Soil Landscape Models at Different Scales Portrayed in Virtual Reality Modeling Language (VRML)

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Abstract

Most state-of-the-art manipulation and visualization of soil data use geographic information systems to portray soil landscapes in two dimensions (2-D). Nevertheless, soil attributes are distributed continuously in three dimensions (3-D) across landscapes. The objective of this study was to investigate the use of Virtual Reality Modeling Language (VRML), a 3-D graphics language suitable for stand-alone or browser-based interactive viewing, to create 3-D soil landscape models at different scales. Four different locations in southern Wisconsin were selected to represent pedon, catena, catchment, and soil region scale. Soil data, including texture, cone index, and depth of soil layers, were used in conjunction with topographic attributes to create 3-D soil landscape models. Spatial modeling techniques comprised 2-D and 3-D ordinary kriging. We used Environmental Visualization Software (EVS) to export the geometry of 3-D objects, which were enhanced to include: (i) viewpoints, (ii) Munsell colors, (iii) texture maps, (iv) 3-D cross-section animation, (v) animations such as zooming, rotation, and (vi) primitive shapes to highlight areas of interest. Virtual reality modeling language is capable of describing and visualizing extremely complex shapes, such as complex soil layers or terrain. Visualization of Munsell soil colors was difficult to implement because there is no hardware and software independent color-management system available in VRML. Animation techniques were valuable to highlight specific characteristics of each model. The accessibility of interactive VRML models via the World Wide Web and the portability of these models across platforms facilitate soil science to enter the virtual world of cyberspace.
**Abbreviations:** VRML, virtual reality modeling language; GIS, geographic information systems; DEM, digital elevation models; TIN, triangulated irregular network; RGB, red—green—blue classification system; CIE, Commission Internationale de l’Eclairage; CRT, cathode ray tube; GIF, graphics interchange format; JPEG, joint photographic experts group; PNG, portable network graphics; WAV, wave form; MIDI, musical instrument digital interface; GPS, global positioning system; CI, cone index; EVS, Environmental visualization software; CI, cone index.

**Keywords:** virtual reality, three-dimensional models, landscapes, horizon
1. Introduction

Simulation modeling is used increasingly to address complex environmental problems. These models require realistic spatial information, including data sets for soils, geology, topography, land use, and management. Commonly, spatial data are stored, manipulated, and visualized in two dimensions (2-D) using geographic information systems (GIS). An exception is elevation data, where x and y coordinates describe the location in space and the z coordinate contains elevation attributes so that digital elevation models (DEM) describe three space dimensions. Recent developments in spatial modeling aim at 3-dimensional (3-D) representations of data. For example, DEM portrayed in triangulated irregular network (TIN) or grid format (Bak and Mill, 1989; Moore et al., 1993; Scarlatos and Pavlidis, 1993; Cook et al., 1996; Su et al., 1996; Hogan and Laurent, 1999) can be overlaid by earth data such as land use and management to produce 3-D representations of a landscape. The relatively few 3-D representations of soils or geologic landscapes currently available are striking. Pereira and FitzPatrick (1998) presented a 3-D model of tubular horizons in sandy soils. Grunwald et al. (19__) used a 3-D spatial interpolation technique to produce a soil landscape model to show the spatial distribution of cone indices. Examples of 3-D terrain representations were given by Su et al. (1996) and Hogan and Laurent (1999). A 3-D visualization of weather data was created by Santa Crus Laboratory for Visualization & Graphics (1999). At a molecular scale, Barak and Nater (1999) developed a gallery of 3-D soil minerals and molecules.

Although the close relationship between soil, landform, and hydrology has long been recognized (Milne, 1935; Huggett, 1975), the development of 3-D models of the soil landscape continuum is mostly lacking. Many research studies use a 2-D design of soil maps (Pennock and Acton, 1989; Sutherland et al., 1993; Osher and Buol, 1998) to address a 3-D
problem. A major challenge is to characterize landscapes as domains where soil, hydrologic, and land form attributes can be considered products of common processes of formation and function in an integrated manner (Gerrard, 1990). The development of 3-D soil landscape models requires (i) terrain attributes to describe elevation changes at the soil surface and (ii) information about the spatial distribution of soil attribute data considering anisotropic vertical and horizontal changes in soil characteristics.

Soil landscape models are scale-dependent. Hoosbeek and Bryant (1992) presented a framework for the classification of pedogenetic models based on relative degree of computation, complexity, and level of organization. Several steps were used to describe at which level a model aims to simulate a natural system. The pedon was placed at the central \( i \)-level. Positive \( i \)-levels include the polypedon \((i+1)\), catena /catchment \((i+2)\), and the soil region \((i+3)\). Negative \( i \)-levels comprise of the horizon \((i-1)\), peds and aggregates \((i-2)\), and molecular interaction \((i-3)\). Common to all soil models is their 3-D character that is an extension in the x, y, and z-direction.

Tools necessary to develop 3-D soil landscape models are (i) spatial modeling techniques to interpolate data and (ii) a computer language for 3-D graphics applications. The application of geostatistical techniques for interpolating soil data in 2-D is state-of-the-art (Alemi et al., 1988; Isaaks and Sivia, 1989; Voltz and Webster, 1990; Knotters et al., 1995; Lookman et al., 1995; Goovaerts, 1997, 1999), while 3-D spatial modeling is not widely used (Goderya et al., 1996; Garcia and Froidevaux, 1997).

The objective of this study was to investigate the use of Virtual Reality Modeling Language (VRML), a 3-D graphics language suitable for stand-alone or browser-based interactive viewing, to create 3-D soil landscape models at different scales. Soil attributes such
as texture, depth of A horizon, reworked loess, and glacial till were used in conjunction with topographic attributes and a 3-D spatial interpolation technique to produce VRML 3-D models, which were made accessible on the WWW. Virtual reality modeling language (VRML) has received limited or no attention by soil scientists. In the next section, we provide an overview of its development and background for introducing its application in soil science.

