4-D Statistical Surface Method for Visual Change Detection in Forest Ecosystem Simulation Time Series

Helen Jenny, Johannes Liem, Melissa S. Lucash, and Robert M. Scheller

***Abstract*—Rising uncertainties associated with climate change compel forest management planning to include forest ecosystem simulations. The output of such models is often of high spatio-temporal complexity and difficult to interpret for the user. This contribution describes a novel visualization method called four-dimensional (4-D) statistical surfaces, which aims at improving the visual detection of change in time series. The method visualizes attribute values as surfaces, which are interpolated and animated over time; the interactive attribute surfaces are combined with color-coding and contour lines to support absolute and relative height judgment as well as faster perception and better location of change. A design study and prototypical implementation of the visualization method is described in this contribution. Time-series simulation results of LANDIS-II, a commonly used modeling tool in forest ecology, as well as a temporal vegetation index dataset (NDVI) are visualized using 4-D statistical surfaces. Usability challenges are addressed based on explorative interviews with a small group of users. The method is not limited to ecological model output; it can be used to create three-dimensional (3-D) temporal animations of arbitrary time-series datasets where parameters are supplied in regular raster format.**

***Index Terms*—Forestry, simulation software, time-series animation, visualization.**

I. Introduction

RISING uncertainties associated with climate change compel forest management plans to consider forest ecosystem simulations of future change. Without considering the effects of climate change using modeling, forest plans may suggest the use of management that leads to undesirable outcomes. For example, timber harvesting of 60-year old aspen may be sustainable under the current climate, but temperatures may significantly limit aspen growth under climate change. Forest simulation models allow users to compare the long-term results of multiple management scenarios under different future climate scenarios, before the activity is executed in the field. By comparing these different scenarios, forest managers can make a more accurate long-term estimate of the consequences resulting from actions taken today or in the years to come.

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Small budgets, lack of available time and lack of GIS expertise may constrain the ability of forest managers to evaluate multiple management scenarios. Also, forest managers often focus more on short-term than long-term planning, which may in fact constrain their creativity and thinking “outside-the-box.” Finally, forests are complex ecosystems that change over time, so evaluating many management and climate scenarios over multiple tree species and time frames across large landscapes can be overwhelming for forest managers and researchers alike.

While the advantages of integrating ecosystem modeling into forest management decision-making are obvious [1], effective and user-friendly spatial visualization software that makes simulation output more accessible to forest managers and modelers is still rare. This contribution describes a design study for a novel interactive visualization method, called four-dimensional (4-D) statistical surfaces, which aims at improving the perception of change in time-series datasets. Our visualization method builds on merging two existing cartographic representation methods: 1) two-dimensional (2-D) animation of time series as maps and 2) static three-dimensional (3-D) representations of attribute data (also known as statistical surfaces).

In Section II, we describe related work in forest ecosystem visualization and review the characteristics and known challenges of 2-D animation and cartographic statistical surfaces. Section III presents a design study that explains how those two representation methods can be combined into a novel visualization method and why we think such a method may have superior characteristics to the separate approaches. Section IV describes the prototypical implementation of the proposed method. In Section V, we demonstrate the method by visualizing future alternative scenario datasets produced by LANDIS-II [2], a commonly used modeling tool in forest ecology. Our interest in creating visualizations for LANDIS-II lets us focus on visualizations at a regional or landscape scale in contrast to visualizing individual forest stands. In addition to LANDIS-II simulation results, we also visualize a commonly used vegetation index (NDVI) over time for the State of Oregon. A small group of geographers was invited to provide comments on the visualization results, which were integrated into our discussion of challenges and future work.

