SELES: A Tool for Modelling Spatial Structure and Change

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Bridging the Gap from Conceptual Landscape Models to Computer Simulation

A gap often exists between conceptual models of landscape dynamics derived by ecologists and planners, and the implementation of these models. Modellers may be faced with two choices: program their model directly or parameterize a pre-existing model. Differences between a conceptual model and a program or pre-existing model may be difficult to identify, and may introduce implicit assumptions. Verifying and updating models may require changes at the implementation level, exacerbating these problems. We believe that model construction should be possible without requiring programming, and this has been one of the goals of SELES (Spatially Explicit Landscape Event Simulator), a tool for building and running models of landscape dynamics. We provide a high-level, structured language that frees modellers from programming, allowing them to focus on the underlying model rather than on implementation details. Our language permits clear and explicit specification of processes that are natural or anthropogenic, continuous or periodic, spreading or non-spreading, deterministic or stochastic, or with a fixed or variable time-step. SELES models can incorporate aspects of cellular automata, percolation models, discrete-event simulation, and spatio-temporal Markov chains. Processes modelled using SELES have included forest succession and encroachment, natural disturbances such as fires, insect outbreaks and flooding, and management activities such as timber harvesting and livestock grazing. The declarative nature of the language supports comparison and modification, allows rapid model prototyping, and provides a structured framework to guide model development.

Advantages of using SELES

I. Declarative landscape modelling
- separates model from the program that runs the model
- models are explicit (i.e. no hidden assumptions)
- eases model prototyping, refinement and comparison
- each component of landscape dynamics can be modelled as an independent sub-model

II. Model state is not fixed
- include spatial layers relevant for model – there is no *required* information that must be provided even if not needed.
- incorporate level of detail appropriate for objectives of model – models can be constructed according to *Occam's razor*
- customizable hierarchical dynamic state. Models can specify state information associated with various levels of dynamic organization

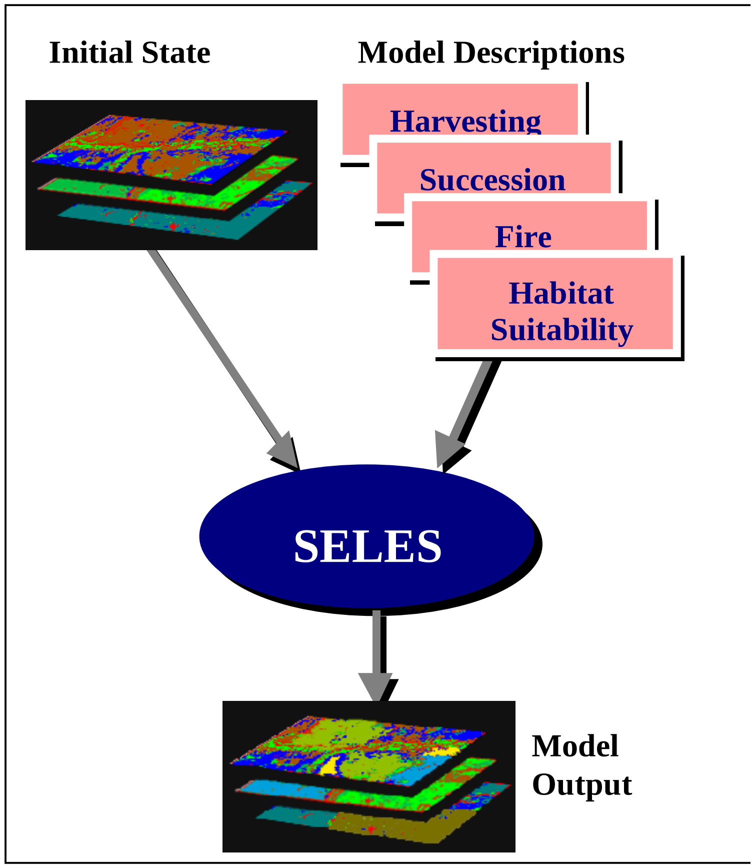
III. Support for a variety of model types
- human and natural
- deterministic and stochastic
- continuous, periodic or episodic
- spreading or non-spreading
- differing temporal scales

These advantages mean that model development can be done efficiently and inexpensively. The modeller determines the data and parameter requirements, not the modelling system. SELES is powerful enough to handle complex models, as prototypes are refined. The Windows interface is simple to use, and the underlying simulation engine has been optimized to handle efficient processing of spatially and temporally extensive models.

