Computers and Electronics in Agriculture
27 (2000) 227–242

Computers
and electronics
in agriculture

www.elsevier.com/locate/compag

TELSA: the Tool for Exploratory Landscape Scenario Analyses

W.A. Kurz [a,*,1], S.J. Beukema [a], W. Klenner [b],
J.A. Greenough [a], D.C.E. Robinson [a], A.D. Sharpe [c],
T.M. Webb [d]

[a] *ESSA Technologies Ltd., 1765 West 8th Avenue, Vancouver, BC V6J 5C6, Canada*
[b] *BC Ministry of Forests, 515 Columbia Street, Kamloops, BC V2C 2T7, Canada*
[c] *Nobility Environmental Software Inc., 1765 West 8th Avenue, Vancouver, BC V6J 5C6, Canada*
[d] *Lookfar Solutions Inc., PO Box 811, Tofino, BC VOR 2ZO Canada*

Abstract

The Tool for Exploratory Landscape Scenario Analyses (TELSA) is a spatially explicit model of vegetation succession, natural disturbances, and forest management activities. TELSA is a strategic planning tool designed to support adaptive management by projecting the consequences of alternative scenarios at the scale of landscape units (i.e. 10 000–200 000 ha) over time frames of decades to centuries. Scenario combine user-specified assumptions about natural disturbances and management activities, and can include 'no action' or historic disturbance scenarios. The simulation model is at the core of a set of tools that also includes a geographic information system, databases, and several user interfaces for scenario definition, data analysis, spatial analysis and the display of results. Spatial characteristics of landscapes, such as fragmentation, patch-size distribution and connectivity are largely determined by management actions and their interaction with natural disturbances. The TELSA toolbox includes a tool for the automated design of management units (i.e. harvest cutblocks), based on user-defined criteria and scenario objectives. TELSA easily evaluates strategic alternatives regarding the size range of management units, their spatial aggregation, the use of adjacency constraints, and the application of different silvicultural systems.

---

* Corresponding author. Tel.: + 1-604-7332996; fax: + 1-604-7334657.
E-mail address: wkurz@essa.com (W.A. Kurz)

[1] Presented at: 'The Application of Scientific Knowledge to Decision making in Managing Forest Ecosystems', May 3-7, 1999, Asheville, NC, USA.

PII: S0168-1699(00)00109-5

TELSA represents vegetation succession as changes in species composition and structural stages of stands, thus projecting landscape conditions in a format that is relevant for the analysis of wildlife habitat and many other resource indicators. Succession pathway diagrams define the transition times between successional classes and, for each class, the probabilities and impacts of disturbance by insects, fire or other agents. These diagrams also define the impacts of management actions on stand structure and vegetation composition. Diagrams can be defined for forests and other vegetation types such as shrub and rangelands. Wildfires and other natural disturbance events that affect vegetation dynamics are inherently unpredictable. The model can use multiple stochastic simulations of each scenario to provide estimates of the mean, range and variability of selected performance indicators.

Keywords: Landscape modeling; Natural disturbances; Vegetation succession; Forest dynamics; Adaptive management

1. Introduction

Adaptive management of terrestrial ecosystems requires that the outcomes of proposed management actions be assessed with regard to their ability to move the systems toward desired future conditions. These conditions can be described by various indicators, such as the distribution of seral stages, the amount of old-growth habitat, the size distribution of forest patches, as well as traditional timber flow projections. Changes in the structure and composition of forested landscapes result from the interaction of forest growth and succession, natural disturbances, and forest management actions. Resource managers and planners therefore require methods for assessing the combined effects of succession, disturbances, and management on future landscape conditions. Many of the existing spatially-explicit tools for simulating landscape dynamics focus either on succession and natural disturbances or on the impacts of forest management (Gustafson, 1996). This paper describes a spatially explicit modeling framework that represents the interactions of forest growth, natural disturbances and forest management, and projects the effects of these interactions on indicators of timber resources, wildlife habitat and other landscape characteristics. This modeling framework is designed to assist stakeholder groups and planners in the assessment of alternative management options at the strategic level. For example, the Landscape Unit Planning Guide of British Columbia (BC Ministry of Forests and Ministry of Environment, Lands and Parks, 1999) defines landscape unit characteristics in terms of spatial and non-spatial indicators. The model assists in the evaluation of the current landscape condition and answers questions about the range of future landscape conditions under various alternative management (or no management) scenarios.