II. Related Work and Representation Methods

A. Forest Ecosystem Visualization

Visualization of forest ecosystems in 3-D has been attempted at the stand and landscape scale, including Forest Visualization Project [3], Stand Visualization System [4], Landscape

Management System [5], and EnVision [6]. Ref. [7] noted that 3-D visualizations in geographic information science and design guidelines for such representations have been mostly geared at representing tangible objects on the Earth's surface (e.g., 3-D city models, touristic mountain panoramas, and landscape visualization). This tendency to cling to the physical world in 3-D representations appears to be also true for forest ecosystem visualizations, as in our review of publications we found species distribution to be the most often visualized content [8], [9]. At a regional scale, shaded terrain draped with 2-D land-use textures dominates; at a more local scale, miniature photorealistic 3-D models of trees are commonly placed on terrain. As one of few exceptions, [10] uses static 3-D surfaces combined with terrain to visualize intangible natural hazard parameters in an alpine environment.

To introduce the time component into forest ecosystem time-series visualization, it is common to generate, classify, and color-code output at specific points in time (time steps). These time steps can be presented in form of multiple static 2-D maps or, less common, can be played in temporal sequence; thus creating a temporal 2-D animation. Such 2-D map animations are used for abstract attribute data visualization as well as for visualizing data with tangible characteristics. Our visualization method aims at combining 3-D representation with 2-D animation characteristics and concentrates on displaying abstract attribute data. Ref. [11] comes closest to our method by dynamically visualizing diurnal population change as 3-D surfaces. Their method differs from ours in that it does not allow for smoothly interpolated time-step transitions.

B. Potential and Challenges of Time-Series Animation

While cartographic 2-D animation has a long tradition as a visualization method for spatio-temporal datasets, a number of challenges are encountered when applying this method. As it is our intention to compensate for some of these challenges with the proposed method, a discussion of cartographic 2-D animation is provided in this section. Compared to static maps, animated maps use time as an additional representational dimension. When a sequence of maps is shown in rapid succession, the observer perceives changes as a fluid motion. It is this emphasis on the change between moments [12] and the possibility of showing a temporal as well as spatial overview of a dynamic phenomenon [13], [14] that constitute the strengths of animation.

However, cartographic animation is not a suitable representation method for datasets where little change occurs, and it can be difficult to interpret when the datasets are very complex. Complex animations cause high cognitive loads, where observers quickly exhaust their cognitive resources and are not able to convert the information shown on animated maps into chunks of meaning that can be remembered [15]. Different complexities can be identified in animation, including animation length (long run time exhausts short-term visual memory), complexity of spatial patterns (spatial heterogeneity), and complexity of the patterns of change (temporal heterogeneity) [15]. Selective attention to specific elements of an animation, e.g., a counting task given to the observer, may lead to change blindness, where elements that were not part of the task go unnoticed [16]. Flickering transitions between time steps can even extend change blindness to large changes [17], and observers often over-estimate their abilities to detect changes in cartographic animations [18].

C. Statistical Surfaces Data Model

The third dimension is commonly used in cartographic representation to portray the tangible world, e.g., to show terrain as the continuous variation of elevation over an area. In his textbook on cartography, [19] describes the statistical surface as a data model, where the third dimension is used to portray a continuous attribute that does not need to have an immediate physical equivalent in geographic space. This data model can be represented in 2-D (e.g., using contour lines to express attribute value) and in 3-D, where two spatial coordinates are combined with a third coordinate as relative height proportional to an attribute value at that 2-D location (e.g., forest biomass computed by LANDIS-II shown as a 3-D surface). Our proposed visualization method adds time as a fourth dimension to the 3-D statistical surface concept by animating 3-D statistical surfaces and thus providing a temporal sequence. We refer to this representation as 4-D statistical surface ($\text{three dimensions} + \text{time}$) and describe a prototypical implementation for creating such representations in Section III.

III. 4-D Statistical Surface Method Design

The complexity of spatial patterns and patterns of change of animated time-series data created with LANDIS-II is high. This makes it difficult for the observer to guide attention to where major change is happening as well as to form a temporal and spatial overview of the shown dynamic phenomena. Therefore, we combined 2-D temporal animation (Fig. 1, left) with the 3-D statistical surface concept (Fig. 1, middle) with the intention of drawing attention to locations where important changes are occurring. In 4-D statistical surfaces, change is expressed by varying the height of the surface proportional to the attribute value at the current time-step. Change occurring between time-steps is thus expressed as a motion.