SELES is useful as a research tool as well as a decision-support tool for management, and for problems related to both conservation and resource management.

How are SELES models constructed?

SELES models are specified in a high-level, structured modelling language that frees landscape modellers from programming, allowing them to focus on the underlying model rather than on the implementation details. The declarative nature of our language permits a clear representation of the underlying model, which, in turn, yields models that are more easily verified, compared, modified, and reused. The SELES simulation engine executes the model, converting the high-level specification into a computer simulation of landscape change. SELES also provides a structured framework that facilitates rapid model prototyping and guides the development of a broad class of spatial landscape models.



SELES models consist of two components:

(i) A set of spatial raster layers and global variables specify the landscape state. These include information that may change during a simulation (e.g., *CanopyDensity* and *ForestAge*), and information that is static (e.g., *Slope* and *Elevation*). The raster layers can come from digital maps from a geographic information system (GIS), a classified digital image from remote sensing, or a synthetic map from one of the SELES static spatial landscape models. A variety of raster formats are supported (e.g. GRASS, ERDAS, and ARC ASCII).

(ii) A set of model descriptions that define the model behaviour. Each dynamic process is specified as a *landscape event*, which is a generic framework for describing the characteristics of an agent of change. 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). A landscape event may have global behaviour (e.g., the interval between insect infestations on the landscape might define the global frequency of an *Outbreak* event); local behaviour (e.g., the likelihood of infestations in forest stands of different ages might define the spatial distribution of *Outbreaks*); and a set of effects or state changes (e.g., in cells where an *Outbreak* occurred, the layer *CanopyDensity* may be reduced and the layer *FuelLoad* may be increased).

Feedback mechanisms between different processes are accomplished through state transitions on one or more raster layers, or global variables, with no direct inter-event communication. This independence of sub-models facilitates model verification and experimentation since sub-models can be selectively included or excluded from a particular scenario.

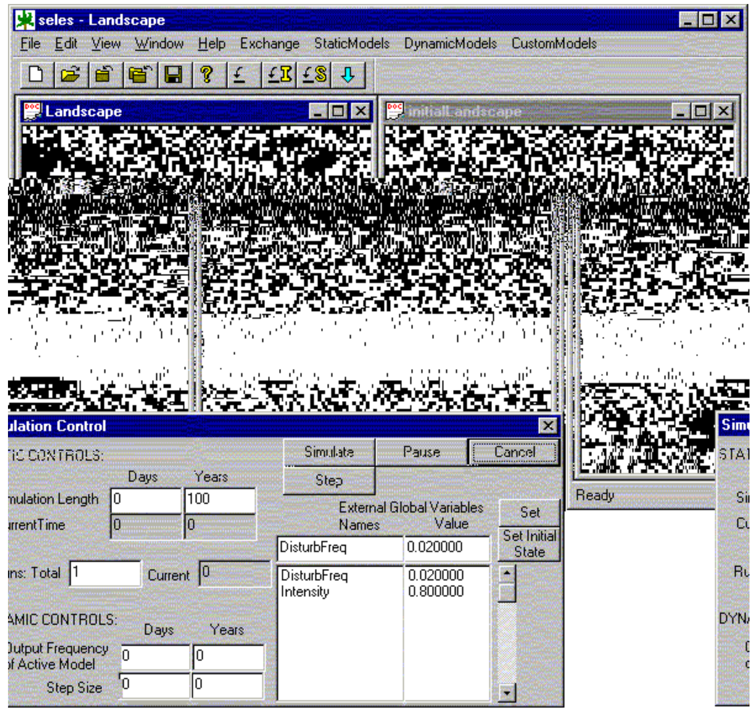
Static models, such as a habitat suitability map, can also be specified in SELES. These can be linked with a dynamic model to produce a sequence of maps that show changes over time. As an example, this feature allows exploration of potential impacts of development according to a land use plan on wildlife habitat.