2. Description of VRML

The development of VRML began at Silicon Graphics, Inc. (SGI) in 1989. Initially, based on SGI’s Open Inventor, the first draft of VRML 1.0 was produced in 1994; VRML 1.0 specified static 3-D objects but was missing key features such as animation and interaction. A significant revision was published as VRML 2.0 in August 1996 by the International Standards Organization’s (ISO) JTC1/SC24 committee, and was accepted as the current ISO standard under the name ‘VRML 97’ (Carey and Bell, 1997). Virtual reality modeling language is a 3-D analog to Hypertext Markup Language (HTML), an open-standard, 3-D graphics language suitable for stand-alone or browser-based interactive viewing. The motivation to develop VRML was driven by the fact that some information is best viewed three-dimensionally.

2.1. VRML features

Code of VRML can be integrated into any World Wide Web (WWW) browser using VRML plug-ins. Within the VRML-capable browser, the user can move around these VRML ‘worlds’ in 3-D, scale and rotate objects, and view updates in real-time. Capabilities of VRML include 3-D interactive animation; 3-D worlds (scenes) comprising of several different 3-D
objects; scaling of objects; material properties and texture mapping (i.e., to drape a photograph and bitmapped art over the face of a VRML object) for 3-D objects; setting of different viewpoints and use of light sources and much more (Lemay et al., 1999). In short, VRML provides the technology that integrates 2- and 3-D, text, and multimedia into a coherent model. When these media types are combined with scripting languages and internet capabilities, an entirely new genre of interactive applications are possible. Virtual reality modeling files may contain references to files in many other standard graphics formats, such as joint photographic experts group (JPEG), portable network graphics (PNG), and graphics interchange format (GIF), which may be used as texture maps on objects, wave form (WAV) and musical instrument digital interface (MIDI) sound formats and files containing Java code (Hunt, 1999), which may be referenced and used to implement programmed behavior for the objects in the VRML worlds. Virtual reality modeling units are not bound to any real-world unit of measurement, such as inches or centimeter, but instead describe a size or a distance within the context of a VRML world. Further information about VRML can be found in Ames et al. (1997), Carey and Bell (1997), Iverson (1998), Crispen (1999), and San Diego Supercomputer Center (SDSC;1999).

2.2 VRML nodes

A VRML file, with a *.wrl filetype, contains all information required to build a VRML world. The key elements of the VRML language are nodes that describe shapes, colors, lights, viewpoints, how to position and orient shapes, animation timers, interpolators, etc. and their properties in a world. Fields define attributes of a node and every value is of a specified field type.
Object-oriented languages, which include C++ (Pohl, 1993) and Java (Hunt, 1999) as well as VRML, support the concept of data abstraction and modularity in program design. These characteristics make object-oriented code portable and increase the flexibility to change of code. An object is defined as a person, place, or thing that knows the value of its attributes and can perform operations on those attributes. A class groups objects based on common characteristics. All objects of a class share the same attribute types and operations. In order to send an operation, a request must be sent to that object. In VRML, the node that groups together nodes is called a parent; the nodes that make up the group are called the group’s children; nodes are parents and fields are children. The inheritance characteristics allow the reuse of code by specializing already existing general solutions. Attributes and operations can be shared among objects in a hierarchical relationship. Items are inherited by the children from parents through the hierarchy. For instance, the fields appearance and geometry are children of the Shape node (parent). Any attribute or operation defined for Shape is available to appearance and geometry.

In VRML, 3-D objects are models extending in three dimensions. A VRML object has a form or geometry that defines its 3-D structure, and it has an appearance based on the material and color from which it is made and its surface texture, like wood or brick (Ames et al., 1997). Coordinates of objects are defined using a 3-D coordinate system with x, y, and z-axis. The origin is defined by the triplet 0.0 0.0 0.0 representing x, y, and z-axis. The shape of every object has to be defined using triplets in relation to the origin (Fig. 1). Standard shapes, “primitives,” provided include the box, the cone, the cylinder, and the sphere. The Shape node contains the field geometry, which specifies the 3-D geometry of an object. For asymmetrical objects, the IndexedFaceSet node is used, which creates face geometry. Within the Indexed-
FaceSet node, the coord field and coordIndex can be used. The coord field lists the coordinates available for building shapes, and the coordIndex field specifies a list of coordinate indexes describing the perimeter of one or more faces.

Two-dimensional objects such as the terrain on the soil surface can be described using the ElevationGrid node, which creates face geometry and may be used as the value of the geometry field in a Shape node. The values of the xDimension and zDimension fields specify the number of grid points in the x and z directions, respectively. The values of the xSpacing and zSpacing field specify the distance between rows and columns in the grid. The value of the height field specifies a list of elevations, one for each grid point, measured in the y direction. Faces are automatically built between rows and columns of the grid. ElevationGrid node format is different from TIN format, which partitions space into a set of contiguous, non-overlapping triangles. Attribute and geometry information is stored for the points, lines, and faces that comprise each triangle. A height value is recorded for each triangle node. Heights between nodes are interpolated thus allowing for the definition of a continuous surface.

2.3 Appearance of VRML objects

An appearance of a shape is specified by two sets of attributes: (i) those that indicate the material color of the shape such as yellow or red, and (ii) those that indicate the surface color, variation, or texture of the shape.