The following paragraphs describe the motivation for specific design choices for the 4-D statistical surface prototype and how these choices are founded on research findings for either 2-D animation or 3-D static representation. By capitalizing on the advantages of both representations, we aimed to create a superior visualization method for change perception and location in spatio-temporal datasets.

A. Increased Attention to Change Through Motion

Ref. [20] argues that coherent motion helps identify cluster patterns more easily and quickly in animated representations compared to multiple static representations, and it has been shown that humans can very well discern micro-motions [21]. In the prototype for 4-D statistical surfaces, a value increase or decrease results in an up- or down-movement of the statistical surface, while in a standard 2-D animation, changes are expressed solely via color changes.

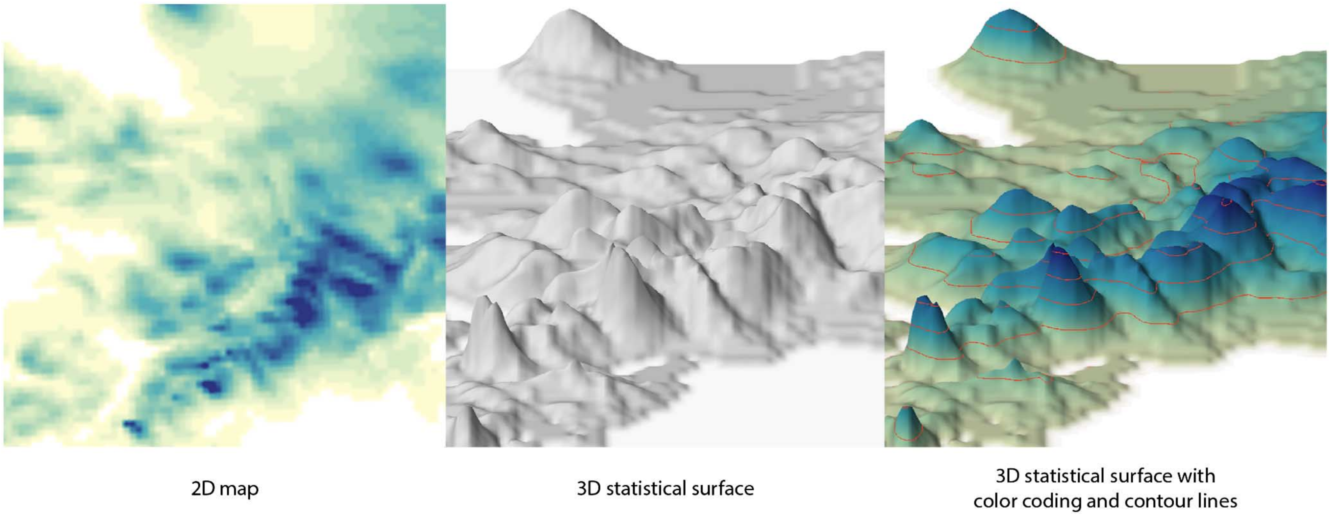

Fig. 1. Comparison of attribute value representations (shown in parallel perspective projection): color-coded 2-D map (left), height-coded 3-D statistical surface (middle), and combination of attribute value encoding by color, contours, and height (right). Data: precipitation forecast for Central Switzerland in mm, January 21, 2010, midnight.

B. Faster User Performance With 3-D Display

Some studies suggest faster user performance [22] better orientation and user enjoyment with 3-D displays (for an overview of comparative 2-D vs. 3-D representation studies [23]). In time-series animation, the quick perception of change is especially important as individual animation frames can only be shown for a limited time to sustain the impression of temporal flow as well as the memory of previous time steps. The animated 3-D representations at the core of the prototype are expected to positively influence change detection.

