The Tardis: A Visual Exploration Environment for Landscape Dynamics

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ABSTRACT

This paper presents the creation of a a visual environment for exploring landscape patterns and changes to such patterns over time. Dynamic landscape patterns can involve both spatial and temporal complexity. Exploration of spatio-temporal landscape patterns should provide the ability to view information at different scales to permit navigation of a vast amount of information in a manner that facilitates comprehension rather than confusion. One way of achieving this goal is to support selection, navigation and comparison of progressively refined segments of time and space.

We have entitled this system *Tardis* after the time machine of Dr. Who, to emphasize the exploration of time dependent data and because our use of elastic presentation has the effect of providing more internal space than the external volume suggests. Of special concern in this research is the extent of the data and its inter-relationships that need to be understood over multiple scales, and the challenge inherent in implementing viewing methods to facilitate understanding.

Keywords: Multi-scale Views, Detail-in-Context, Viewing Algorithms, Information Visualization, Multi-dimensional Data

1. INTRODUCTION

The SEED (Simulating and Exploring Ecosystem Dynamics) project aims to create of a suite of tools that facilitate the process of building and examining simulations of spatially explicit models of landscape dynamics. This research has a dual focus, the simulation of landscape dynamics and the visualization of the information that these simulations produce. These together provide a powerful addition to the available set of techniques for research and management at the landscape scale.

Spatially explicit models of landscape structure and change are increasingly used for complimenting empirical studies, evaluating management strategies, and developing theory in landscape ecology. Our simulation tool SELES (Spatially Explicit Landscape Event Simulator) provides a structured framework to guide development and to facilitate rapid prototyping of spatial landscape models. One of the goals of SELES is to separate the specification of model behaviour from the mechanics of implementing such a model on a computer. SELES models are specified in a high-level, structured modeling language that frees landscape modelers from programming, allowing them to focus on the underlying model rather than the implementation details. The SELES simulation engine executes the model, converting the high-level specification into a simulation of landscape change. The SELES language is declarative, and thus permits a clear representation of the underlying model, which, in turn, yields models that are more easily verified, compared, modified, and reused. SELES models can include aspects of cellular automata,[1] discrete-event simulation,[2] and spatio-temporal Markov models.[3] Integrating models of both natural and human-caused processes gives researchers, managers and decision-makers a means with which the impacts of various management actions can be evaluated for their effect on landscape structure over time.

The output of simulations of landscape dynamics can be extensive in a number of dimensions. The spatial extent of the landscape under study and the resolution of data can produce information layers that are rich in complexity. Simulations over long time periods can result in long temporal sequences. In addition to the spatio-temporal dimensions, there are two other pseudo-dimensions: attribute and replicate. The attribute dimension

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consists of the characteristics of the landscape structure. It is usually represented by a number of features, such as vegetation species composition and age, soils, elevation, management zones, etc. Depending on the processes included in the model, some characteristics will be static, while others will undergo changes over simulated time. The attribute dimension results in separate, but correlated spatio-temporal information.

The replicate dimension is a result of the fact that models constructed using SELES are often stochastic, and each simulation projects a possible future of landscape changes. To gain an understanding of the range of variation that may result from models, multiple simulations are often run in a Monte-Carlo manner. Like the attribute dimension, this replicate run dimension results in a set of separate spatio-temporal information. Thus, there will be one spatio-temporal dataset for each attribute during each Monte-Carlo run. Clearly, there is a potential to produce an overwhelming quantity of information.

Establishing a visual representation of SELES information and its inter-relationships is an important factor in making the results generally accessible for analysis and model verification and refinement. Providing the ability to examine different aspects of SELES data (e.g. input conditions, landscape states, individual landscape changes, statistics gathered from landscape data, etc.), in an integrated visual environment supports understanding and analysis of the results. This paper provides an overview of a visual exploration environment that allows exploration of spatial and temporal landscape data, such as the results of landscape simulations, by progressively presenting refined segments of space and time. Of special concern in this research is the extent of the data and its inter-relationships that need to be understood over multiple scales, and across many information dimensions (spatial, temporal, attribute and run-replicate), and the challenge inherent in implementing viewing methods to facilitate understanding.

This paper will start with a brief overview of SELES in order to provide an understanding of the data it generates and then focus on Tardis, the visualization environment.

