THE USE OF VRML FOR VIRTUAL SOIL LANDSCAPE MODELING

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The utilization of three-dimensional (3-D) graphical design and scientific visualization of the soil landscape continuum is still in its infancy. The objective of this study was to investigate the use of Virtual Reality Modeling Language (VRML) to create virtual 3-D soil landscape models representing natural soil landscape components. Virtual Reality Modeling Language is an object-oriented, 3-D graphics language suitable for stand-alone or browser-based interactive viewing. Our virtual soil landscape models showed the spatial distribution of soil patterns and terrain characteristics. We were able to integrate features from geographic information systems, such as storage and manipulation, with features from scientific visualization, such as 3-D graphical design, animation of objects, interactivity and accessibility via the World Wide Web.

Keywords: 3-D graphical design; VRML language; scientific visualization; soil landscape models; GPS systems; DEM.

1. INTRODUCTION

Geographic information systems (GIS) store, manipulate and visualize spatial data. Scientific visualization (SciVis) transforms numerical or symbolic data and information into geometric computer generated images [29]. Scientific visualization research and development have focused on issues pertaining to three-dimensional computer graphics rendering, time series animations, and real-time, interactive displays

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on computers. GIS and SciVis developed in parallel to each other and inefficiencies associated with geographic visualization exist [14,29]. However, virtual reality (VR), a multisensory, interactive, computer-based environment in which the user becomes an active participant in a virtually real world [16], offers new and exiting opportunities. Virtual reality enables users to move towards a finer emulation of the complexities of the 'real world' in space and time [10,21]. The main focus in virtual reality is on interaction, which combines adequate presentation of the environment with its manipulation [37]. Responsive VR should operate in real-time, i.e., the response time and update rate of the system is high enough so that the boundary between user and virtual environment seems to vanish [4]. In VR, the user can navigate through ambient environments and interact fully with spatial information of various types. Desktop VR is the most commonly used form of VR systems due to the widespread distribution of personal computers in the workplace. Here, conventional PC software is used to create and view artificial worlds in the office and over the internet [10]. In contrast, immersive VR requires the user to be subject to stimuli affecting many senses, including vision, hearing, balance, and touch; such systems require head-mounted displays, audio speakers, moving platforms, and tactile gloves, and their cost at present is a barrier for widescale distribution.

Virtual reality and SciVis distributed via the World Wide Web (WWW) allow wide access to geo-referenced spatial data. Modeling of real world systems provides an advanced means to assist with visual data exploration and decision making. We define 'model' as an abstract, formal representation of a system. It is 'formal' in the sense that the representation is provided with a level of clarity that affords execution of the representation on a computer [11]. Models are cognitive tools for reasoning about system behavior and interactions between model components. Models are translated into code, which is a linear sequence of source lines written with programming languages such as C++ [27], JAVA [18] and Virtual Reality Modeling Language (VRML) [1]. Object-oriented languages support the concept of data abstraction and modularity in program design. These characteristics make object-oriented code portable and increase the flexibility to change 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*. Object-oriented design makes it simple to reuse code by specializing already existing general solutions, which is defined as 'inheritance'. *Attributes* and *operations* can be shared among *objects* in a hierarchical relationship.

In SciVis and graphical design, code is used to create, manipulate and visualize objects. Virtual Reality Modeling Language is a 3-D graphics language suitable for stand-alone or browser-based interactive viewing. While VRML is an object-oriented language, *nodes* represent *classes* and *fields* denote attributes of *nodes*. *Field values* define attributes like color, size, or position, and every *field value* is of a specific *field type*, which describes the kind of values allowed in the *field*. In 1996, VRML 2.0 was accepted as the current standard by the International Standards Organization's (ISO) JTC1/SC24 committee under the name 'VRML 97' [5]. VRML files can be accessed on the World Wide Web (WWW) using web browsers and 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 for 3-D objects, setting of different viewpoints, linkage to other computer languages (e.g. Java scripts), references to files in many other standard graphics formats, web-based access, use of light sources, and much more [22]. Further information about VRML can be found in [1,5,19,8], and Web3D/VRML Repository [30].