The VRML uses the RGB (red {R}, green {G} and blue {B}) classification system to specify the amount of red, green and blue light to mix together to produce a color. The color field of the IndexedFaceSet node and Material node specifies RGB values as three floating-point values, each one between 0.0 and 1.0. The RGB color system is not directly related to
human color perception and is not strictly definable in any of the Commission Internationale de l’Éclairage (CIE)-defined color space systems. Instead, RGB is signal intensity information supplied to a cathode ray tube (CRT) monitor, which is related to light output by a power function, the exponent of which is commonly termed ‘gamma’. Varying the amount of gamma value changes not only the brightness, but also the ratios of R to G to B (Jackson et al., 1993; Computer Graphics Systems Development Corporation, Mountain View, CA, 1999). A perceptual color space has a color gamut boundary of irregular shape, somewhere between an ellipsoid and a double cone, because of the asymmetrical response of the human visual system. In contrast, the RGB color gamut has a rectangular shape (Jackson et al., 1993). Furthermore, RGB coordinate values are generally not transferable between devices, that is they will not reproduce the same color from one device to another. Virtual reality objects are usually displayed on computer monitors or printed with output devices. Gamma values usually averages 2.5 but range from 1.7 to 2.7 on different platforms, graphic cards, different computer system configurations, and software. Most standard PCs have no gamma correction. Common graphics software, such as Adobe Photoshop, allows the user to set gamma correction values. Netscape and other common web browsers do not perform any gamma correction. An image has an inherent gamma value built into the data, whether the file format stores this value or not (file gamma). Popular WWW file formats such as GIF and JPEG do not store file gamma; in contrast, Targa and PNG do store file gamma (Pankove, 1980; Poynton, 1994).

Texture maps such as photographs and bitmapped art can be mapped on any VRML shape and draped over the face of the objects. The value of the texture field within the Appearance node provides a node specifying a texture image to be applied to a shape. Texture
mapping attributes are specified in the *ImageTexture node*, *PixelTexture node* and *Movie Texture node*, which specify texture-mapping attributes and may be used as the value of the *texture field*. For example, location of texture maps, repeating texture maps, and width and height of the image.

The appearance of a model also depends on shading. Shading gives the viewer the sense that a shape is 3-D. When light shines on a shape, the sides facing the light are bright and the sides facing away from the light are dark. Sides of an object that are partially facing the light have an intermediate brightness that depends on how much they face the light. Each VRML browser automatically includes a light for the viewer. This automatic light is positioned so that it shines on the world’s shapes from the viewpoint viewers use to view the VRML world. If the viewer moves the object to the right, so does the light; if the viewer moves the object to the left, so does the light. The VRML-capable browser automatically computes darker colors as it shades the side of a shape, gradually darkening the shading color as it progresses from the lighted sides of the shape to the unlighted sides. Additional light sources such as point light (e.g., lamps) or directional light (e.g., sun) might be added to a VRML world, which is discussed elsewhere (Ames et al., 1997).

Another tool used to view 3-D models realistically is reflection. In the real world when light rays strike a surface, some are absorbed by it, some are reflected off it, and some are transmitted through the surface. The way light reflects off a real-world surface depends on the surface material, its roughness, its temperature, and its electrical properties, in short, real-world physics of lighting is very complex. Virtual reality uses simplified methods of simulating real-world lighting. Diffuse reflection bounces light off a surface in random directions, scattering it around. Since each ray striking the surface bounces in a different
random direction, the overall effect is one of a gentle, diffuse lighting on a shape. Diffusivity depends on the angle of the surface in relation to the light source. The more directly the surface faces the light, the more diffuse light reflects. The *diffuseColor field* of the *Material node* controls the color of the light reflected by diffuse reflection. Specular reflection bounces light off a surface in a way that makes shiny surfaces reflect the world around them. Ambient light is light that has bounced from the surface many times and provides an overall illumination for a defined space. The *ambientIntensity field* of the *Material node* provides the control of the ambient-light level in a VRML world. Using a high ambient intensity for a shape makes it subject to lighting by the world’s ambient-light level, which is determined by the light sources in use. A low ambient intensity for a shape makes it less subject to ambient lighting (Ames et al., 1997).

In VRML, viewpoints are used to highlight different positions and orientations of the VRML worlds for users. At each new viewing position, the browser snaps a picture and displays the picture on the screen. Viewpoints provide a shortcut mechanism so that viewers can jump, walk or fly to a new position. The *Viewpoint node* is a child of the *Transform node*. The *position field* within the *Viewpoint node* specifies a 3-D coordinate for the location of the viewpoint and the *fieldOfView field* specifies an angle, in radians, indicating the spread angle for observing the viewpoint. A large angle creates a wide-angle camera-lens effect, while a small angle creates a telephoto camera-lens effect (Lemay et al., 1996).

Animations in VRML include rotating, scaling and moving shapes. To start, stop and otherwise control animation, the *TimeSensor node* acts as a clock. For example, the *PositionInterpolator node* describes a series of key positions available for use in animation and the *OrientationInterpolator node* describes a series of key rotations available for use in an
animation. Features for interactive applications are also available. For example, a sensor can be attached to a shape that senses viewer actions with a pointing device, such as a mouse.

3. Materials and methods

3.1. Study areas

Soil data and topographic data for this study were collected for four different sites at different scales, ranging from pedon, polypedon, catena /catchment to soil region. All sites were located in southern Wisconsin, where soils are formed in reworked loess overlying glacial till. Depending on scale, different techniques for mapping of soil and topographic data were used.

3.1.1. Site 1

Site 1 represents the central $i$-level, i.e., the pedon scale. This site is located on the Arlington Agricultural Research Station, Univ. of Wisconsin-Madison. Current land use is a corn ($Zea$ $mays$)--alfalfa ($Medicago$ $sativa$) rotation. The pedon was mapped as fine-silty, mixed, mesic Typic Argiaquolls (Schoeneberger et al., 1998), and is located in a closed depression. Upslope soils were mapped as fine-silty, mixed, mesic Typic Argiudolls (Schoeneberger et al., 1998). The pedon is located 269.0 m above sea level.

3.1.2. Site 2

Site 2 represents a catena $(i+1)$ with a size of 2.73-ha located on the West Madison Agricultural Research Station, Univ. of Wisconsin-Madison. Soil data were collected with a profile cone penetrometer; soil cores were measured for texture, bulk density and water
content. Data were collected on a 10-m grid (total number of sampling points: 273) where penetration data were collected vertically continuously and soil core data (4.3-cm diam.) were randomly collected at 21 penetration locations and analyzed in 5-cm increments within specific horizons. Soil texture was analyzed using the hydrometer method by the UW Soil and Plant Analysis Laboratory (Madison, WI). Soil water content and bulk density were measured by oven drying soil samples of known volume. The site was mapped as fine-loamy, mixed, mesic Typic Argiudolls. The site had been planted with alfalfa (*Medicago sativa*) for the past 3 yr.