2. THE INFORMATION SPACE

The visualization tools being developed as a part of the SEED project are generally applicable to the investigation and analysis of any large set of temporally varying, spatially explicit data. The work to date with these tools has focused on their application to the data generated by the SELES engine.[4]

A landscape is a heterogeneous region that is composed of a mosaic of different patches, and generally contains at least a few interacting ecosystems.[5] They are commonly defined in the range of 103 to 106 hectares.[6,7] Analyses of landscape structure, function, and/or change typically involve large spatial scales, and processes acting over long time frames. In addition to difficulties arising from these characteristics, empirical experiments in landscape ecology are often hampered by the impracticality of experimental manipulation and a lack of suitable replicates.[8] Thus, the development of models to complement empirical studies is critical for:

- Extending our understanding of the natural processes driving landscape dynamics;
- Predicting the consequences of management actions;
- Developing theory in landscape ecology[8,9]

The state space for SELES models includes a set of GIS (Geographic Information System) raster layers. That is, each layer is a rectangular grid of cells that represents a different spatial attribute for the landscape under study, such as elevation, aspect, species, etc. The values in a raster layer can be continuous (e.g. elevation in metres, stand age) or categorical (e.g. species or community type, management zone). Some layers may be static in a model, while others will be dynamically modified. Landscape dynamics are modeled using a general framework called a landscape event. Each landscape event is a semi-independent model of landscape change, usually reflecting a single key process (e.g. seed dispersal, forest succession, ungulate grazing, timber harvesting, or fire). The behaviour of a landscape event can be influenced by, and may modify, the landscape state layers. A landscape event may have global behaviour (e.g., the interval between insect infestations on the landscape), local behaviour (e.g. the likelihood of insect infestations in different forest stands), and a set of effects or state changes (e.g. insect infestations may modify a canopy density layer). The sub-models may be stochastic, deterministic or incorporate elements of both. Feedback mechanisms between different processes are accomplished through state transitions on one or more raster layers, or global variables. A SELES simulation includes a set of initial raster states, stored in GRASS GIS format, and one

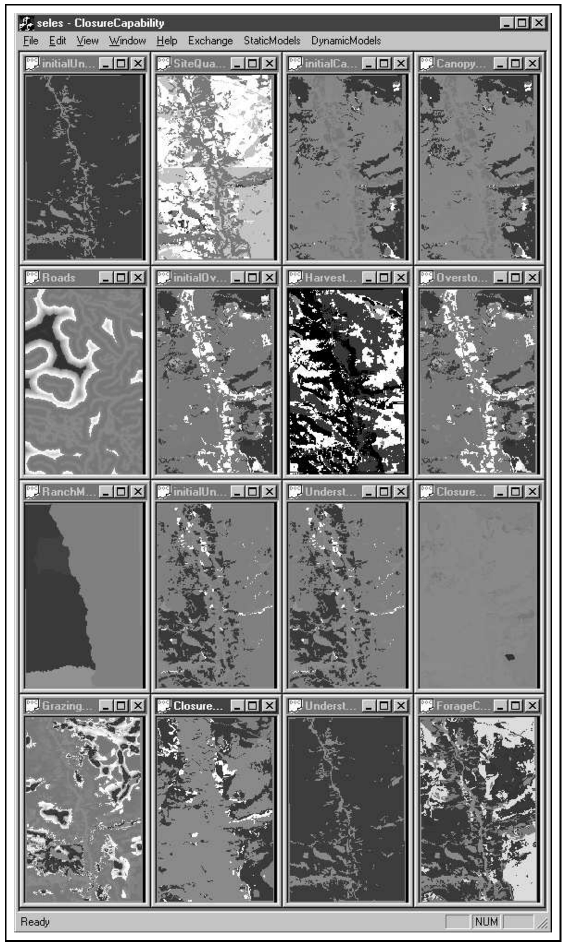


Figure 1. Some of the many attribute layers that make up the state of one particular simulation in the SELES system

or more landscape events. The simulation engine interprets and executes the landscape events. As the simulation proceeds, landscape events make changes to the spatial state. The available output of a simulation includes a sequence of spatial states for any of the landscape layers as well as a complete record of the sequence of events that resulted in changes to the landscape state. Figure 1 shows a sub-set of the initial state rasters for a simulation run.

After a simulation has been run, we automatically assemble these simulation records into a database that facilitates the selective retrieval of individual events based on type, temporal filtering and spatial selection. This step is crucial for visualization because it provides access to the complete set of state changes that occurred during a simulation, including the spatial location and time of the change as well as which spatial attributes were modified. Our post-processing of SELES simulation database has an additional benefit in that it makes the simulation and visualization tools independent. The visualization tools are not tied directly to SELES output formats, but instead understand the spatio-temporal database that we create. Other spatio-temporal information (or any 3-dimensional information for that matter) that can be organized in our database format can be loaded into our visualization environment.

3. EXPLORING SPATIO-TEMPORAL DATA

SELES is capable of generating vast quantities of information as a simulation runs for a long period, operating on several, potentially large, spatial layers. A visual representation of this information and its inter-relationships is an important factor in making the results generally accessible for analysis, model refinement and report generation. Providing the ability to examine different aspects of SELES data (eg. input conditions, landscape states, individual landscape changes, statistics gathered from landscape data, etc.), in an integrated visual environment supports understanding and analysis of the results.