Output from simulations can include a time series of maps for selected layers, or record files that track use-defined quantities through the simulation. Map outputs can be loaded into a GIS for post-simulation analysis, while record files can easily be input into database or spreadsheet programs.

The following pages provide some examples of models that have been constructed using SELES, and give an idea of the range of possible modelling tasks that might be addressed using this tool.

I. Landscape ecology theory

Spatial simulation models have often been used in landscape ecology to explore the relationship between landscape pattern and disturbance dynamics. To facilitate ease of analysis and interpretation, these types of models typically involve a simple spatial plane (e.g. a homogeneous or two-state univariate landscape), and incorporate a minimum number of processes and/or relationships. For example, disturbance has been modelled as a random event that occurs with a given frequency (probability of initiating) and intensity (probability of spreading to neighbouring cells). The following illustrates a simple example of a SELES model that replicates the experiment described in Turner *et al.* (1989). This scenario has a single layer that we call *Landscape*, and one process that we call *Disturbance*. The landscape has two states that differentiate sites that are and are not prone to the disturbance. The behaviour of *Disturbance* is controlled by two global variables: *DisturbFreq* specifies the proportion of prone cells in which the process will initiate, while *Intensity* specifies the probability of spread from an affected cell to an adjacent prone neighbour. The adjacent figure shows sample output from this model. The initial state of the landscape is to the right of the final state.



II. Fire ecology

Two recent studies used SELES to examine variability in fire regimes, and the degree of uncertainty in fire frequency estimates. Lertzman *et al.* (1998) built a stochastic model of a high-severity fire regime to generate synthetic landscape age-structure maps; whereas Fall (1998) built a model of a low-severity, stand maintaining fire regime to generate synthetic fire-interval data sets. The primary state information is a time-since-fire layer that records the time since the last fire, while the primary event is fire. Probability distributions for both the return time of fire to the landscape and the extent of each fire were derived empirically from fire history studies.

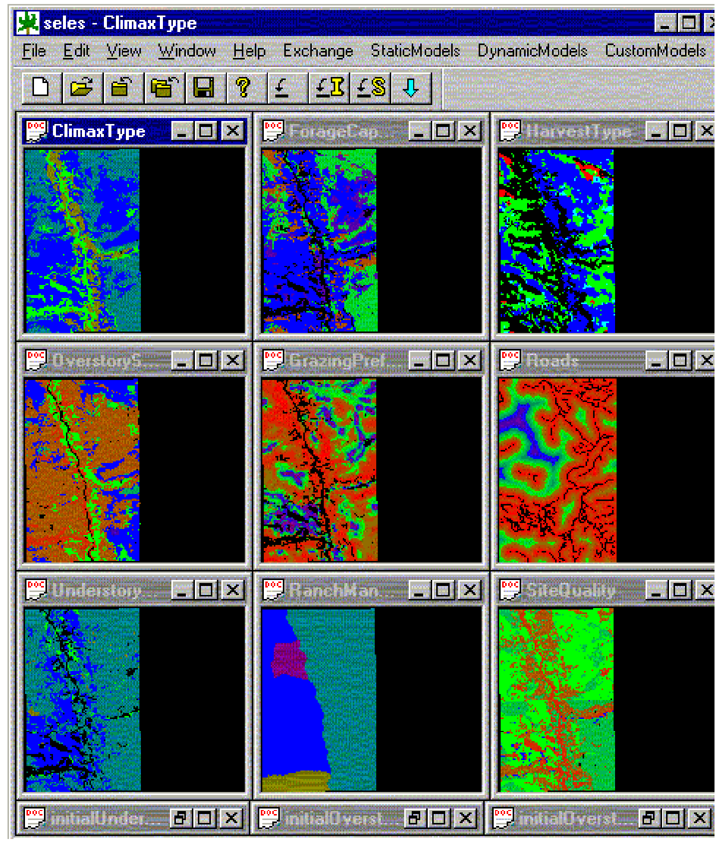
Although these models form a very simplified representation of fire occurrence over time, the purpose was not to create a predictive tool, but rather to generate statistically similar replicates of the empirical fire histories from the modelled systems. These "synthetic fire history" replicates allowed the authors to gain some insight into how variability in a process (the occurrence of fire in this case) translates into variability in landscape pattern. They were also able to delineate a "range of natural variability" (Swanson *et al.*, 1993) for the fire regimes, and draw a distinction between the "fire regime" and the particular sequence of historical fires. In addition, Lertzman *et al.* (1998) use the synthetic time-since-fire maps to estimate the fire frequency for each synthetic replicate in a manner identical to the methods used in empirical studies of fire history in high-severity fire regimes (see Johnson and Gutsell, 1994).