2. Model description

2.1. Overview

TELSA, the Tool for Exploratory Landscape Scenario Analyses, is a spatially-explicit model of vegetation succession, natural disturbances, and forest management activities. It is designed as a strategic planning tool that operates on areas of 10 000 to over 200 000 ha, depending on the questions being explored and the available computer resources. TELSA includes several components, each of which interacts with a central MICROSOFT ACCESS™ database (Fig. 1). All TELSA components run on high-end personal computers with Windows NT 4.0, Windows 95 or Windows 98 operating systems.

The use of TELSA in strategic planning involves several steps:

1. Initial setup of the spatial information and specification of model assumptions about vegetation succession, natural disturbances, and management.
2. Preparation of information about the impacts of forest growth, natural disturbances, and management actions on the vegetation in the landscape.
3. Definition of other scenario assumptions.
4. Simulation of the landscape dynamics.
5. Spatial analysis of the resulting maps.
6. Review and analysis of all results using graphs, tables, and maps.

Groups of these steps can be repeated iteratively to refine various scenario alternatives. Each of these steps will be described in more detail in the following sections.

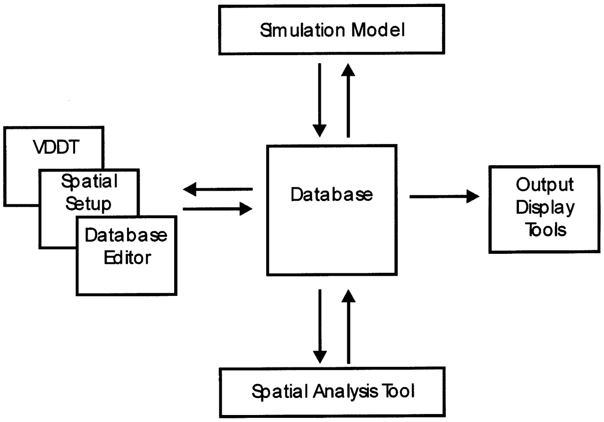

Fig. 1. The main components of the TELSA tool box and their relationships. The central database stores all information about the simulated landscape, the assumptions incorporated in each simulation, and the model results. Various tools facilitate the input of user assumptions, the preparation of spatial input files, and the analysis and display of model results. VDDT, the Vegetation Dynamics Development Tool, is described further in the text.

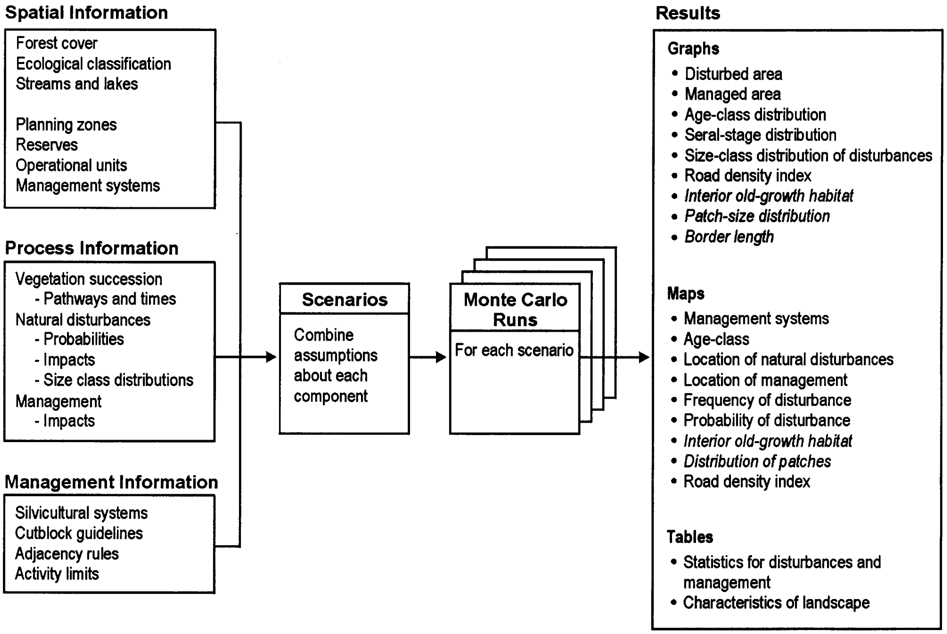

Fig. 2. TELSA's main input requirements and the output generated by the model. Output indicators in italics require the use of TELSA's spatial analysis tool to process simulation results.