To abstract the real environment, virtual objects can be used to represent natural system components such as air, soil, and water to create a virtual environment or virtual reality. Human perception is three-dimensional and, therefore, realistic geographic VR requires three dimensions. To address environmental issues such as erosion, high nitrate loads in surface waters, pesticides in ground water, soil quality, global warming and carbon sequestration potential of different soils, VR can support scientific interpretation and analysis of the real environment, decision making and/or planning. Modeling and scientific visualization of natural systems assists in making extremely complex systems more transparent.

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This paper focuses on soil landscapes. Soil has been defined as a natural body consisting of layers or horizons of mineral and/or organic constituents of variable thickness', which differ from the parent material in their morphological, physical, chemical, and mineralogical properties and their biological characteristics [3]. The soil system can be subdivided into model components such as physical, chemical and biological components. The physical soil components are represented by *attributes* such as texture, pore system and color. The physical soil system is hierarchical, where macro and micro features can be distinguished. For example, a soil physical system has specific macro-structure such as prismatic and the prisms consists of microstructure such as fine-angular blocky structure. The U.S. Soil Taxonomy used for soil classification in the U.S. has a hierarchical structure [35].

Commonly, soil horizons are distinguished by morphological characteristics such as texture, structure, color, consistency, redoximorphic features, etc. [31]. Horizons are defined by specific morphological factor combinations. If one of the morphological characteristics is changing along a soil profile a new horizon is identified. The upper boundary between the soil system and the atmosphere is defined by a two-dimensional surface, and can be represented by terrain attributes such as elevation, slope and aspect. The lower boundary between the soil system and the lithospheric system is often fuzzy depending on the presence of pedogenic and lithogenic properties.

Currently, the relatively few 3-D representations of soils and landscapes available are striking and, at the microscale, include: a 3-D model of tubular horizons in sandy soils [25], the three dimensional macropore network in undisturbed soil [26], a 3-D model of water content and macropore structure based on computer tomography [15], and a gallery of 3-D soil minerals and molecules at the atomic scale [2]. At landscape-scale, VRML has been used to create 3-D models showing the spatial distribution of cone index values [13]. At the Cooperative Research Centre in Australia, research is now being directed from 2-D to 3-D mapping of regolith and associated attributes [7]. These 3-D models are being used to improve the way researchers communicate, visualize, analyze and map the regolith, with the aim of developing more accurate, effective and predictive models for mineral exploration in highly weathered terrain. Other examples of 3-D terrain representations are those of Su et al. [34] and [17]. Scientific visualization of the soil landscape continuum is still in its infancy.

The objective of this study was to investigate the use of Virtual Reality Modeling Language (VRML) to create virtual 3-D soil landscape models representing natural soil and landscape components using an object-oriented concept.

2. MATERIALS AND METHODS

2.1 Study areas

Soil data and topographic data for this study were collected from three different sites at different scales, ranging from pedon[1] to catchment to soil region. All sites were located in southern Wisconsin at the Arlington Agricultural Research Station, University of Wisconsin-Madison, where soils are formed in reworked loess overlying glacial till. Depending on scale, different techniques for mapping of soil and topographic data were used.

The pedon on site 1 was mapped as fine-silty, mixed, mesic Typic Argiaquolls [31], and is located in a closed depression. Upslope soils were mapped as fine-silty, mixed, mesic Typic Argiudolls [31]. Current land use on site 1 is a corn (*Zea mays*)–alfalfa (*Medicago sativa*) rotation. The pedon is located 269.0 m above sea level. A Trimble 4600 LS differential global positioning system (GPS), single frequency, dual port, with an internal 4600 LS antenna (Trimble; Sunnyvale, CA)[2] was used to conduct a kinematic survey for the study site to derive a digital elevation map (DEM) with 1-m grid size (vertical resolution error ± 8 cm).