C. Smooth 3-D Animation Flow

Ref. [24] speculates that interpolating smooth transitions between 2-D animation frames visually prepares users to detect small changes. They also found that participants tended to watch smoothly interpolated 2-D animations at higher speed. The presented prototype implements interpolation of 3-D statistical surfaces at different time frames to provide smooth animation flow in three dimensions and time.

D. Intuitive Relative Size and Spatial Trend Judgment

In the 4-D statistical surface prototype, spatial differences in value can be perceived as direction (e.g., stair steps for gradual change), which may be more intuitive to interpret and possibly faster to perceive than changes in color gradient. While accurate size judgment can be negatively influenced by 3-D central perspective projection (see Section V, below), relative visual comparison of values represented by height may be more intuitive and analogous to routine spatial tasks than comparing colors in 2-D, especially under time pressure.

E. Choice Between Central and Parallel Perspective

Foreshortening of background elements due to central perspective projection can negatively influence size judgment. Same size elements are drawn on the display smaller in the background than in the foreground. However, [21] argues that the observer of 3-D representations can perceive background objects at the actual size (size constancy) if a satisfactory set of depth cues (e.g., shading and occlusions) is used in the representation. This allows the user to apply size constancy to 3-D representations just as to objects perceived in real life.

The developed prototype shows attribute values as a shaded surface. It allows the user to switch between central perspective projection and parallel oblique projection. The latter shows same size elements in the foreground and background at same display size, which is also helpful when low-height background values would be reduced beyond recognition in central perspective projection.

F. Multiple Visual Encoding of Attribute Value

In addition to encoding attribute value as height, height is combined with color and contour lines in the prototype (Fig. 1, right) to better support relative size judgment as well as absolute size judgment for reasons given in Section V.

G. Providing a Geographic Reference to the Observer

To facilitate geographic orientation on 4-D statistical surfaces, no-data areas or a selected threshold value can be textured with elements of a 2-D map. The result is a discontinuous statistical surface that appears to be floating on top of a 2-D map and thus facilitates geographic orientation.

IV. Prototypical Implementation

A. Rendering of 4-D Statistical Surfaces and Interactivity

Customized software was developed to implement animated statistical surfaces. The software is written in Java and builds on JOGL [25], a Java interface for OpenGL [26] for building interactive views of statistical surfaces. OpenGL is a standard application-programming interface for generating 2-D and 3-D computer graphics.