TELSA requires three categories of input: spatial information, process information, and management information (Fig. 2). It was designed to operate in large landscapes containing thousands of polygons. The polygon boundaries delineating different vegetation types and forest stands must be provided as a map file. For each polygon, vegetation cover and, where applicable, age are required attributes. A map of streams, wetlands and lakes is required. An ecological classification provided either as map or as polygon attributes is required if the ecological strata are used to determine vegetation dynamics. For example, applications of TELSA in British Columbia stratify the landscape into biogeoclimatic variants (Pojar et al., 1987), while applications in the US are based on potential vegetation types (Quigley and Arbelbide, 1997).

Planning zones are areas within the landscape for which management rules are defined. Riparian reserves or buffers, parks, old-growth management areas, wildlife management zones, or community watersheds can all be delineated and used to modify or exclude management activities. Operational units can be defined to sequence and distribute management actions in the landscape. As discussed in more detail below, management systems are assigned to ecological strata and planning zones.

Process information required by TELSA describes the effects of succession, disturbances and management actions on vegetation characteristics, as described in more detail below.

Management information contains a set of rules that describe, for each planning zone, the various management systems that may be used in the scenarios, and the size range of management units (e.g. cutblocks) that will be evaluated. The management information also includes adjacency rules, activity limits and various other rules that can be used in the scenarios. Management systems define the sequence of silvicultural activities in a stand, the range of stand ages in which the activities occur, and the size range of management units in which the activities will be applied. For example, users could define management systems that include site preparation, planting, stand tending and repeated partial cutting entries at 40-year intervals. A second system could be based on natural regeneration and large clearcuts. In some of our case study applications dozens of management systems have been defined and applied to the various ecological strata.

2.2. Initial setup

The purpose of the initial setup phase is to pre-process some of the spatial information used by the simulation model. The two major factors that determine landscape characteristics, forest management and natural disturbances, require different representations of space in the model. Natural disturbance events occur in a wide range of sizes, and can affect only parts of a stand or cross stand boundaries, ecological strata and planning zone boundaries. Thus, disturbances are represented in the model using the smallest spatially explicit spatial entities, which we call simulation polygons, and a single disturbance can affect from one to many hundreds of simulation polygons. Conversely, management actions are applied to areas with similar ecological characteristics within defined boundaries and of given sizes. Management actions are represented using spatial entities consisting of one or more simulation polygons. We call these larger spatial entitles management units. Both simulation polygons and management units are created through an automated process that incorporates some basic spatial information about the study area and various user-defined assumptions.

The first step in this automated process is the creation of simulation polygons. The basic input map identifies the forest cover polygons that are delineated through air photo interpretation and which represent areas of similar age, tree species composition and other vegetation characteristics (Fig. 3). These polygons are often much larger than the areas that would be affected by a single management action or by some natural disturbances. Moreover, these polygons can cross boundaries relevant to management decisions, e.g. riparian buffers or other planning zones. Thus forest cover polygons are first subdivided by intersecting their boundaries with the boundaries of user-defined planning zones such as riparian reserves, riparian management zones, community watersheds, or other special management areas.

Many of the resulting polygons are still too large to represent some natural disturbances. The polygons are therefore further subdivided using a Voronoi tessellation (Okabe et al., 1992). The algorithm used in a Voronoi tessellation generates a grid of points and draws lines that are equidistant to adjacent points. The resulting network of lines intersects with the existing polygon boundaries to

Fig. 3. An example of the simulation polygons created through the overlay of forest cover polygons (heavy lines) and other planning zone boundaries (riparian reserves — dark shading, and riparian buffers — hatched), followed by a Voronoi tessellation (light lines). Simulation polygons are created from the intersection of all boundaries. Note that slivers less than 1 ha (user-defined) created by the Voronoi tessellation have been recombined with the adjacent polygon with similar characteristics. The tessellation also does not affect those polygons that initially are less than 2 ha (user-defined). This figure is only a small excerpt from a much larger landscape.