A Trimble 4600 LS differential global positioning system (GPS), single frequency, dual port, with an internal 4600 LS antenna (Trimble, 1996; Sunnyvale, CA)\(^1\) was used to georeference sampling locations. The GPS unit was also used to conduct a kinematic survey for the study site to derive a DEM with 1-m grid size (horizontal resolution error ± 4 cm; vertical resolution error ± 8 cm). Elevations ranged from 321.3 to 329.6 m above sea level.

### 3.1.3. Site 3

Site 3 represents catchment scale, i.e., the \(i+2\) level. The site encompassed 23.7 ha. Thickness of A horizon and depth of the silty parent material were measured on a 27.4-m grid (total number of sampling points: 325). At each sampling location, samples were obtained using a bucket auger and silt probe to expose the subsurface, and a tape measure to record the

\(^{1}\) Mention of company or product does not constitute endorsement by the Univ. of Wisconsin-Madison to the exclusion of others.
depths. Thickness of the A horizon and depth of the silty parent material values were only documented if found within 152 cm of the surface (Fagan, 1999). Site 3 is located in Columbia County, which was buried under the Green Bay lobe during the Wisconsin glaciation. Soils were mapped as fine-silty, mixed, mesic, Typic Argiudolls. The native vegetation was primarily prairie grass prior to cultivation. This area has been under cultivated agriculture for approximately 150 yr (Clayton and Attig, 1997).

We used a DEM with a horizontal resolution of 27.4 m. Point elevation data were collected with a theodolite, where vertical resolution is on the order of centimeters. Elevation values were relative to a benchmark arbitrarily set to 30.5 m and all elevation points were measured relative to this benchmark. Elevations ranged from 30.5 m to 33.9 m.

3.1.4. Site 4

Site 4 represents soil region scale, i.e., the i+3 level. The soil region is located on the Arlington Agricultural Research Station, Univ. of Wisconsin-Madison and was 100-ha in size. Soil data were derived from the Map Unit Interpretation Database (MUIR) with a scale of 1:15,840. Soil map units were Plano silt loam (0 to 2 and 2 to 6% slope) – fine-silty, mixed, mesic Typic Argiudolls; Ringwood silt loam (1 to 6 and 6 to 12% slope) – fine-loamy, mixed, mesic Typic Argiudolls; Joy silt loam (0 to 4% slope) – fine-silty, mixed, mesic Aquic Hapludolls; Ossian silt loam (0 to 3% slope) – fine-silty, mixed, mesic Typic Haplaquolls; Saybrook silt loam (2 to 6% slope) – fine-silty, mixed, mesic Typic Argiudolls; and Rotamer loam (2 to 6 and 12 to 20% slope) – fine-loamy, mixed, mesic Typic Argiudolls. All soil map units have in common that soils are formed in silty sediment and the underlying glacial till,
however, thickness of silt varies considerably. Land use varied between alfalfa, corn, and oat (Avena sp.) among and within fields.

We used a DEM with horizontal resolution of 4-m and vertical resolution error of ± 0.5 m derived by an analysis of aerial photographs. Original scale of the photos was 1:20,000, which were scanned at a pixel size of 30 µm resulting in 1-m pixel. Based on a stereo-pair analysis, a point elevation model was created with 4-m grid spacing, which was interpolated to produce a DEM (Environmental Remote Sensing Center and Civil & Environmental Engineering, Univ. of Wisconsin-Madison, internal communication). Elevations ranged from 321.2 to 328.5 m above sea level.

3.2. VRML methods

Several 3-D objects build up a VRML world. We used Environmental Visualization Software (EVS-NT Standard Version; Ctech Development Corporation, Huntington Beach, CA) to export the geometry of 3-D objects using the IndexedFaceSet node. Surfaces were created using 2-D ordinary kriging and volumes (layers) were created with linear interpolation in the vertical direction between these surfaces. Soil attributes such as texture or penetration resistance were interpolated based on 3-D variograms, which plot semivariance on the z-axis, distance (h) between data pairs in the x-y plane (horizontal) on the x-axis and distance (h) between data pairs in the z-plane (vertical) on the y-axis. Variograms are displayed in three-space as a surface. The observed values were interpolated horizontally and vertically using 3-D ordinary kriging based on variograms (EVS, 1997).

We added and modified VRML nodes in the code output of EVS using a text editor to build enhanced VRML worlds to include: (i) viewpoints, (ii) Munsell colors, (iii) texture
maps, (iv) 3-D cross-section animation, (v) animations such as zooming, rotation, and (vi) primitive shapes to highlight areas of interest.

Generally, for all soil landscape models, we used a \textit{fieldOfView} value of 0.083 as a compromise between large and small angle camera-lens effects. We suggest the use of \textit{diffuseColor field} for the visualization of soil landscape models because soils are dull surfaces that exhibit diffuse reflection but only a little specular reflection. \textit{Diffusecolor} values of 0.3 0.3 0.3 in the \textit{Material node} were used, which make the colors look slightly darker than their Munsell notation. However, it gives the model a realistic 3-D appearance. Dull shapes typical of soils are illuminated by ambient lighting. Therefore, we suggest an \textit{ambientIntensity} of 0.301.

Commonly, the Munsell classification is used to describe soil colors. Because VRML uses the RGB color classification, Munsell colors had to be converted to RGB values. We scanned the Munsell color chart with a Hewlett Packard ScanJet 6100C scanner set for ‘true colors (16 million colors)’ and ‘no gamma correction’. For each scanned Munsell color, RGB values were determined using Adobe Photoshop 4.0 with ‘no gamma correction’ and ‘ambient light: medium’. We decided to use no hardware and software gamma correction while converting Munsell to RGB values. For comparison, the Munsell Conversion Software 4.01 (GretagMacbeth; New Windsor, NY) was used to convert Munsell colors to RBG values using a gamma correction of 2.2, assuming that a gamma correction of 2.2 makes images ‘look average’ on most platforms. The RGB colors had to be connected to each coordinate of the soil landscape model using the \textit{color field} of the \textit{IndexedFaceSet node}. The material color method was also used to color specific layers of our soil landscape models (e.g., coloring soil texture).
3.2.1. Site 1

For the pedon at Site 1, the material coloring method and texture mapping method was used, where a scanned photograph in JPEG format of the pedon was draped on the faces of the VRML pedon object coded as IndexedFaceSet node. An enhancement to zoom into the model was added using the Viewpoint node. The Viewpoint of the default pedon model had a Position field of 0 0 120, whereas the zoomed Viewpoint had a Position field of 0 0 80.