Site 2 represents the catchment scale and is 23.7-ha in size. The native vegetation was primarily prairie grass prior to cultivation and has been under cultivated agriculture for approximately 150 yr. Thickness of the A horizon and depth of the silty parent material were measured on a 27.4-m grid at 325 sampling points. At each sampling location, samples were obtained using a bucket auger and silt probe to expose the subsurface and a tape measure was used to measure the depths. Thickness of the A horizon and depth of the silty parent material values

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[1] pedon: a three-dimensional body of soil with lateral dimensions large enough to permit study of horizon shapes and relations. Its surface ranges from 1 to 10 m^2 (Soil Science Society of America, 1997)

[2] Mention of company or product does not constitute endorsement by Heidelberg College or the Univ. of Wisconsin-Madison to the exclusion of others.

were recorded only if found within 152 cm of the surface [9]. Soils were mapped as fine-silty, mixed, mesic, Typic Argiudolls. We used a DEM with a horizontal resolution of 27.4 m. Point elevation data were collected with a theodolite, with vertical resolution on the order of centimeters. Elevation values were relative to a benchmark arbitrarily set to 30.5 m and all elevation points, ranging from 30.5 m to 33.9 m, were measured relative to this benchmark.

Site 3 represents the soil region scale and is 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 the 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. The original scale of the photos was 1:20,000, which were scanned at a pixel size of 30 µm resulting in 1-m per 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.

A similar data set was used in [13]; however, here our focus is on VRML coding and abstracting virtual soil landscape models from real world soil and terrain data.

2.2 VRML Methods

A summary of all *nodes* and *fields* used in this paper is given in Table 1. For example, the *Shape node* specifies VRML 2-D and 3-D objects, where the *field geometry* defines the 3-D form, or geometry of the

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Table 1. Description of nodes and fields used to create VRML 3-D soil landscape models.

Node	Fields	Description of nodes
Appearance	Material texture	Defines the appearance attributes of the shape (color, surface texture)
Background	groundColor skyColor	Creates background for a world using a textured panorama box, a ground sphere outside that box, and a sky sphere outside the ground sphere. The box and sphere are conceptually infinitely large and surround the virtual world.
Color	Color	Creates a list of colors
Coordinate	Point	Creates a list of coordinates
DirectionalLight	ambientIntensity direction intensity	Creates directed light source whose rays travel in parallel in a specified direction
ElevationGrid	color height normal xDimension xSpacing zDimension zSpacing	Creates face geometry for 2-dimensional objects
Group	children	Groups together nodes
IndexedFaceSet	color colorIndex coord coordIndex normal normalIndex solid texCoord texCoordIndex	Creates face geometry for 2 and 3-dimensional objects
IndexedLineSet	coord coordIndex color colorIndex	Creates polyline geometry
ImageTexture	url	Specifies texture mapping attributes
Material	ambientIntensity diffuseColor emissiveColor transparency	Specifies material attributes
NavigationInfo	headlight type	Provides information about the viewer's avatars and how it navigates using the current viewpoint
Normal	vector	Creates a list of normal vectors

Node	Fields	Description of nodes
ScalarInterpolator	key keyValue set_fraction value_changed	Describes a series of key colors available for use in an animation
Shape	appearance geometry	Specifies VRML objects
Sphere	radius	Creates sphere-shaped primitive geometry
Text	fontStyle length size string	Creates text geometry
TextureCoordinate	point	Specifies a list of texture coordinates
TextureTransform	rotation	This node builds a new texture coordinate system relative to the original texture coordinate system
TimeSensor	enabled cycleInterval cycleTime loop	Creates a clock that generates events to control animation
TouchSensor	enabled isActive isOver touchTime	Detects a viewer's touch and outputs events describing when and where the viewer touched the sensed shape
Transform	children rotation scale scaleOrientation translation	Creates a new coordinate system relative to its parent coordinate system
Viewpoint	description fieldofView orientation position	Specifies a viewing location within the coordinate system
WorldInfo	Title info	Provides information about the VRML world (metadata)