A SELES simulation operates on spatial data that changes over time. Of the several challenges in visualizing SELES data, we have focused on those issues involved in visually exploring the spatial-temporal relationships and those involved in displaying large rasters layers. The Tardis environment provides spatial and spatio-temporal representations and allows the user to shift data from one type of representation to another providing an easy transition between options for best exploring the data that interests them.

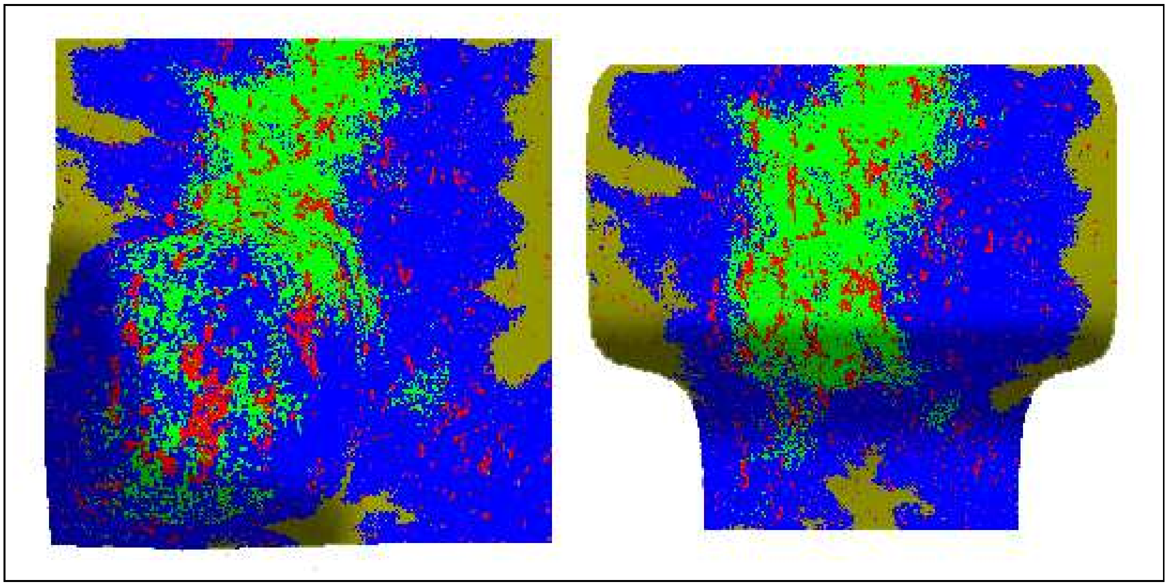


Figure 2. Distortion viewing reveals local detail in a spatial layer

The inclusion of in-context browsing of both the temporal and spatial dimensions is motivated by the research in distortion viewing (for surveys see[10–12]). In particular we extend the directions in 3DPS (3-Dimensional Pliable Surface)[13] and 3D visual access distortion.[14] While we have continue with the basic concept in our initial prototype temporal cube,[15] we have modified our approach to deal with larger and more complex volumes of data. Our use of the third dimension to display temporal data relates work done by Baker.[16]