3.2.2. Site 2

Layers of soil landscape model on Site 2 were colored with RGB values corresponding to Munsell colors. A north-south facing cross-section animation was added to visualize the distribution of layers within the model. A data scaling factor of 25 was used to scale elevation values to visualize high and low elevations. The DEM was coded in IndexedFaceSet node format.

3.2.3. Site 3

A zoom animation was integrated to highlight areas of interest. Additionally, sphere shapes were added to the VRML worlds, which changed their colors from transparent to dull using a ColorInterpolator node controlled by a TimeSensor node. Yellow spheres highlighted heterogeneous areas and blue spheres highlighted homogeneous areas in terms of depth changes in soil material. A data scaling factor of 25 was used to display elevation values.

3.2.4. Site 4
Two different VRML formats were used to create a DEM for Site 4. The first used *IndexedFaceSet node* and the second used *ElevationGrid node* structure. A data scaling factor of 25 was used to display elevation values to visualize small and large elevations. For comparison, ArcView GIS 3.0 (Environmental Systems Research Institute Inc, Redlands, CA; 1999) was used to store and manipulate elevation data in *grid* format and to transform it into TIN format. The DEMs were compared in terms of their visualization quality, storage size, and ability to be combined with texture mapping.

All VRML models were validated for syntax with Chisel 1.0 (Trapezium LLC, Brooklyn, NY; 1999) for improving the quality, performance and reliability of our VRML worlds. The CLEAN feature of Chisel was used to remove coordinate points and code that were unnecessary or redundant. Our VRML soil landscape models were loaded into Netscape Navigator 4.x (x: .08 to .7) with Cosmo Player 2.1 plug-in (Silicon Graphics, 1999).

4. Results and discussion

A gallery of VRML soil landscape models at different scales is accessible via the WWW at http://www.soils.wisc.edu/soils/3D_SL_models/3Dsoils.html.

4.1. Site 1

The pedon and its location within a topo-sequence are shown in Fig. 2. Munsell colors implemented in RGB were used as alternative to false colors for both models. The first pedon (A) was created using no gamma correction and the second pedon (B) was created using gamma-corrected values, while converting Munsell soil colors to RGB values (Fig. 2). The precise rendering of those pedons in print and on the screen differ from device to device and depend on the hardware and software gamma correction. There is no hardware and software
independent color-management system currently available in VRML. Color management using color calibration and standardization exists but is not routinely applied to most desktop applications. One of the most challenging problems in cross-media color reproduction is dealing with mismatches between the color gamuts of various devices such as computer monitors and printers. The Munsell color specification is based on perceptual principles using hue, value and chroma, which are based on the visual characteristics of pigment in paint rather than light. Munsell colors are able to describe small and large color differences. Tables 1 and 2 list the Munsell and RGB values used for color conversions. Munsell colors were dark brown in the top layers with 7.5 YR 2/0 and 10 YR 3/2; lower layers showed 10 YR 6/6 and 7.5 YR 5/4. Visualization of both pedons was affected more or less by numerous factors. These include the gamma correction of devices such as different computer systems (e.g., Macintosh, Sun workstations, IBM PC), monitors, brightness and contrast settings on the monitor, graphic cards, printers and software gamma correction, the ambient light in a room where the computer is, display options activated, and finally personal taste. Accurate color interchange between Munsell soil colors and RGB values and to a specific output device is not routinely standardized, which makes the process subjective. An alternative color specification, which offers a precise means of specifying a color stimulus under fixed viewing conditions using X Y Z tristimulus values, was defined by the CIE. This color system is an international standard and has become the basis of all industrial colorimetry; however, it is not available in VRML (Jackson et al., 1993). In 1976, the CIE published specification for two color spaces: CIELUV for representing additive color media, including emissive phosphor displays such as computer monitors; and CIELAB for subtractive color media such as printers, where light is absorbed by colorants such as pigments. Associated with both specifications is the lightness
scale denoted by \( L^* \), ranging from 0 to 100, 0 being ideal black (total absence of light) and 100 being the reference white. A drawback of CIE is that real world viewing conditions are very different from the controlled industrial conditions under which the CIE system of colorimetry can be applied. Instead of a single color chip under a known illuminant, complex 3-D scenes containing objects exhibit the entire gamut of colors, affected by shadows and reflections, and a variety of illuminants. Although color representation in VRML is limited to the RGB color specification, it was possible to visualize color differences in top to bottom layers. For example, the top layer showed a dark brown color, which was influenced by large organic matter content. In contrast, we found brownish yellow colors in the bottom layers, which represented parent materials, lacustrine sediments and glacial till, respectively. Coloring of objects in VRML is also compromised by shading and lighting, which is important for the 3-D appearance of objects. The texture mapping used to portray pedon C highlighted structural and color differences of soil layers. Displayed colors of the texture map saved in JPEG file format were non-gamma corrected. Visualization of pedon C was influenced by the same factors as listed above.

The soil landscape models can be rotated to view the model from different directions (Fig. 3). The original, EVS-generated VRML files visualizing the pedon and the topo-sequence had sizes of 1.4 MB (megabytes) and 1.8 MB, respectively, which is storage intensive. Using Chisel software and gzip compression, the file sizes were reduced to 57 KB (kilobytes) and 125 KB, respectively. In the process of “cleaning” by Chisel, the number of redundant polygons was reduced from 34,666 to 19,228 in the topo-sequence model. The compressed VRML models downloaded faster into web browsers than the original VRML models containing redundant information in the point nodes. The VRML source code
structure, limited to nodes and fields necessary to describe the shape and appearance of the models, of the pedon model is listed in the appendix.