shape. In VRML, 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 [1]. The shape of every object is defined using triplets in relation to the origin. Soil landscapes are asymmetric 3-D objects and therefore we had to use the *IndexedFaceSet node* to create face geometry. We used Environmental Visualization Software (EVS-NT Standard Version; Ctech Development Corporation, Huntington Beach, CA) to export the geometry of 3-D objects. Additional VRML code was added to enhance VRML models. Surfaces were created using 2-D ordinary kriging and volumes (layers) were created with linear interpolation in the vertical direction between these surfaces.

We used the *Shape*, *Appearance*, *Material, IndexedFaceSet, Coordinate, Normal* and *Color nodes* to describe the geometry and appearance of our soil landscape model. For example, 3-D objects representing soil layers of site 1 were coded as:

```
Shape {
     appearance layer1 Appearance {
          material Material {
               ambientIntensity 0.301
               diffuseColor 0.3 0.3 0.3 }
     }
     geometry IndexedFaceSet { solid FALSE
          coord Coordinate {
               point [ -31.39 577.5 -272.4, -6.856
          567.3 -270.1, etc.]}
          coordIndex [ 0, 1, 2, -1, 1, 3, 2, -1,etc.]
          normal Normal { vector [ -0.3124 0.1031 -
     0.9443,
               0.09592 0.2025 -0.9746, etc.]}
          color Color { color [ 0.91 0.89 0.84, 0.91
     0.89 0.84, etc.]}
     }
}
```

We used the *coord* and *coordIndex field* within the *IndexedFaceSet node.* The *coord field* listed the coordinates available for building shapes, and the *coordIndex field* specified a list of coordinate indexes describing the perimeter of one or more faces. Virtual Reality

Modeling Language uses the RGB (red, green and blue) 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* specify RGB values as three floating-point values, each one between 0.0 and 1.0. In this context, 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 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).

Because VRML uses the RGB color classification, Munsell soil colors collected in the field had to be converted to suit. 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, a value that makes images 'look average' on most platforms. The RGB colors had to be connected to each coordinate of the soil landscape model using the *color field* of the *Color node*. The material color method was used to color specific layers of our soil landscape models. To visualize structural and color changes along the soil profile on site 1, we used the VRML texture mapping method. We scanned a photograph of the soil profile in JPEG format and draped it on the faces of the VRML soil profile object coded as *IndexedFaceSet node*. Our VRML code used *Shape*, *Appearance*, *Material*, *ImageTexture*, *TextureTransform*, *Texture Coordinate nodes* and was written as:

```
Shape {
    appearance Appearance {
        material Material {
            texture ImageTexture { url
        "picture_soilprofile.jpg" }
            textureTransform TextureTransform {
        rotation -1.58 }}
```