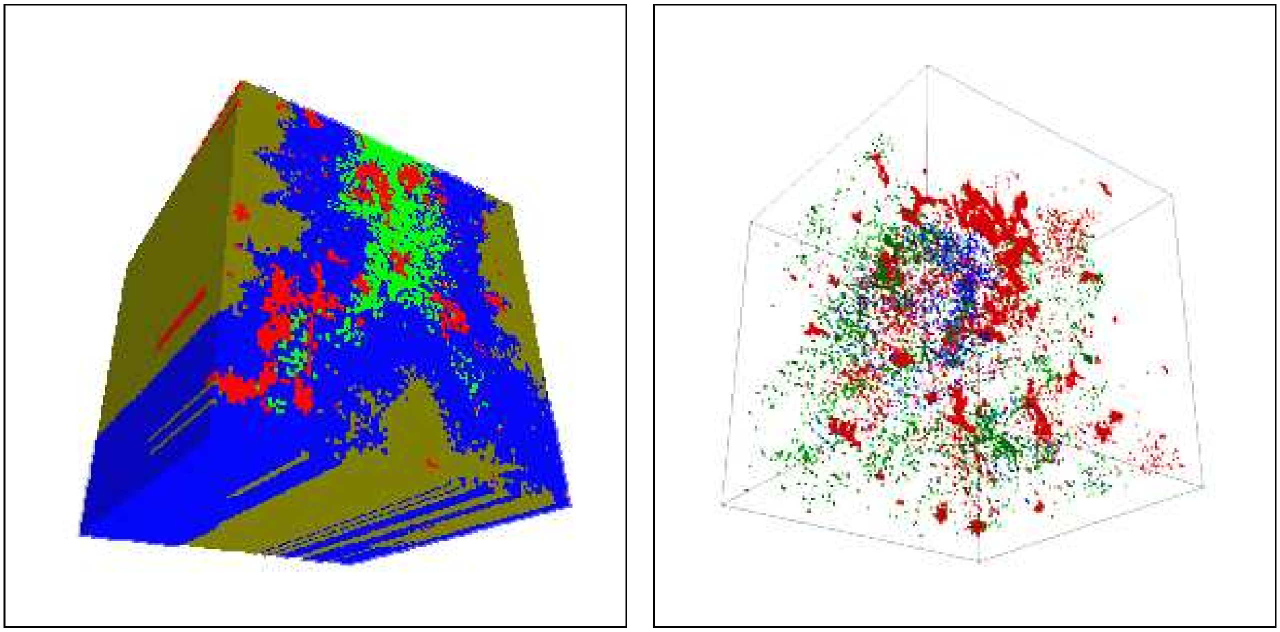
3.1. Two-Dimensional Spatial Complexity

The start state for a SELES simulation is a set of GIS layers that hold information about the initial conditions such as vegetation coverage, altitude and soil conditions. Some of these layers are *static* in that they are used as input from the simulation na d are not changed by the simulation. Others are *dynamic* in that they will change over the simulated time. Once particular simulation is read into Tardis, any of the initial state layers can be displayed as single layer rasters. Figure 1 shows some of the initial state maps for the Dog Creek model.

The individual raster layers that describe the state of a landscape in SELES can be vast spatially. In particular, the rasters generally have spatial dimensions that are greater than screen resolution. The intention is to provide visual access to these layers that will allow for examination of the detailed development of the landscape within its global context. For interactive exploration of vast 2D data we have incorporated our detail-in-context browsing method 3DPS.[13]

3DPS addresses interactive exploration of two-dimensional spatial information. This tool allows selection of areas of interest and then magnifies them in context, revealing required local detail without losing position in the global picture. Several variations of non-occluding magnification lenses (i.e. lenses that do not hide the contextual information) are available in 3DPS. Two examples of non-occluding lens types are illustrated in Figure 2. On the left is an orthogonal lens that allows magnification of square regions, and on the right is a lens that extends for the width of the image allowing a uniform magnification effect that is similar to a scroll. Both of these lens types maintain context, allow interactive search and can be used in conjunction.

Furthermore, with 3DPS, the Tardis integrates the more familiar panning-and-zoom type of access with flexible detail-in-context viewing, with the unique provision of a smooth transition between the two styles with an interactive-context level.



(a) An entire block

(b) The sparse structure generated by the individual events situated spatially and temporally

Figure 3. Spatio-temporal block

3.2. Spatio-Temporal Block

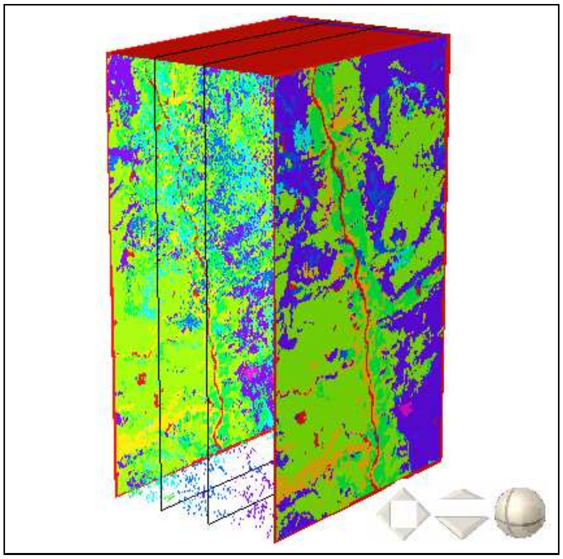
A SELES simulation operates on spatial data generating information about changes through time. This information can be thought of as 3D, having two spatial dimensions and one temporal dimension. By stacking sequential temporal layers one atop the other, the entire set of changes to a single dynamic layer during a simulation can be displayed as a 3D spatio-temporal block (Figure 3(a)). The bottom layer represents the initial state and the top layer represents the situation at the end of the simulation. The exposed sides of the cube represent changes through time at the boundaries of the landscape. A variety of representations and interactions with the spatially arranged temporal data now become possible.

The individual events responsible for the changes in the landscape over time may be rendered by converting their time of occurrence to an appropriate position along the temporal axis. This *sparse* structure (Figure 3(b)) illustrates the relatedness of densely packed event sequences such as fires and logging events.