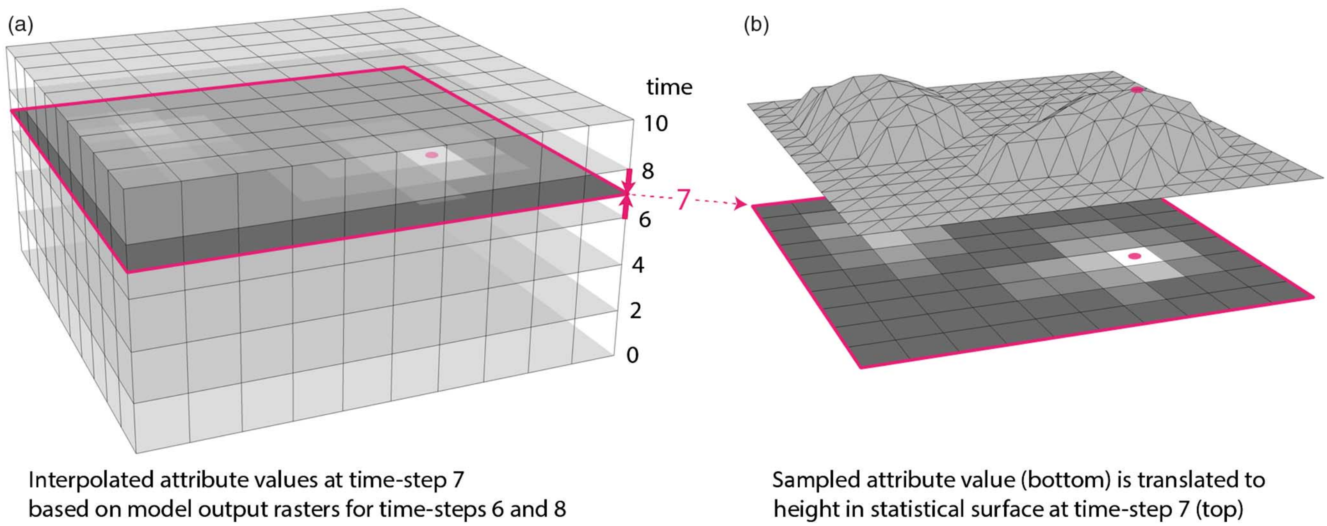

Fig. 2. 3-D texture and smooth interpolation of time steps (left) and translation of attribute raster values to heights in a triangle mesh of statistical surface (right).

Using the prototype, the user loads a series of regular raster grids containing attribute values where each raster grid represents a time-step. One grid at a time is displayed as shaded 3-D surface, starting by default with year zero. The user can choose to play a sequence of smoothly changing surfaces or stop at a specific time-step. During the animation, the user can zoom in and out of the surface display as well as rotate it and change shading parameters.

B. 3-D Texture Interpolation for Smooth Animation Flow

A regular raster containing attribute values is interpreted by the software as height values (z-coordinate) and translated into a 3-D surface. This is illustrated in Fig. 2 (right), where the largest value in the raster (red dot) is interpreted as highest point of the surface.

To avoid abrupt, incoherent visual changes between larger time steps, a 3-D texture is used for interpolation. If one imagines stacking georeferenced regular output rasters of LANDIS-II in temporal order on top of each other, the result is a space-time cube where the up direction represents the progression in time (Fig. 2, left). This data structure is called a 3-D texture. By specifying a point in time on the temporal axis of the 3-D texture, the algorithm can identify the raster corresponding to that time-step. The rasters in the 3-D texture represent the spatial distribution of attribute values over time, e.g., biomass at every valid data location in the test site area computed in 2-year time steps over a decade. In the example given in Fig. 2 (left), the 3-D texture cube contains six rasters. If a time is selected for which a model-computed raster does not exist (e.g., year seven), the values of the raster cells are linearly interpolated to provide smooth-looking transitions in the 3-D animation. The openGL vertex shader, an element of the graphics processor, uses the values of the 3-D texture to adapt the height coordinate of each geometry vertex in the 3-D statistical surface at the given time-step of the animation.

C. Attribute Value Color-Coding, Contour Lines, and Choice of Projection

To help the user judge relative and absolute attribute value represented by height, two additional ways of encoding attribute value were added to the animated 3-D surfaces: 1) color-coding and 2) contour lines. For color coding, the user can select a color ramp (colors and class boundary), which is used by the OpenGL fragment shader to assign color to the statistical surfaces. This is analogous to hypsometric color-coding of terrain. If desired, attribute values that lie below a certain threshold, e.g., no value or 0, can be colored according to a 2-D map texture instead of applying the color ramp. The effect of using information from the map texture is that statistical surface components appear to float on a map background. Research suggests that diverging user attention from the animation to a legend may break observed animation flow [15]. For this reason, contour lines were added to the statistical surfaces using an algorithm described by [27] so that users can better estimate attribute values without having to move their gaze away from the statistical surface.

It is difficult to estimate if the individual user receives enough depth cues to accurately judge relative height in central perspective projection as explained in Section III.E. For this reason, in addition to central perspective projection, parallel oblique projection was implemented as a choice. The user can toggle the view between the two projections.

