach to reconstruct and visualize virtual soil-landscape models implemented in VRML. Our approach utilizing geographic information technology has the following characteristics:

- Geo-data model: polyhedron-based or voxel-based
- Multi-variate: a variety of different subsurface attributes can be used for geo-data modeling and visualization (e.g. bulk density, taxonomic classes, texture, soil horizons, drainage classes, etc.)
- Multi-dimensional: reconstructed soil-landscape models are emulated in 3D geographic space
- Transferable: the object-oriented modeling approach is not limited to a specific geographic location
- Scalable: models can be developed at small and large scale (e.g. pedons, catenas, and soil regions)
- Expandable: the 3D soil landscape models can be updated with new data as they become available
- Interactive: users can interact and communicate with models (e.g. scale, rotate, and access subsurface data and metadata)

Virtual reality (VR) is a way for humans to visualize, manipulate, and interact with virtual environments and extremely complex data. Desktop VR uses computer monitors and the World Wide Web (WWW) to display virtual models. Our virtual soil-landscape models implemented in VRML are disseminated via the WWW, which is an inexpensive way to distribute information to a wide variety of users. Clients can interact with virtual models and scale, move, and explore objects.

Limitations of the presented approach are largely those due to the availability of soil and topographic data used to reconstruct models and complexity and size of soil-landscapes. Complex models extending over large areas with great detail slow down loading times and interactivity functions in web browsers.

We presented a web-based approach to reconstruct and visualize soil-landscapes in a 3D format. Reconstruction and geographic visualization facilitate the exploration, analysis, synthesis, and presentation of geo-referenced information. Geographic information technology facilitates the solution of numerous land resource problems including informed decision-making, assessment of environmental quality, farm management, land use planning, and many more. Shiffer (1992) argues that users gain an improved understanding by viewing information from several different graphical perspectives. Krygier (1999) notes that combining multimedia elements (e.g. WWW, 3D visualization, interactivity) can produce insight that would not arise from use of the elements alone. In the realm of education, Freundschuh and Hellevik (1999) note that students can be encouraged to become active participants, rather than passive learners, by appealing to their multi-sensory learning ability with interactive media. Virtual soil-landscape models are beneficial in disseminating geo-referenced earth data to educators, researchers, government agencies, and the general public.

Emerging geographic information technology enables the development of advanced 3D soil-landscape models describing continuous changes of soil and landscape attributes. We suggest to direct future research towards collection of high quality and resolution land resource data and development of 3D geostatistical methods. Three-dimensional scientific visualization is a powerful tool to help us see what is invisible from above the ground.

Acknowledgements

We wish to thank our collaborators in various aspects of our research reported here: K. McSweeney and B. Lowery, University of Wisconsin-Madison and G. Hart and A. I. Malik for support in collection of data. This research was supported by the Florida Agricultural Experiment Station and approved for publication as Journal Series No. R-09172.

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