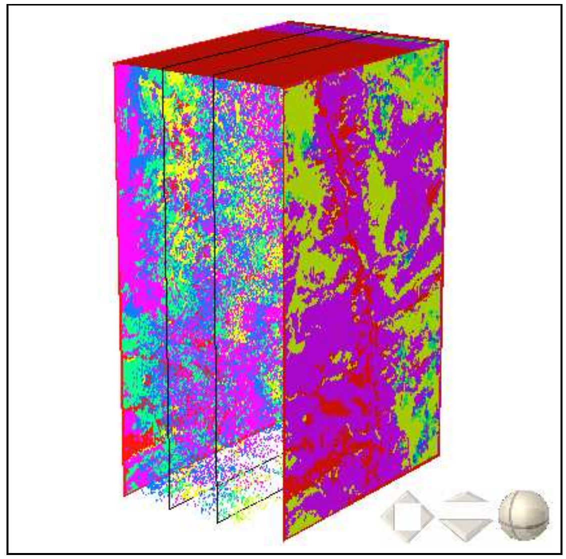
In Tardis, for every dynamic layer with events stored in the database, the data exists to create a spatio-temporal block. These blocks are distinct in that they each have their own start state and set of state changes. They are also related in that they are part of a single simulation run. Once the database for a particular simulation is read into Tardis, any of the static layers can be displayed as single layered rasters and any of the dynamic layers can be displayed as a spatio-temporal cube. Figure 4 shows the spatio-temporal blocks for two dynamic layers for which SELES has generated record files: the overstory seral stage and the understory seral stage. In Figures 4(a) and 4(b) the spatio-tmeporal block is open on one side, showing the intial and final states of the simulation for the two dynamic layers; overstory and understory. In Figures 4(c) and 4(d) the initial state is not displayed giving a better view of the sparse structure.

3.3. Interacting with Spatio-Temporal Block

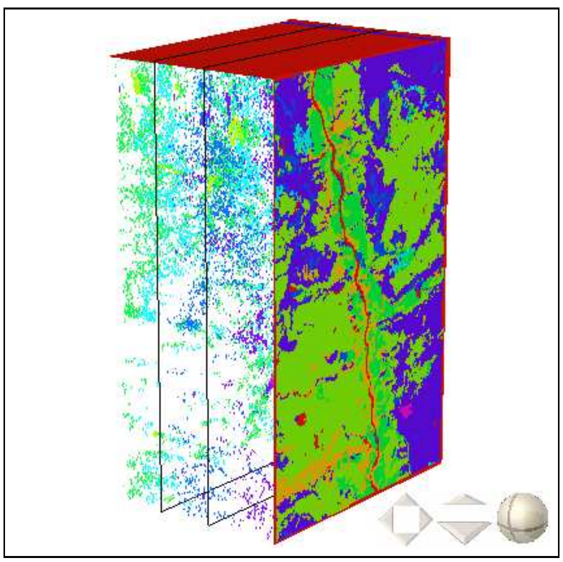
Spatial and spatio-temporal sampling planes (Figure 5) may be interactively moved through the data, picking up as a texture the contents of the spatio-temporal cells that they intersect. One of these planes is spatial and displays the state of the landscape at a given point in time. Two of these planes are *spatio-temporal transects* or a line across the landscape as it changes over time. Moving the spatial layer along the time axis allows reversible replay of the



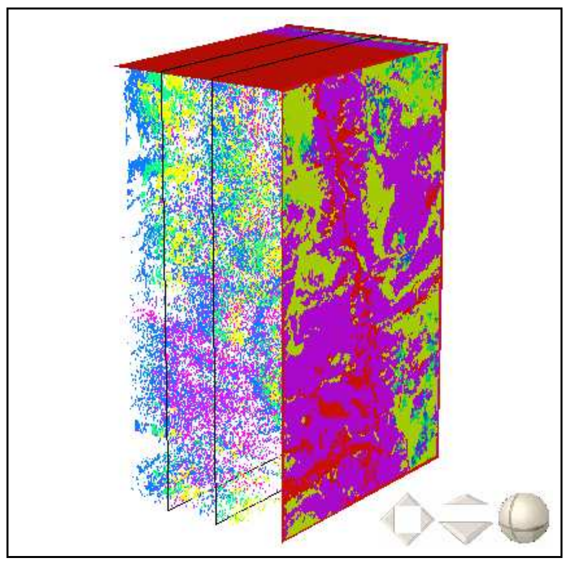
(a) The initial and final states for the dynamic layer: overstory seral stage



(b) The initial and final states for the dynamic layer: understory seral stage



(c) The point cloud of the sparse structure for the overstory seral stage



(d) The point cloud of the sparse structure for the understory seral stage

Figure 4. The spatio-temporal block for two dynamic layers of a single simulation run

simulation. Moving a spatio-temporal transect shows the changes across time. The interaction of the planes allows visual exploration of the relationships across space and over time.

A spatial landscape layer at any point in time, or a spatio-temporal transect is a two-dimensional representation and as such may be examined in increased detail with the distortion browsing tool 3DPS,[13] giving in-context access to the maximum resolution of the data available in the simulation record (Figure 2).