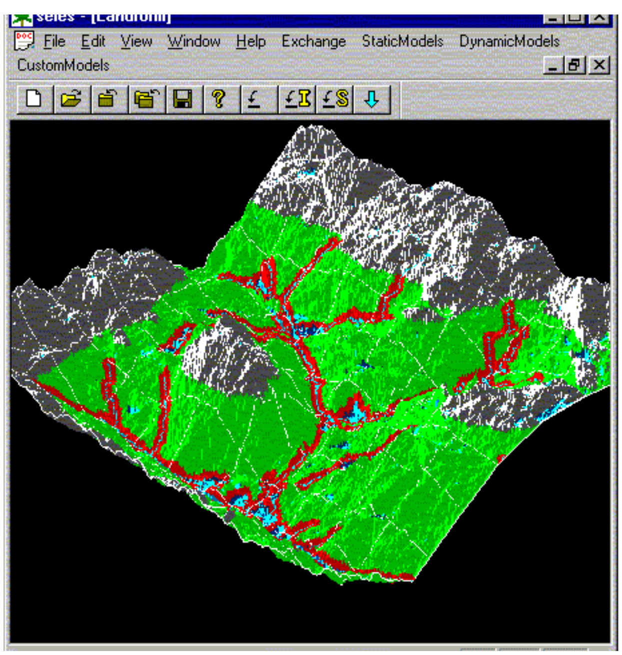
Similarly, Fall (1998) used the synthetic fire interval data sets to reconstruct the fire frequency via methods commonly employed in low-severity fire regimes (see Agee, 1993). The difference between these fire frequency estimates and the true fire frequency for the model provided a quantitative measure of the magnitude of bias and uncertainty associated with empirical fire frequency estimates. The authors found that it is possible to estimate historical fire frequency with some accuracy and to derive a formal confidence interval for that estimate. However, they also showed that the high degree of variability apparent in these systems, and the temporal and spatial scaling inherent in fire history data sets, impede our ability to make some of the inferences commonly drawn from fire history studies. They were also able to identify and make recommendations about several key aspects of fire history sampling design that can minimize the bias and uncertainty in an empirical study. SELES proved to be a powerful tool for this type of theoretical development and methods testing.

III. Grassland biodiversity

In collaboration with the British Columbia Ministry of Forests, we developed a model for assessing impacts on the structure and pattern of grasslands due to interactions between timber harvesting, cattle grazing and natural disturbance. The study area is in the dry interior of British Columbia, and consists of mixed grasslands and forests which may have an herb understory. Of particular concern is the encroachment of forest into grassland areas that is occurring as a result of fire suppression. The model has several landscape events and spatial layers, some of which are shown in the adjacent figure. From left to right and top to bottom, the layers represent overstory seral stage, cattle forage capability, permitted harvest type, understory seral stage, cattle grazing preference, distance to nearest road, canopy closure percentage, ranch management type and site quality.