Soil textures for the pedon model and the topo-sequence are shown in false colors in Fig. 4. The Ap, A/B, Bt, and 2BC layers were silt loam, whereas Btg was silty clay loam and 3C was sandy loam. A detailed description of morphological characteristics is given in Table 3. The 2BC horizon was formed in lacustrine sediments overlying a 3C horizon formed in glacial till. The topo-sequence represents soils formed in different parent material ranging from reworked loess, lacustrine sediments, and glacial till, with a strong local influence of relief. The Bt and Btg horizons were formed due to illuviation of clay. Different hydrological behavior of parent materials have formed the soils of the topo-sequence, where a thicker Ap horizon is found on the toeslope position when compared to the backslope and shoulder positions. A horizon thickness increased from the top to the bottom of the topo-sequence in response to a shift from dominantly erosional to depositional processes. Redeposition of loess took place during the time loess accumulated and in a continuous and progressive manner to the present day. At the toeslope position, we found layers of over-thickened reworked loess indicated by the silt loam texture. Soils were well drained on upslope regions; however, there is evidence of drainage impedance in the lower horizons. The 3-D topo-sequence and pedon models were able to portray the distribution soil layers realistically.

4.2. Site 2

Compressed file sizes ranged from 66 KB for the soil landscape model on Site 2 to 119 KB for the cone index model. Reduction of redundant data from the original VRML files was 76% for the soil layer model and 67% for the cone index model. Soil layers for Site 2 and a
cross-section animation in the north-south direction is shown in Fig. 5. The model showed that shallow, reworked loess cover occurred on eroded soils on shoulder and backslope positions, whereas thick reworked loess deposits occurred on footslope and toeslope positions. Erosion and deposition are responsible for particle translocation, which shaped this landscape for several thousand years. The visualization of topographic attributes (elevation, slope, aspect) in conjunction with soil layer thickness was well represented in VRML, explaining the distribution of reworked loess and glacial till across the landscape.

Penetration resistance values were interpolated based on the 3-D variogram shown in Fig. 6. The distribution of penetration resistance, cone index (CI) in kPa (Fig. 6), showed small CI close to the soil surface. Large CIs were found in the bottom layers. A detailed description of the relationship between CI and texture, bulk density and water content can be found in Grunwald et al. (19__b). Generally, large sand content (>75 %), large bulk densities (>1.4 Mg m\(^{-3}\)), and small water contents (<15 m\(^3\) m\(^{-3}\)) were associated with large CI (> 4,000 kPa) indicating glacial till material. In contrast, CI (<4,000 kPa) were associated with large silt content (>60%), smaller bulk densities (<1.4 Mg m\(^{-3}\)) and larger water contents (>20 m\(^3\) m\(^{-3}\)).

4.3. Site 3

For the soil landscape model on Site 3, data for depth of A horizon, reworked loess and glacial till were available (Fig. 7). The DEM was plotted as separate object coded in \textit{IndexedFaceSet node} format on top of the soil landscape model. The zoom function in Fig. 7 highlights a mildly undulating landscape, where reworked loess was thick when compared to higher elevated areas. In contrast, higher elevated areas showed shallow reworked loess
overlying glacial till material. The animation function using yellow and blue spheres for homogeneous and heterogeneous areas, respectively, was a helpful tool to highlight specific characteristics (Fig. 8). File size for the soil layer model on Site 3 was 144 KB.

### 4.4. Site 4

For Site 4, a DEM and soil map units were visualized as 2-D maps (Fig. 9). Descriptive information for each soil map unit was available from the MUIR database, but could not be visualized in 2-D. The same data were used to create a 3-D soil landscape model, which comprised A, Bt, and C horizons and A, Bt, Bg, and Cg horizon sequence, respectively. Soil map units in depression areas such as Joy and Ossian showed a horizon sequence of A - Bt - Bg - Cg, indicating a seasonal high water table resulting in redoximorphic features in the Bg and Cg horizon. On higher elevated areas the horizon sequence was A - Bt - C, indicating eluviation and illuviation were dominant processes.

The 2-D grid DEM had a file size of 509 KB, the 2-D soil map of 60.4 KB and the 3-D soil landscape model using the IndexedFaceSet node format had a size of 582 KB (63 KB after compression, i.e. the removal of redundant data). For comparison, topographic information for Site 4 was plotted in TIN format with a file size of 60.3 KB and ElevationGrid node format with a file size of 440 KB (no compression available). The TIN format aims at optimizing file size using a small number of triangle faces for homogeneous areas and many triangle faces for representation of heterogeneous areas with large elevation differences. The faces of the TIN DEM were shaded to provide a sense of depth and insight into the form of the surface modeled. This format was smaller in size than the other DEM formats.
The VRML ElevationGrid node DEM created face geometry based on connecting four elevation points to build quadruple faces. In total, 62,500 elevation points were used to create the DEM. Rotating and moving the ElevationGrid node DEM in a web browser was very slow when compared to the DEM created with IndexedFaceSet node format. Furthermore, the elevations for the soil region appeared noisy and a clear visualization of elevation differences was difficult. The VRML implementation in IndexedFaceSet node format was quite different. Elevations were smoothed, which was due to ordinary kriging, which tends to smooth sharp elevation differences of adjacent elevation points. The ElevationGrid node format is a very compact way of representing terrain. For example, the VRML code in ElevationGrid node format was written as:

```vrml
group {
  geometry ElevationGrid {
    xDimension 250
    zDimension 250
    xSpacing 4.0
    zSpacing 4.0
    height [8156.25, 8174.27, 8174.12, followed by
      62,497 height values]
  }
}
```

where the number of rows and columns was 250 and the spacing between height values was 4.0 m. The height values were stored subsequently, where original heights were scaled with a factor of 25. The same information in IndexedFaceSet node format required much more code, of the form:

```vrml
group {
  geometry IndexedFaceSet {
    coord Coordinate {
      point [ 4 0 8146.18, 8146.18,
```
where the x, y, and z information for each data point were described in the `coord field` and additionally the `coordIndex field` specified a list of coordinate indexes describing the shape of faces. For realistic 3-D representation, shading was used in VRML for `ElevationGrid node` and `IndexedFaceSet node` representations. The `ElevationGrid node` format is limited to represent 2-D objects such as DEM; in contrast, `IndexedFaceSet node` format is able to represent 2-D and 3-D objects.