As it is often of particular interest to examine the changes from one time unit to the next, we have developed a browsing method that allows one the move through the spatio-temporal cube in a similar manner to which one

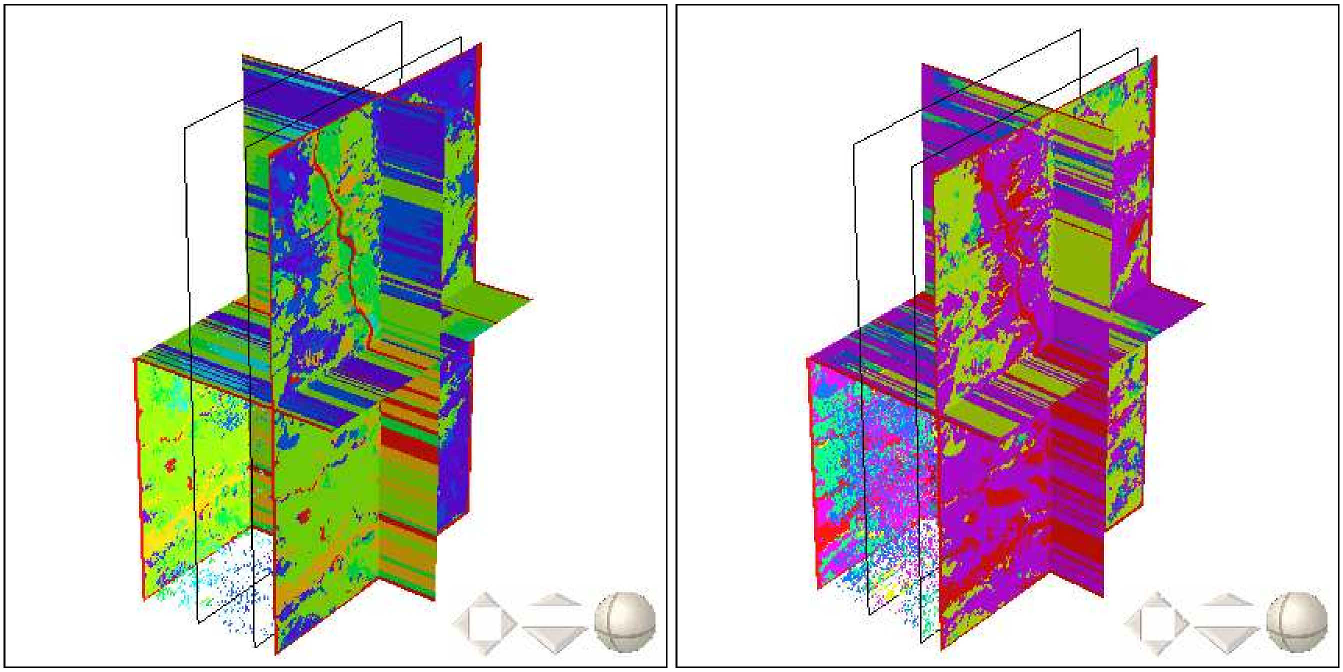


Figure 5. Moving the sampling planes in the spatio-temporal block

would turn pages in a book. The block opens, displaying two adjacent temporal layers (of some arbitrary temporal duration, and one can interactively move forward or backwards in time. This technique not only provides an intuitive approach to visualizing simulation results and comparing successive states of the landscape, but it also takes advantage of efficient graphics techniques for manipulating this vast information space interactively through use of textures. We have illustrated the *book* opening along the temporal axis. It can also open across either of the spatial axes.

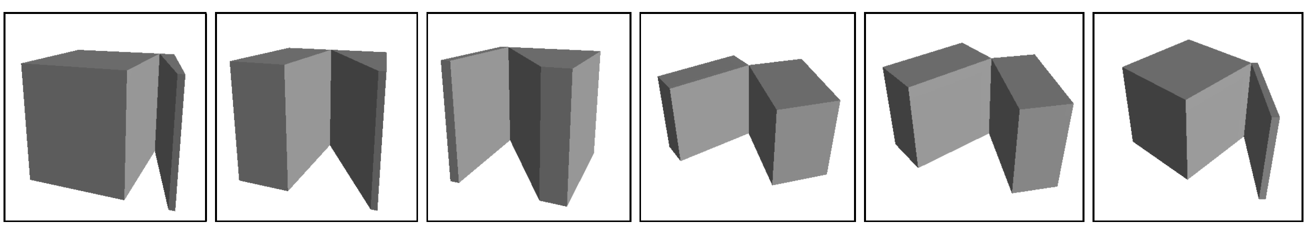


Figure 6. Browsing possibilities with the book: The three images on the left show *softcover* variations, the three images on the right show *hardcover* variations

At this point we are looking at two variations of the book metaphor. Figure 6 (left three images) show one variation which we think of as the *softcover* style. The compression required to create the space for the opened pages is applied to *front* or open side of the book. Figure 6 (right three images) shows an alternate or *hardcover* opening style. Here as the book opens the *spine* or far side of the cube bends allowing the opening to happen without compressing the front sections. Figure 7 shows the softcover version with texture applied.