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```
        }
    geometry IndexedFaceSet {
        coord Coordinate {
            point [ -1.0 1.66 1.0, 1.0 1.66 1.0,
        etc.] }
        coordIndex [ 0, 4, 5, 1, -1, etc.]
        texCoord TextureCoordinate {
            point [ 0.0 0.0, 1.0 0.0, etc. ] }
        texCoordIndex [ 0,1,2,3,-1, etc. ]
        solid FALSE
    }
}
```

Within the *ImageTexture node*, the *url field* specifies the file name and graphical format (e.g, jpg: joint photographic experts group) used for texture mapping. The *texCoord field* specifies the texture coordinates available for texturing faces within the face set and the *texCoordIndex field* specifies a list of texture-coordinate indexes describing the perimeter of one or more texture cookie cutters. The *solid field* specifies a TRUE or FALSE value indicating whether the geometry specified by the faces in the face set is solid. The faces of a solid nearer to the viewer obscure the backsides of more distant faces on the same shape. When the VRML browser is informed that a face set is solid, it can avoid drawing the backsides of faces and speed drawing time. In these models, we used "solid FALSE" because the exporting program does not always specify the vertices of the polygons in a counterclockwise direction, a defect in EVS but not unusual among programs for which VRML export is not their primary feature.

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 users can jump, walk or fly to a new position. 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 [13]. Generally, for all soil landscape models, we used a *fieldOfView* value of 0.083 as a compromise

between large and small angle camera-lens effects. For example, the pedon model had a *position field* of 0 0 120, whereas the zoomed *Viewpoint node* had a *position field* of 0 0 80.

The appearance of a model depends on shading. Shading gives the viewer the sense that a shape is 3-D. Virtual Reality Modeling Language automatically computes darker colors as it shades the sides of a shape, gradually darkening the shading color as it progresses from the lighted sides of the shape to the unlighted sides. [1]. Virtual reality uses simplified methods of simulating real-world lighting such as diffuse and specular reflection, and ambient light. We suggest the use of the *diffuseColor field* for the visualization of soil landscape models because soils are dull surfaces that exhibit diffuse reflection but only a little specular reflection. Values of 0.3 0.3 0.3 for *diffuseColor* in the *Material node* were used, which make the colors look slightly darker than their Munsell notation but gives the model a realistic 3-D appearance. Dull shapes typical of soils are illuminated by ambient lighting and we therefore suggest an *ambientIntensity* of 0.301.

To show the x, y, and z dimension of VRML soil landscape models, we added scales, which were coded using *IndexedLineSet nodes*. For example, the x-axis of the soil layer model on site 1 was coded as follows:

```
 Group { children [
     DEF x_axis Transform { translation -5.0 -4.0
-7.0
          children [ Shape {
              appearance Appearance { material
          Material{}}
              geometry Text { string "1 m"
                  fontStyle FontStyle {
                  size 0.8 } } } ] }
     DEF y_axis Transform { etc. } } } ] }
     DEF z_axis Transform { etc. } } } ] }
     DEF 3_scale_bars Transform {
          translation -7.0 -4.0 -7.0
          rotation -0.5596 0.5473 0.6223 0.0
          children [ Shape {
              appearance Appearance {
                  material Material {
```

```
emissiveColor 1.0 1.01.0
diffuseColor 1.0 1.0 1.0 } }
geometry IndexedLineSet {
coord Coordinate { point [
0.0 0.0 0.0, 1.9 0.0 0.0, 0.0 6.2 0.0,0.0 0.0
1.9]}
 coordIndex [0,1,-1, 0, 2, -1, 0,3,-1 ] } }
     ] }
     ]
}
```

The *Group node* provided basic node grouping features, which can be manipulated as a whole. The value of the *children* field specify a list of children nodes to be included in the group. We used a *Shape node* for the value of the *children field* and a *Text node* to create labels for the scale bars. The *IndexedLineSet node* represented the x, y and z scales. The value of the *coord field* specified a node listing the coordinates available for building lines within the line set. The value of the *coordIndex field* specified a list of coordinate indexes describing the path of the three lines representing the x, y, and z-scale axis.

For site 2, we used the *ElevationGrid node* to visualize the terrain data on top of the soil layer model. This node has been designed specifically to build terrain models. To use this node the dimensions of the terrain grid, the cell spacing and an array of height values are required input. An advantage of this node is the ease with which the terrain can be modelled, and the smooth visual appearance that can be achieved because of the ability of VRML browsers to interpolate between grid cells.

Animation is the change of something as time progresses. To start, stop, and otherwise control animation, the *TimeSensor node* acts as a real-world clock. When turned on, the sensor starts ticking until it is turned off. If the sensor is never turned off, it continues ticking until a new VRML file is baded into the browser, or until the VRML browser is exited. To highlight areas of interest we added sphere shapes to the VRML soil landscape model of site 2. Spheres changed their colors from transparent to dull using a *ScalarInterpolator 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. We coded the following VRML *nodes* and *fields*:

```
Group { children [
     DEF Ball_blue Transform { translation -3.5 -
1.0 1.0
          children DEF ACube Shape {
               appearance Appearance {
                    material DEF BallColor
               Material {
                         diffuseColor 0.3 0.3 0.3
                         transparency 0.5 } }
               geometry Sphere { radius 1.5} } },
 # analog: define yellow sphere
DEF Clock TimeSensor { cycleInterval 8.0 loop
TRUE },
DEF TransparencyPath ScalarInterpolator {
     key [0.0, 0.5, 1.0 ] keyValue [0.0, 1.0,
     0.0] }
] }
ROUTE Clock.fraction_changed TO
TransparencyPath.set_fraction
ROUTE TransparencyPath.value_changed TO
BallColor.set_transparency
```

The value of the *transparency field* specifies a transparency factor between 0 and 1, with 0 creating opaque shapes and 1.0 making them completely transparent. We chose a transparency factor of 0.5. The *ScalarInterpolator node* uses a list of key fractional times and key floating-point values in its *key* and *keyValue fields*. Driven by a *TimeSensor node*, the *ScalarInterpolator node* uses linear interpolation to compute intermediate floating-point values. The *value_changed eventOut* of the interpolator was routed to the *Material node's transparency field* to cause the sphere transparency level to vary.

An interactive application feature, a *TouchSensor node*, was added to the soil-landscape model. This sensor was attached to the upper layer of the soil-landscape model. Pointer-device movement (a mouse) triggered the upper layer to be moved by the pointer-device.

All VRML models were validated for syntax with Chisel 1.0 (Trapezium LLC, Brooklyn, NY) 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 was

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unnecessary or redundant. Our VRML soil landscape models were loaded into Netscape Navigator 4.7 using the Cosmo Player 2.1 plug-in (Computer Assoc., Inc., 2000).

3. RESULTS AND DISCUSSION

Our VRML soil landscape models are accessible via the WWW at http://www.soils.wisc.edu/soils/3D_SL_models/3Dsoils.html. Users can interact with soil landscape models and trigger animations.

The pedon at site 1 and its location within a topo-sequence are shown in Fig. 1. 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 Ap, A/B and 2BC horizons have a silt loam texture and Btg was silty clay loam (Fig. 1). The Btg horizon showed redoximorphic features indicating seasonal high water table. Soil structure in Ap was moderate fine and medium subangular blocky, friable; in A/B medium platy to massive, firm; in Btg, strong coarse prismatic, very firm; and in 2BC, single grain to massive. The Ap, A/B and Btg horizon was formed in reworked loess material, 2BC in lacustrine sediments, and

Fig. 1. Different VRML techniques were used to color soil models at site 1.
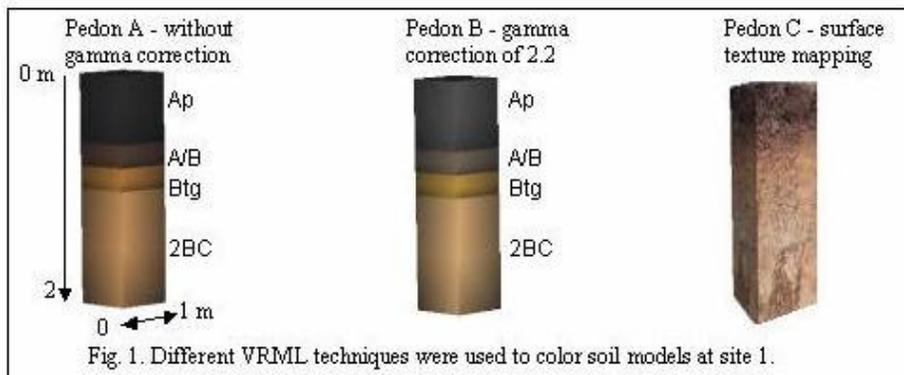
3C in glacial till. The 3-D topo-sequence and pedon models were able to portray the distribution of soil layers realistically. For example, the thickness of the A horizon increased from the top to the bottom of the topo-sequence in response to a shift from predominantly erosional to depositional processes.