The landscape events *UnderstorySuccession* and *OverstorySuccession* specify spatio-temporal Markov chains for changes in seral stage to the vegetation layers. *Age* and *CanopyClosure* maps are also updated by these events. The landscape event *Fire* is a process-based, stochastic fire occurrence model (similar to Li et al., 1997). The landscape events *Grazing* and *TimberHarvesting* both model management activities. Grazing follows maps that specify ranch management strategies and pasture locations. Global variables control the amount of grazing allocated to each ranch. There are three types of *TimberHarvesting*: clear cutting, partial cutting for forestry objectives and partial cutting for range objectives. *HarvestTreatment* maps specify the overlapping spatial areas in which each type of cutting is permitted. Global variables are used to control the number of cut blocks harvested per year.





IV. Endangered species risk assessments

In collaboration with a researcher in the Centre for Applied Conservation Biology at the University of British Columbia, we developed a spatial model to assess the risk of local extinction for endangered tailed frogs under different management regimes. Tailed frogs inhabit the upper reaches of fast mountain streams, and are sensitive to changes in their habitat. We have spatially embedded a matrix population model (Caswell, 1989) of frog life stages (egg, tadpole, juvenile, young adult and adult), within a dynamic landscape that includes debris flows, logging and fires. We are exploring the effects of increases in disturbance rates caused by development on the probability of population persistence under different assumptions of fecundity, survival and dispersal capabilities. The figure shows the elevation model of the study area overlaid by the landform map, showing water (streams and lakes), riparian areas, upland forest and alpine areas.

V. Integrating Natural Disturbance and Spatial Timber Supply Modelling

The goals of the Enhanced Forestry Management Pilot Project (EFMPP) in the Invermere Forest District

VI. Land Use Planning

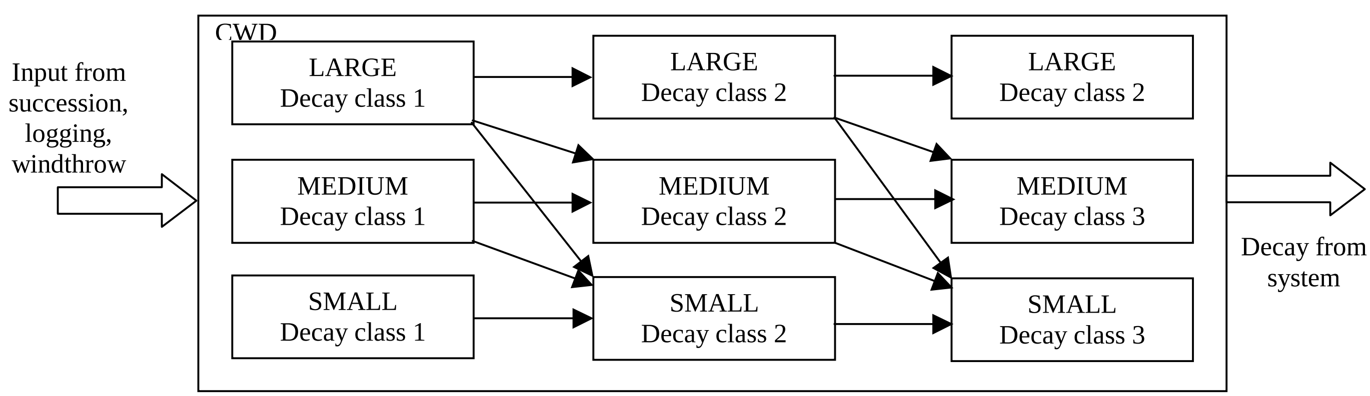
A number of processes have been initiated in the province of British Columbia, Canada to address the need to balance ecological, social and economic interests in landscape management. One process, called a Land and Resource Management Plan (LRMP), has been initiated in the Iskut-Stikine region in northwestern B.C., covering an area of approximately 5 million hectares. This relatively wild area contains significant mineral resources and some timber while supporting valuable habitat for species sensitive to development (e.g., grizzly bear, caribou) and the lifestyles that depend on wilderness. In collaboration with researchers at the provincial forest service, we constructed a SELES scenario to explore the interactions between wildfire and timber harvesting. Our goal was to support this planning process by developing a tool to facilitate understanding of the ecological dynamics of this large landscape using a spatial simulation model.