3.4. Varying Temporal Scale

In addition, local control of the temporal scale has been provided in the spatio-temporal cube. As events such as fires and forest succession occur in landscape layers, they have temporal dependencies and interrelationships. The time-scale over which these changes occur may vary widely depending on the type of event. A fire may spread across a patch of forest in a few hours or days, whereas the encroachment of one species of vegetation on the territory of another may take several years or decades to complete. The ability to interactively control the scale of the temporal axis, both locally and globally, while maintaining both temporal and spatial context is essential for the examination

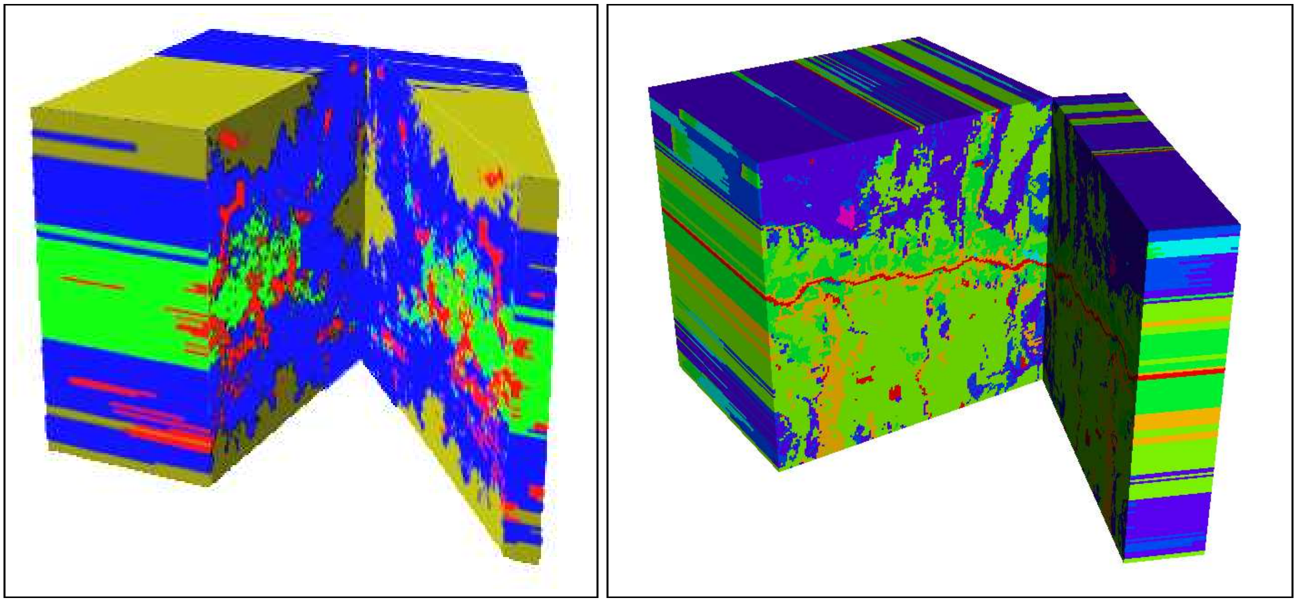
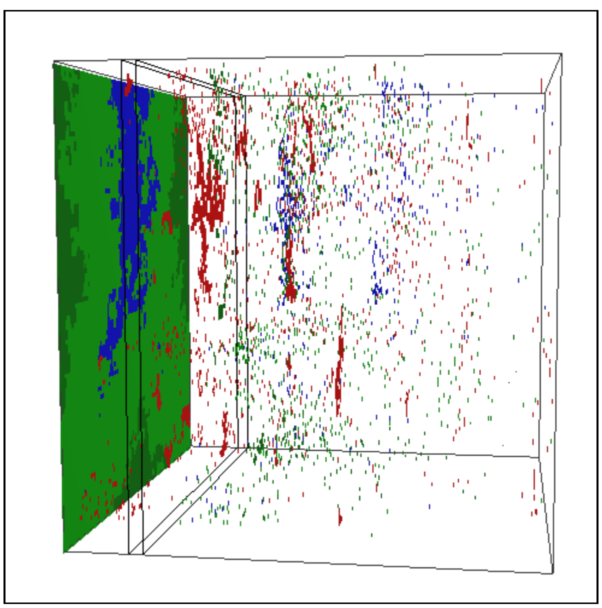
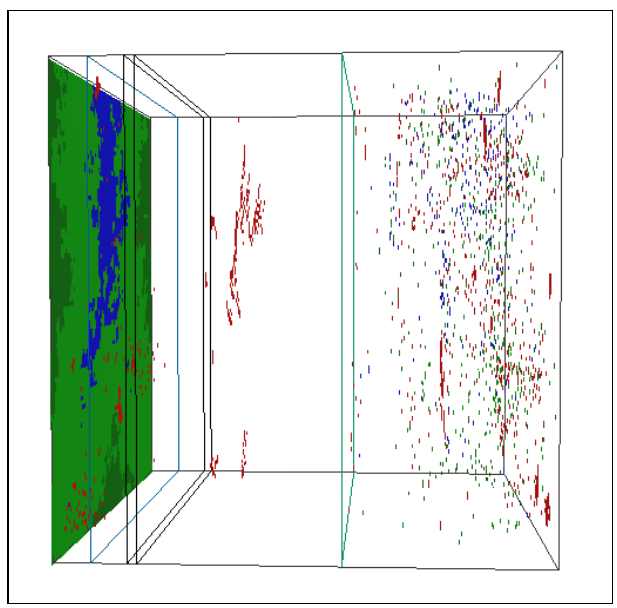