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. 1). The precise rendering of VRML models in print and on the screen differ from device to device and depend on the hardware and software gamma correction, for example, gamma correction of devices (Macintosh, Sun workstations, IBM PC), monitors, brightness and contrast settings on the monitor, graphic cards, printers, software gamma correction, the ambient room lighting, display options activated, and finally personal taste. Gamma values usually average 2.2 but range from 1.7 to 2.7 on different platforms, graphic cards, 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.
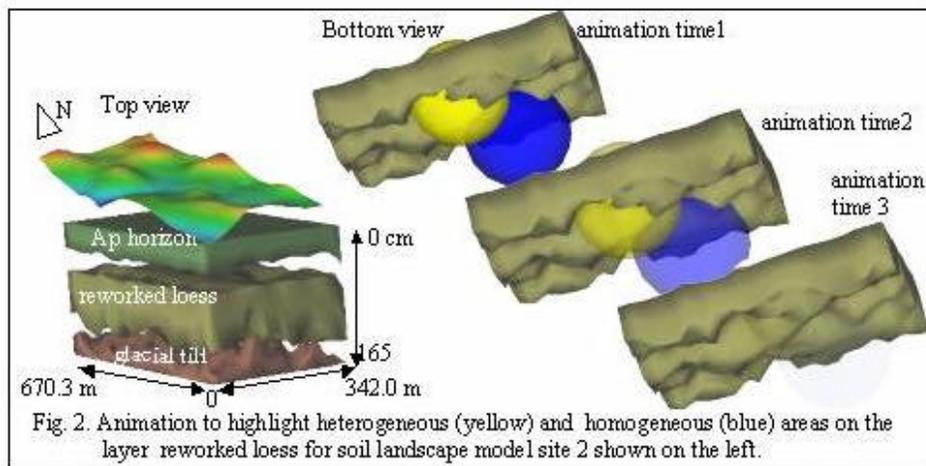
The Munsell color specification is based on perceptual principles using hue, value and chroma, which are based on the visual characteristics of paint pigment rather than light. Munsell colors are able to describe small and large color differences. The RGB color system is not directly related to human color perception and is not strictly definable in any of the Commission Internationale de l'Éclairage (CIE)-defined color space systems. The RGB color gamut has a rectangular shape [20] in contrast to perceptual color space, which 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. Simulation of shading and lighting is another factor that influences the visualization of colors using VRML. Color management using color calibration and standardization exists but is not routinely applied to most desktop applications. Virtual Reality Modeling Language does not offer a hardware and software independent color-management system. 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). 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 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 is possible to visualize color differences in top and bottom layers. The top layer shows a dark brown color, which is influenced by greater organic matter content. In contrast, we found brownish yellow colors in the bottom layers, which represent parent materials, lacustrine sediments and glacial till, respectively.

The texture mapping used to portray pedon C highlights 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. Popular WWW file formats such as GIF (graphics interchange format) and JPEG do not store file gamma. In contrast, Targa and PNG (portable network graphics) formats store file gamma [24,28].

The soil layer model showing different soil materials is plotted in Figure 2. The DEM is plotted as separate object coded in *ElevationGrid node* format on top of the soil landscape model. The advantage of this node is the smooth visual appearance that can be

Fig. 2. Animation to highlight heterogeneous (yellow) and homogeneous (blue) areas on the layer reworked loess for soil landscape model site 2 shown on the left.

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achieved because of the ability of VRML browsers to interpolate between grid cells. Moore et al. (1999) stress two main disadvantages: (i) large arrays of grids may be slow to maneuver in virtual space and large grids have to be tiled for efficient rendering and navigation and (ii) the height values are represented in the y plane with eastings in the x plane and northings in the z plane, which causes perceptual misunderstandings for spatial scientists familiar with the modeling in x, y spaces and requires transformations in order to simplify conversion between VRML positive axes and real world axes (Moore et al., 1999). The soil-layer model at this site showed a thick layer of reworked loess on lower elevated areas and a thinner layer of reworked loess on higher elevated areas. The animation function using yellow and blue spheres for homogeneous and heterogeneous areas, respectively, was a helpful tool to highlight specific characteristics (Fig. 2). File size for the soil layer model on site 2 was 144 KB.