According to this goal, our main focus was the dominant and secondary forest species and age across the landscape, using a spatial resolution (cell size) of 25 ha. We needed to develop sub-models for forest succession, fires and logging. In a series of short workshops, we met with experts on local ecology, natural disturbance and management. The succession model was based on a literature review and expert advice, and it responds to landform, stand-initiating disturbance type, and biogeoclimatic zone. The logging model was based on discussions with a local planner, and is primarily driven by the volume of wood harvested annually. This stochastic model produces harvest patterns consistent with recent harvesting activity, where the precise location of individual cut-blocks is controlled by a number of constraints (e.g. a stand cannot be harvested adjacent to a stand under 15 years old). Finally, the fire model combines statistical and empirical models of fire frequency and size with more process-based models of ignition and spread. Due to the limited duration of the fire history record, it does not adequately account for the effect of catastrophic fires, which can have a profound influence on long-term forest patterns (Foster et al. 1998). We combined the empirical data with a statistical component derived from a provincial-scale analysis by the B.C. forest service of fire return intervals and sizes by “natural disturbance type” (NDT), which are zones with similar fire regimes. The process-based components were taken from expert opinions of local fire behaviour.

VII. Coarse woody debris dynamics

The main purpose of the Tofino/Tranquil Creeks Landscape Model is to explore changes in coarse woody debris (CWD) over time due to a variety of natural processes and management actions, and the resulting impacts on the habitat for CWD dependent species. The model is presently in a prototype stage. Initial sub-models for CWD decomposition and forest succession have been built. Sub-models for logging, salvage and windthrow as well as habitat suitability indices will be added to the prototype.

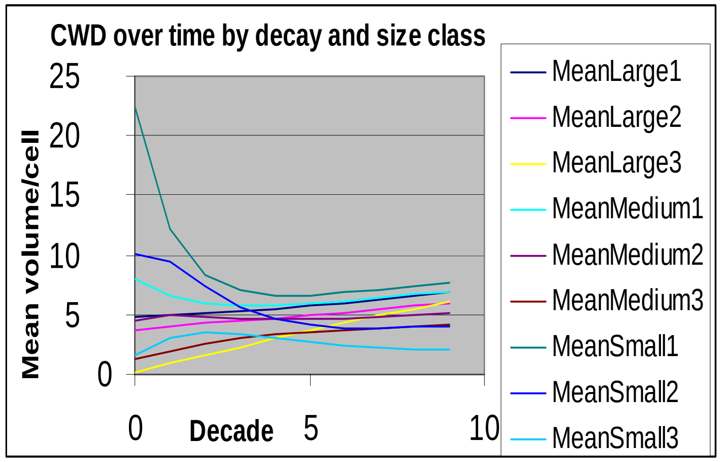
The volume of CWD per grid cell is tracked according to three size classes (large, medium, small), three decay classes (sound, partially decomposed, mostly decomposed) and two species classes (Cedar and non-Cedar). Decomposition is modelled annually. Each year, an overall proportion of CWD decays out of the system at rates obtained from the literature. The following is a conceptual diagram of the decomposition sub-model for non-cedar species. Decomposition models the changes that occur within the CWD state, and loss out of the system due to decay.



Inputs to the CWD system come from the living forest, and are modelled using other sub-components, including succession, logging and windthrow. Salvage is an additional, anthropogenic cause of CWD loss.

Succession tracks the age and volume of wood in each cell of the landscape, using parameters derived from (Wells, 1996; Wells and Trofymow, 1997).