The visualization of large data sets might be compromised by generalization. For example, computational stability is required for variogram production preceding ordinary kriging with large data sets. In EVS, a deterministic random pair search selection algorithm was implemented to limit the total number of pairs that are considered in the variogram production when the number of potential pairs exceeds 50,000. Users can also reduce the number of data pairs by reducing the pair search range for computing variograms.

5. Conclusions
Despite the availability of object-oriented 3-D graphic languages and technically advanced hardware in terms of speed and display ability, there appears to be no prior use of these tools in soil science. In this study, we investigated the use of the object-oriented 3-D graphics language VRML to create 3-D soil landscape models at different scales. Virtual reality modeling language is attractive for soil landscape modeling because (i) it mimics natural landscapes and creates realistic 3-D scientific representations, (ii) VRML soil landscape models are accessible for any user via the WWW, and (iii) soil landscape models have merit for educational and research activities such as updating soil information systems, environmental assessment studies, water quality simulation modeling, and site-specific management. The VRML aims at mimicking real-world perception using simplified mechanism for lighting, shading and reflection.

Virtual reality modeling language integrated soil and topographic attributes into coherent, continuous 3-D soil landscape models. Shapes of objects, for example soil layers, were described in 3-D using the IndexedFaceSet node. Virtual reality modeling language has capabilities to describe and visualize extremely complex shapes, such as erratic soil layers or terrain. These capabilities are limited only by (i) data availability and (ii) spatial modeling techniques. In this study, we illustrated the use of soil and topographic data at different spatial scales. Scale largely determined the amount of data collected and its spatial resolution. Three-dimensional spatial modeling techniques are still in their infancy. Implementations of 3-D kriging methods, other than ordinary kriging, are not yet available in commercial software packages. Visualization of Munsell soil colors was difficult to implement using VRML. However, we should stress that this is true for every cross-media color reproduction. There is no standardized color-management system available, which can be used for digital
visualization. Animation techniques to change objects of a VRML world are valuable to highlight specific characteristics of each model. This study investigated relatively static topographic and soil attributes; however, the potential to visualize 3-D transport processes within and on soils using animated VRML movie techniques is enormous. We anticipate that VRML will make it possible for soil science to move from 2-D soil portraits to dynamic 3-D soil landscape models.

LITERATURE CITED


Longman, Inc., Reading, MA. Available on-line with updates at


Wis. Geol. Nat. History Surv., Madison, WI.


Computer Graphics Systems Development Corp. 1999. Available at


Silicon Graphics. 1999. Cosmo Software. Available through links at the VRML Repository,


Crispen, B. 1999. VRML works. Available at http://home.hiwaay.net/%7Ecrispen/vrmlworks/

(posted 22 May 1999; verified 1 Aug. 1999).

Ctech Development Corporation. 1997. EVS-NT Standard Version (Environmental

Environmental Systems Research Institute Inc. 1999. ArcView GIS 3.0 software. Available at


Fagan, P. 1999. Identification of landscape heterogeneity for testing the efficacy of a targeted

Garcia, M, and R Froidevaux. 1997. Application of geostatistics to 3D modelling of
contaminated sites: a case study. p. 309-325. In A. Soares et al. (ed.) Geostatistics for

Gerrard, A.J. 1990. Soil variation on hillslopes in humid temperate climates. Geomorphology


And Sons, Chichester, New York.

and kriging combined with regression for spatial interpolation of horizon depth with
censored observations. Geoderma 67:227-246.

Indianapolis, IN.

the regional distribution of phosphate sorption capacity parameters (Feox and Alox) in

Milne, G. 1935. Composite units for the mapping of complex soil associations. Trans. 3rd


Osher, L.J., and S.W. Buol. 1998. Relationship of soil properties to parent material and
landscape position in eastern Madre de Dios, Peru. Geoderma 83:143-166.


Pennock, D.J., and D.F. Acton. 1989. Hydrological and sedimentological influences on

Pereira V., and E.A. FitzPatrick. 1998. Three-dimensional representation of tubular horizons
Redwood City, CA.

Amsterdam, The Netherlands.

San Diego Supercomputer Center (SDSC). 1999. National Laboratory for
Computational Science and Engineering. SDSC, Inc., VRML and Java 3D
Repositories managed by the Web3d Consortium. Available at

Santa Cruz Laboratory for Visualization & Graphics. 1999. Weather data from
around Santa Cruz and Monterey, CA. Available at
http://www.cse.ucsc.edu/research/avis/slug.html (posted 13 Feb. 1998; verified

features with three-dimensional terrain models in real-time. p. 372-381. In
DC.

Ctr, Lincoln, NE.

Su, A., S.-C. Hu, and R. Furuta. 1996. 3D topographic maps for Texas. Available at

57:169-178.