V. Discussion of Results

We have visualized a number of examples with the 4-D statistical surface method and asked three geographers, one with forest ecology expertise, to comment on the results. Figs. 3–5 show examples of visualization output for LANDIS-II. LANDIS-II is a landscape model designed to simulate forest succession, climate change effects, seed dispersal and disturbances (e.g., fire, wind, harvesting, and insects), for landscapes of 10 000 to 20 000 000 ha. The test area shown in the LANDIS-II

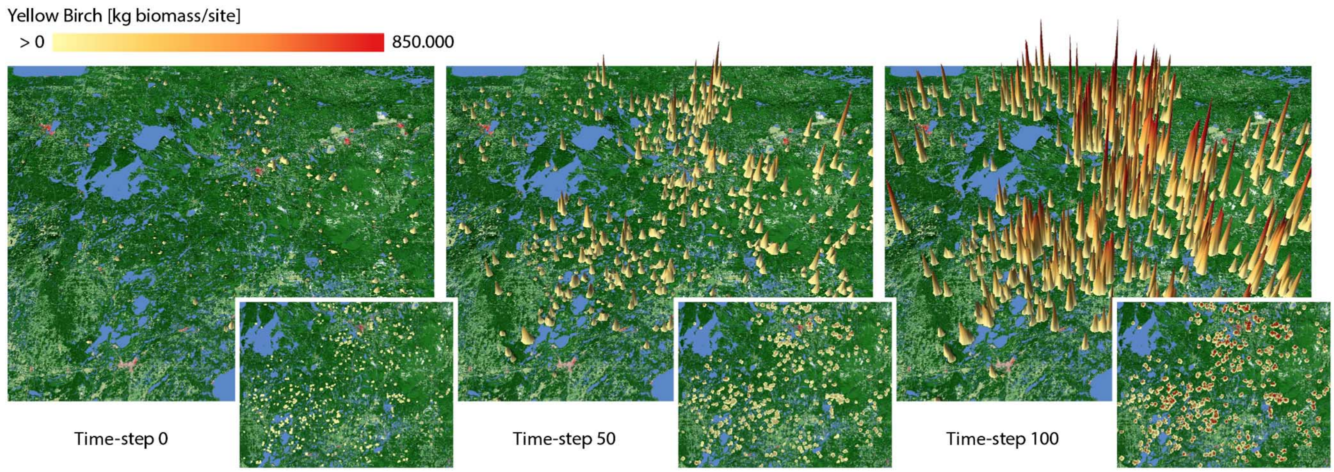

Fig. 3. Snapshots of 4-D statistical surfaces showing the distribution and quantity of yellow birch (in kg biomass per 4 ha site) over time in northern Minnesota; statistical surface based on time-series rasters computed with LANDIS-II; reference map texture based on USGS National Landcover Database; rendered in central perspective projection. Small inlets show time-steps in 2-D.

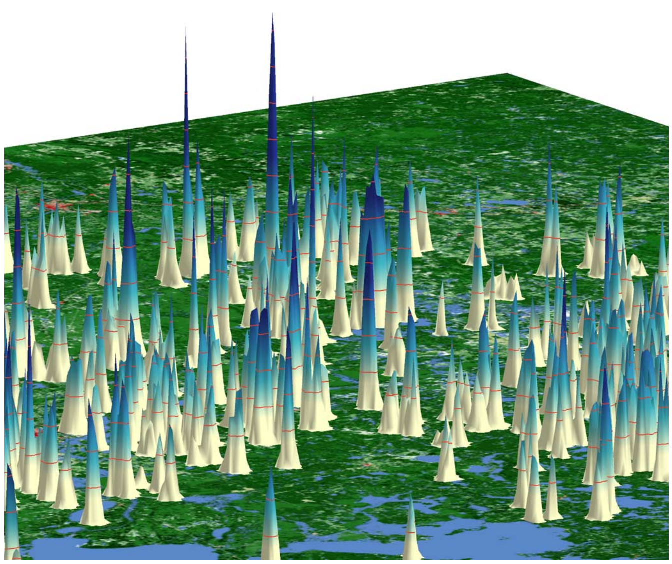

Fig. 4. Close view of interrupted statistical surface showing contour lines, color-coding, 2-D map for geographic orientation; rendered in parallel perspective projection.

examples is the Chippewa National Forest and adjacent public and private forest areas in northern Minnesota.