The adjacent graph shows a sample output from one 100-year simulation, where the volume of CWD in (m^3) in each size/decay class was output every 10 years, and where the suffixes 1, 2 and 3 indicate decay classes (sound, partially decomposed and decomposed).

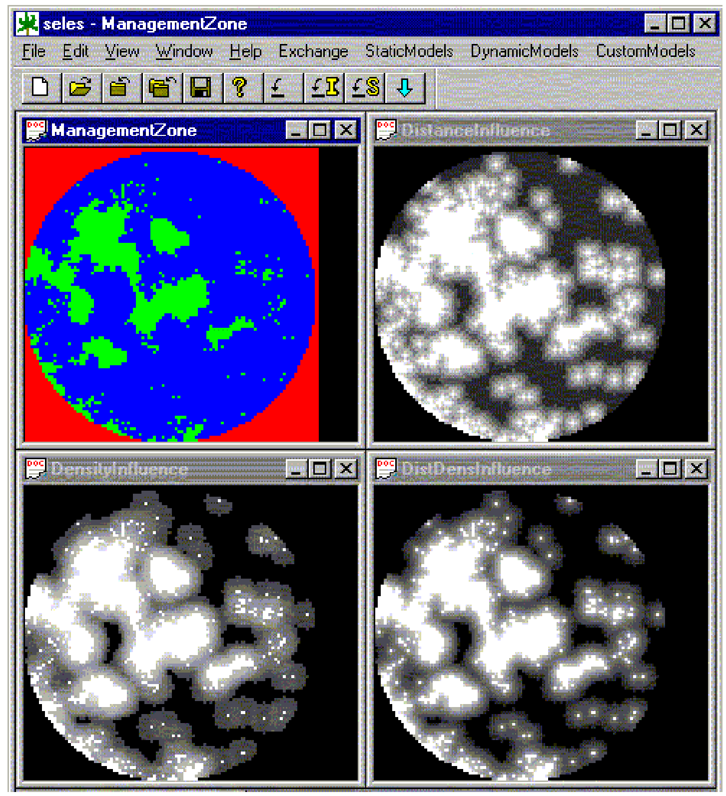


VIII. Assessing alternative harvesting techniques

Forest management in some areas (e.g. public land in coastal British Columbia) is moving away from clearcut harvesting to *variable retention* (VR) systems that leave patches, individual trees and biological legacies (e.g. snags, coarse woody debris). We developed an interacting set of SELES models that generates VR cutting patterns, and produces a set of spatial statistics on these patterns. A variety of constraints can be specified on the patterns to generate, including the percentage of forest to retain, and the size and spatial distributions of patches. Given a generated or input VR cutting pattern, a number of spatial and summary statistics are computed, including:

- the distance of each cell from an uncut cell.
- the proportion of uncut cells within a distance of one tree height from each cell in the landscape
- an index that combines the influence of both the density and distance of uncut trees, where influence declines with distance. Thus, a cell with a few close uncut neighbours may have the same value as a cell with many further uncut neighbours.

These influences can be computed for harvested or unharvested cells. The former might be useful to check if a cutting pattern meets regulatory requirements, or to estimate the shading by retained trees to determine possible growth impacts. The latter might be used to estimate ecological effects such as the amount of remaining interior forest. The current model implements only a fraction of the possible directions that might be followed for a variable retention generator and analyzer, and many extensions are possible.



The above figure shows a sample pattern generated with 20% retention (upper left image). Retained areas are shown in green (lighter), cut areas in blue, and areas outside the management zone (the matrix) in red (dark). The distance influence statistic is on the upper right, the density influence is on the bottom left, and the combined index is on the bottom right.

Other projects have included sub-models for river flooding, insect outbreaks (mountain pine beetle, hemlock looper and spruce budworm), forest diseases (root rot), potential stream flows (e.g. for predicting the location of fish bearing streams), animal dispersal through corridors connecting habitat patches, and changes to mountain caribou habitat suitability over time.

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