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Fig. 10. Visualization of DEM using different formats.
Table 1. Munsell color converted to RGB values using no gamma correction for soil layers at Site 1.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Munsell color value</th>
<th>RGB †</th>
<th>(Standardized RGB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>7.5YR 2/0</td>
<td>24 23 26</td>
<td>(0.09 0.09 0.10)</td>
</tr>
<tr>
<td>A/B</td>
<td>10 YR 3/2</td>
<td>64 42 27</td>
<td>(0.25 0.16 0.11)</td>
</tr>
<tr>
<td>Bt</td>
<td>10YR 4/3</td>
<td>111 73 46</td>
<td>(0.44 0.29 0.18)</td>
</tr>
<tr>
<td>Btg</td>
<td>10YR 5/8</td>
<td>161 101 33</td>
<td>(0.63 0.39 0.13)</td>
</tr>
<tr>
<td>2BC</td>
<td>10YR 6/6</td>
<td>184 128 72</td>
<td>(0.72 0.50 0.28)</td>
</tr>
<tr>
<td>3C</td>
<td>7.5 YR 5/4</td>
<td>148 106 68</td>
<td>(0.58 0.42 0.27)</td>
</tr>
</tbody>
</table>

† RGB, red green blue 8-bit scale (0 to 255).
Table 2. Munsell colors converted to RGB† values using a gamma correction of 2.2 at Site 1.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Munsell color value</th>
<th>R</th>
<th>G</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>7.5YR 2/0</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>A/B</td>
<td>10YR 3/2</td>
<td>99</td>
<td>85</td>
<td>69</td>
</tr>
<tr>
<td>Bt</td>
<td>10YR 4/3</td>
<td>130</td>
<td>107</td>
<td>81</td>
</tr>
<tr>
<td>Btg</td>
<td>10YR 5/8</td>
<td>173</td>
<td>127</td>
<td>44</td>
</tr>
<tr>
<td>2BC</td>
<td>10YR 6/6</td>
<td>193</td>
<td>154</td>
<td>96</td>
</tr>
<tr>
<td>3C</td>
<td>7.5YR 5/4</td>
<td>175</td>
<td>142</td>
<td>111</td>
</tr>
</tbody>
</table>

† RGB, red green blue.
Table 3. Morphological characteristics for pedon, Site 1.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth</th>
<th>Texture</th>
<th>Structure</th>
<th>Special features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0 to 26</td>
<td>Silt loam</td>
<td>Moderate fine and medium subangular blocky, friable</td>
<td></td>
</tr>
<tr>
<td>A/B</td>
<td>26 to 36</td>
<td>Silt loam</td>
<td>Medium platy to massive; firm</td>
<td></td>
</tr>
<tr>
<td>Btg</td>
<td>36 to 50</td>
<td>Silty clay loam</td>
<td>Strong coarse prismatic; very firm</td>
<td></td>
</tr>
<tr>
<td>2BC</td>
<td>50 to 207</td>
<td>Silt loam</td>
<td>Single grain to massive</td>
<td></td>
</tr>
<tr>
<td>3C</td>
<td>207 +</td>
<td>Sandy loam</td>
<td>Massive</td>
<td></td>
</tr>
</tbody>
</table>

† RMF, redoximorphic features.
Fig. 1. Three-dimensional coordinate system to build VRML objects.
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Fig. 3. Rotation of soil-layer model site 1 simulating different viewpoints.
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Fig. 5. Soil layers colored with Munsell colors and cross-section animation on site 2.
3-D variogram
x-axis: distance (h) between data pairs in the x-y plane (horizontal)
y-axis: distance (h) between data pairs in the z-plane (vertical)
z-axis: semivariance
asymmetrical, spherical variogram (range: 116.6; sill: 1,000 and range: 150.0; sill: 1,109)

Fig. 6. Variogram and spatial distribution of cone index on site 2.
(data scaling factor DEM: 25)
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Fig. 8. Animation to highlight heterogeneous (yellow) and homogeneous (blue) areas on the layer reworked loess for soil landscape model site 3.
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Data scaling factor: 25

3-D DEM;
*TIN* format

Fig. 10. Visualization of DEMs using different formats.
Appendix
#VRML V2.0 utf8
WorldInfo { title "pedon model developed by S.Grunwald" }
Background { skyColor 0 0 0 }
DirectionalLight { ambientIntensity 1
    intensity 0 }
DirectionalLight { direction 0 0 1 }
DirectionalLight { direction 0 0 -1 }
NavigationInfo { headlight FALSE
    type [ "EXAMINE", "WALK" ] }
Viewpoint { description "default view"
    position 0 0 120
    fieldOfView 0.0828 }
Viewpoint { description "zoom"
    position 0 0 80
    fieldOfView 0.0828 }

#shape and appearance of layer Ap
DEF _3D_Plume Transform { translation 0.2829 3.848 0.4953
    scale 0.03447 0.03447 0.03447
    rotation -0.5596 0.5473 0.6223 2.038
    children [
        Shape {
            appearance DEF _3D_Plume_app Appearance { material Material {
                ambientIntensity 0.301
                diffuseColor 0.3 0.3 0.3
            }}
            geometry IndexedFaceSet { solid FALSE
                coord Coordinate { point [ 1.4 43.72 -36,.....,0.525 -42.72 -72,]}
                coordIndex [0, 1, 2, -1,........,5211, 5213, 5212, -1,]}
                normal Normal { vector [0 1 0,........., 0 -0.8944 0.4472,]}
            }
        }
    }
#color layer Ap
color Color { color [0.09 0.09 0.10,.........,0.09 0.09 0.10,]}

#shape and appearance of layer A/B
DEF _3D_Plume Transform { translation 0.2829 3.848 0.4953
    scale 0.03447 0.03447 0.03447
    rotation -0.5596 0.5473 0.6223 2.038
    children [
        Shape {
            appearance DEF _3D_Plume_app Appearance { material Material {
                ambientIntensity 0.301
                diffuseColor 0.3 0.3 0.3
            }}
            geometry IndexedFaceSet { solid FALSE
                coord Coordinate {
                    point [1.4 43.72 -84,........,0.375 -42.72 -96,]}
                    coordIndex [0, 1, 2, -1,........,3699, 3701, 3700, -1,]}
                normal Normal { vector [0 1 0,........., 0 -0.8944 0.4472,]}
            }
        }
    }
normal Normal { vector [0 1 0, ........, 0 -1 0,]}

#color layer A/B
color Color { color [0.25 0.16 0.11, ........,0.25 0.16 0.11,]}}}

#shape and appearance of layer Btg
#color Btg
#shape and appearance of layer 2BC
#color 2BC