Figure 7. Opening the *book* shows two adjacent pages

of these phenomena. This ability to adjust local and global scaling in the display of changing information over time means that processes that proceed at vastly different rates can be compared within the same visualization. This provides a means by which the nature of the spread of a fire over a landscape (a process that may be days or hours in duration) can be examined at the same time as the contagion of a landscape with an invading species (a process that may be months or years in duration).



(a) The sparse structure with a spatial layer containing a large fire selected. Red indicates the absence of land coverage, therefore fires appear as large irregular red regions



(b) Stretching time for the chosen layer. As this fire occurred over only a few days it is still relatively flat on this scale

Figure 8. Adjusting the temporal scale

Consequently we introduce a one dimensional orthogonal stretch along the temporal axis. The user chooses a time interval to expand. As the chosen time interval expands the remaining sections compress as necessary. The effect is that of an elastic time axis. The actual adjustment process involves expanding the chosen interval and moving the adjoining intervals correspondingly, then the entire layout is re-scaled to fit the display space. The basic idea behind the geometric adjustment is similar to that used in.[17,18]

Figures 8(a) and 8(b) illustrate this in sequence. First a time interval is chosen (Figure 8(a)). Here we have selected a year containing a large fire (the large grouping of red features). The fire appears flat when the scale is in years. Then this in interval is stretched to display time in days (Figures 8(b)). This reveals the cone-shape illustrating the spread of the fire over time. The expanded section of the display provides the additional space required to display more of the detail which exists in the time axis.

3.5. Attribute and Replicate

The attribute and replicate information dimensions in a SELES simulation provide a challenge to the application of visualization techniques. Developing a meaningful method by which the variation in the evolution of one layer over different simulation runs, or simultaneous changes in a different inter-dependent attribute layers can be explored over the evolution of a simulation is a daunting problem. For now we provide a means of tying multiple visualization tools together. Each tool applied to a distinct layer (differentiated by attribute, replicate, or both) but the interaction of the user on any one of the tools controls all in the linked set. By this means the process of exploration and navigation need not be repeated across many layers before detailed examination and comparison can begin.

For purposes of comparison, the spatio-temporal blocks for each recorded dynamic layer can be displayed simultaneously. Any spatial layer from a spatio-temporal block can be selected and displayed individually in the same manner as any of the static layers. These individually displayed layers can be explored separately or in conjunction. Exploring two or more layers in conjunction will automatically provide the same manipulation techniques in all linked layers. For example, if a particular magnification lens is applied to one of the layers it will also be applied to the other linked layers. The lenses for each linked layer will have the same properties such as, type, degree of magnification and precise location. In this manner one can explore the relationships across multiple layers that effect each other, as shown in Figure 4 and 5.

4. CONCLUSION

The concepts in this visualization environment have developed iteratively in conjunction with the development of the SELES simulation engine. Researchers, developing increasingly realistic models with SELES, have provided motivation for support of more complex dynamics. This in turn has driven the need for more flexible visualization tools. We are continuing to investigate the possibilities and new challenges this data presents. For instance, the visualization environment can been used to verify individual aspects of a SELES model during development.

The spatio-temporal block provides high-level access to the simulation data. In exploring the spatio-temporal block, whether by flipping through it as a book or moving the sampling planes, users may select regions or slices that are of particular interest and then move to a more detailed exploration method (e.g. adjusting the local temporal scale, distortion viewing of spatial layers, or selecting sub-regions of the data). This provides a tightly coupled means of performing drill-down operations on the data set while maintaining the contextual situation of the detailed data.

ACKNOWLEDGMENTS

This work was supported by a grant from Forest Renewal B.C. and a postgraduate scholarship from the Natural Sciences and Engineering Research Council of Canada. We also acknowledge resources provided by the Graphics and Multimedia Research Lab at Simon Fraser University and Intel. The authors are grateful for helpful and insightful suggestions from J. Fall, K. Lertzman, T. Poiker and members of the Resource and Environment Management Laboratory.

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