The 3-D soil landscape model of site 3 consisted of A, Bt, and C horizons and A, Bt, Bg, and Cg horizon sequences, respectively (Fig. 3). Soil map units in depression areas 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 translocation and accumulation of clay-sized particles in the Bt horizon. A coherent VRML soil landscape was built representing real world soil patterns and terrain characteristics based on readily available data from a soil information database. Similar results indicate that virtual reality can utilize spatial data collected for map making and digital spatial datasets. [10].

Fig. 3. Three-dimensional VRML soil layer model site 3.
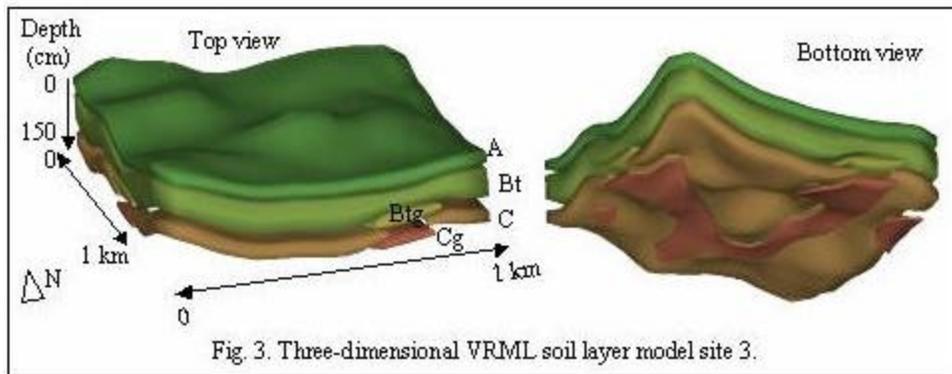
4. CONCLUSIONS

For three different sites, we created virtual 3-D soil landscape models representing natural soil and landscape characteristics using VRML. Scientific visualization using VRML facilitated creation of virtual 3-D objects in this study. Currently, VRML lacks georeferencing spatial data using map projections. An official GeoVRML Working Group (1999) has been established within the VRML Consortium to develop geographic functionality within the VRML specification. This is a step in the direction of a true virtual reality GIS. Virtual Reality Modeling Language provides the ability to model and manipulate spatial data and promises a powerful tool for spatial scientists. Geographic information system vendors are developing pseudo VR environments such as the ESRI 3D Analyst add-on to ArcView; however, these software packages lack full functionality of 3-D graphical design such as 3-D volume rendering of objects.

In the context of cross-media color reproduction and digital visualization which endeavors to draw virtual reality closer to the real environment, we stress the importance of cross-field collaboration between computer scientists, graphical designers and soil and environmental scientists.

Three-dimensional VRML worlds are accessible via the WWW, which opens the way to the development of more meaningful ways of representing, and therefore communicating scientific information. The WWW has turned the internet into a large storage facility for information of many types. Virtual reality facilitates visualization of information, storage of data in 3-D format, and allows the user interact with virtual environments representing real (or natural) environments. We believe that virtual soil landscape modeling has merit for educational and research activities such as improved visualization of soil information stored in databases, environmental assessment studies, water quality simulation modeling, and site-specific management.

of Wisconsin Nonpoint Pollution and Demonstration Project, and the Univ. of Wisconsin--Madison College of Agric. and Life Sci.

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Fig. 1. Different VRML techniques were used to color soil models at site 1.

Fig. 2. Animation to highlight heterogeneous (yellow) and homogeneous (blue) areas on the layer reworked loess for soil landscape model site 2 shown on the left.

Fig. 3. Three-dimensional VRML soil layer model site 3.