Fig. 3 shows snap-shots of the distribution and quantity of biomass (kg) of yellow birch over time per 4 ha site in northern Minnesota at time-steps 0, 50, and 100 years. The method produces a 3-D animation, which we can, unfortunately, only document via static figures for this contribution. The statistical surface appears discontinuous, as locations, where yellow birch does not occur, are filled in with a 2-D topographic map texture for better orientation.

Fig. 4 shows, up close, the cone-like landscape that results from noncontinuous data occurrence or availability. It is challenging for the user to place values coded only by height within a value range. Contour lines in combination with a color gradient are meant to assist the user with this task.

Contour lines and color gradient on disrupted surfaces allow for value comparison, similar to reading off class breaks in a legend. This can be especially helpful when comparing foreground elements with perspectively foreshortened background elements. We are considering labeling or color-coding contour lines to further support value identification. Generally, the interviewed users mentioned that they found it easier to compare color-coded cone heights in the 3-D representation compared to comparing only colors in the 2-D representation (Fig. 3, inlets).

The interviewed geographer with forest ecology background commented that a volume-based representation would be preferable, where site areas are extruded to represent a volume (cuboid or prism) as forest industry is often interested in volume indication. Currently, cartographic theory assumes that observers cannot judge volume well [28] and use height when asked to estimate volume. If area units differ and values are indicated per area unit, the height of the prism could vary between units with the same attribute value. For this reason, we preferred smooth surface representations that are less likely to be interpreted as volume and that support height judgment.

Fig. 5 shows the net primary productivity of carbon per year in northern Minnesota forested areas. Note the ring of high productivity in the center of time-step 45. The ring-shaped increase and decrease in carbon production is a reoccurring spatio-temporal pattern. The interviewed users agreed that compared to 2-D animation (small inlets in Fig. 5), the vertical up and down movement of the ring-shaped increase and decrease in the 4-D statistical surface helped them better identify this pattern.

When playing the animation at a faster pace, the users identified the spatio-temporal pattern easily in the 4-D statistical surface; when played at a relatively slow pace, users mentioned that they lost track or did not notice the pattern. These observations are in agreement with observations on the influence of display speed on change detection in 2-D animation: a too-slow display speed can break the temporal flow of the animation, whereas a fast pace can lead to overlooking change.

The dataset in Fig. 6 presents data unrelated to LANDIS-II. It shows the Normalized Differenced Vegetation Index (NDVI) for Oregon over the course of a year. NDVI is the most commonly used vegetation index based on remote-sensing data and available in raster format. We selected this dataset to show results for a

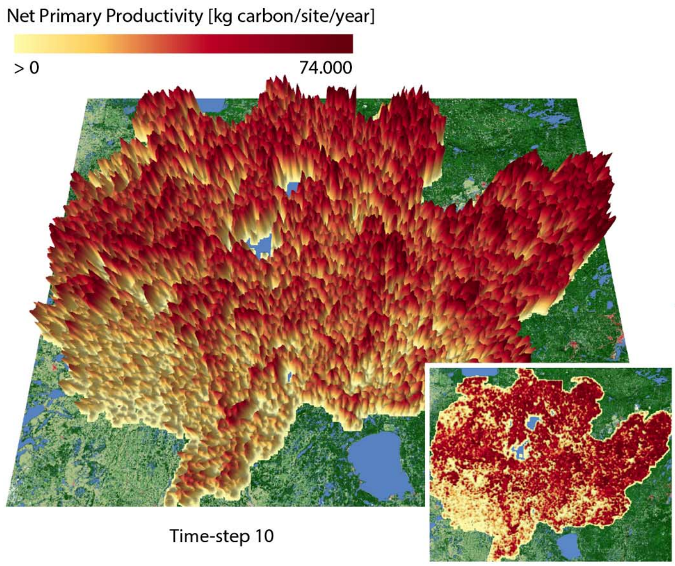

Fig. 5. Net primary productivity per year in northern Minnesota computed with LANDIS-II; rendered in central perspective projection. Small inlets show time steps in 2-D.

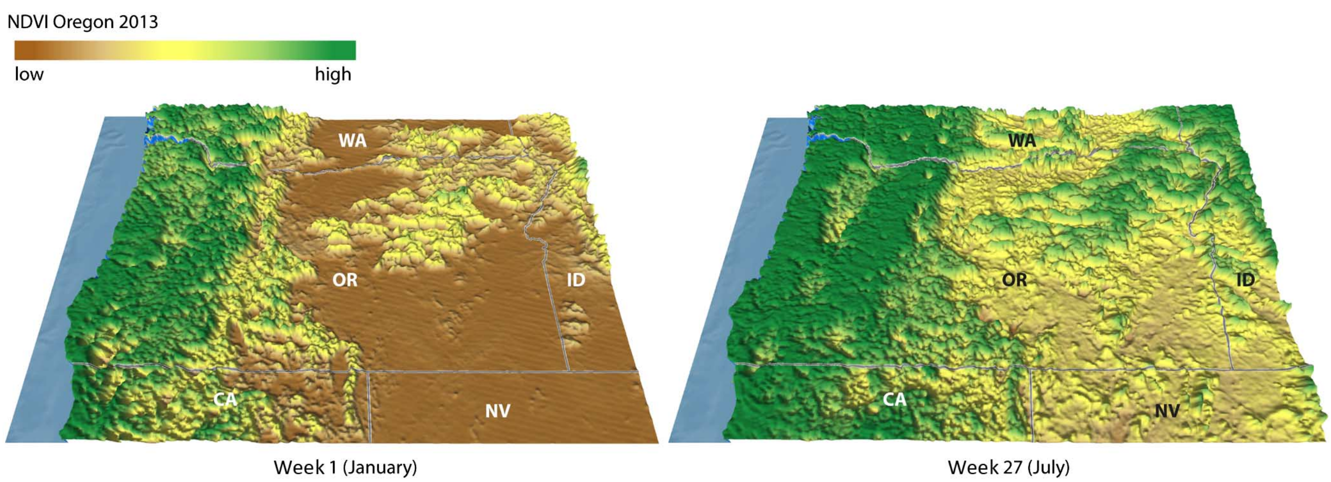

Fig. 6. Two time steps from an NDVI for Oregon over the course of a year; rendered in central perspective projection.

surface with continuous data availability and to demonstrate that our method can be used for many types of raster datasets. A color gradient was applied to the vegetation index range, with brownish colors for lower and greenish colors for higher index values. High values were assigned a higher height value than low values. One of the users of our pilot study mistook the 4-D statistical surface for an animated physical forest model, assuming that the third dimension was used for terrain and tree height instead of showing NDVI, a thematic attribute. Most users have not been exposed to smooth, continuous surfaces describing an abstract attribute and may mistake it more easily for terrain altitude, which represents a challenge for the application of 4-D statistical surfaces.

VI. Conclusion and Future Work

This design study describes the implementation and discussion of a novel visualization method, which combines the concepts of temporal animation and 3-D statistical surfaces to improve visual awareness and location of change in complex time series. The method can be applied to arbitrary time-series data encoded as regular rasters; possible applications of the method thus go beyond visualizing forest landscape model output. Future work will include a formal user evaluation of the presented method and prototype.

In addition to change expressed through variation in height, a horizontal movement associated with change can in some cases be discerned, e.g., a contiguously spreading value increasing from east to west also produces a horizontal attribute movement. We would like to further investigate if a combination of vertical and horizontal movements unique to 4-D surfaces improves the identification of spatio-temporal patterns. It is also not clear if users still perceive horizontal movements when the 4-D statistical surface is discontinuous.

Occlusion of background elements by foreground elements is a challenge for all types of obliquely viewed 3-D representations.

Currently, functionality for interactive rotation and zoom, while the temporal animation runs, is available in our prototype. It would be interesting to examine if automatically altering the viewpoint of the observer during the animation to show identified areas of change with less occlusion would be helpful. Areas of change could also be pointed out using saliency reinforcement and cueing, which have recently become a focus of research in 2-D map animation.

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