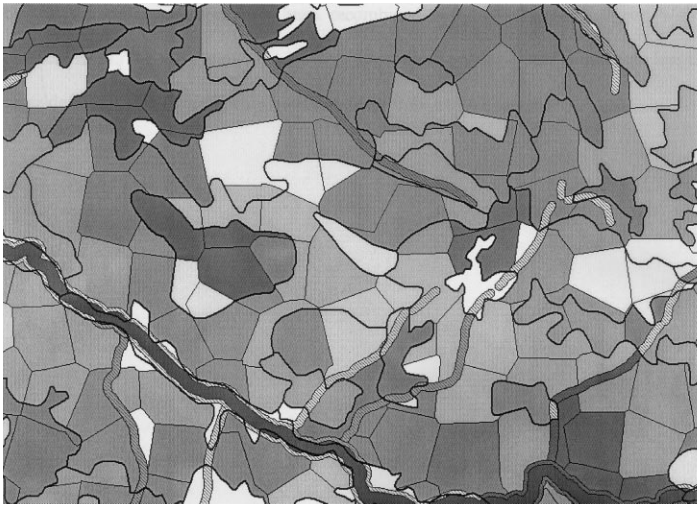

Fig. 4. The landscape from Fig. 3 after simulation polygons have been combined into management units based on user-defined criteria such as cover type and age. Different shades identify separate management units. The target size range of these is defined by the user. Note that small linear features, such as riparian buffers are maintained as separate management units.

define the boundaries of the simulation polygons (Fig. 3). With the tool developed for this task, users can control the point spacing in the x and the y directions as well as the variance used in the placement of points. For example, specifying a 200×200 m grid with no variance would yield square polygons of 4 ha where no other boundaries are intersected. Increasing the variance in point placement will result in irregularly shaped polygons. Where tessellation lines intersect with existing polygon boundaries, smaller polygon sizes will result. The user can control the minimum size of forest cover polygons below which no further subdivision will occur, as well as the minimum size of slivers that will be tolerated during the tessellation. To reduce the number of polygons in the database, the algorithm does not tessellate lakes and other non-vegetated parts of the landscape. Simulation polygons allow TELSA to represent the details of small or narrow linear features in the landscape that are difficult to represent in a grid-based model unless very small, and therefore numerous, grid cells are used.

The second step in the automated process is the creation of management units. The tool included with TELSA allows users to define different sizes and spatial arrangements of management units, and to design these management units without relying on the expensive development of engineer-designed harvest blocks.

The size of management units selected for a particular scenario depends on the intended management actions. Prior to creating management units, users must therefore define one or more sets of management systems as described above. Users then assign one or more management system to each combination of ecological stratum and planning zone and define the proportion of the area assigned to each system. If more than one management system is assigned to a specific area, users can also define the desired aggregation of these systems. For example, a user could define that the management within a given planning zone will be 30% medium-size clear cuts and 70% large partial cuts, and that the two systems will be randomly interspersed within the planning zone. Alternatively, three different management systems could be defined for an area, with the further specification that areas to which each management system is applied be aggregated, resulting in large contiguous areas to which similar management systems are applied. At this stage, users can also choose to set aside patches of reserves (e.g. wildlife tree patches) that will be protected from management activities.

The tool used in the spatial setup phase generates management units by combining simulation polygons that meet certain criteria of similarity (Fig. 4). Users can further specify the distribution of management units in the landscape. The tool will generate clusters of management units ranging from highly aggregated to randomly distributed (Fig. 5). This automated design of management units gives users control over the range of management unit sizes, the mixtures of management systems, and the various spatial arrangements of these mixtures. This flexibility can generate realistic cutblock configurations and allows for multiple spatial scenarios to be simulated efficiently without the cost or time constraints of engineered cutblock designs. The tool provides planners with the full spectrum of options required to explore and assess spatial alternatives at the strategic level.

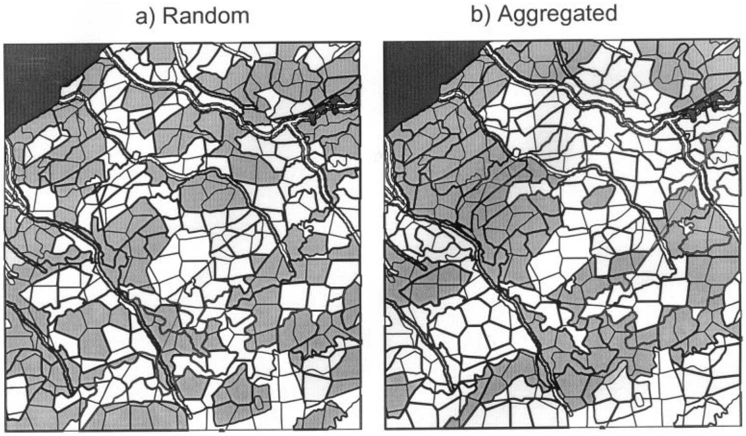

Fig. 5. Management units (heavy lines) belonging to two management systems (e.g. a partial cut system (white) and a clearcut system (gray)) are distributed within the landscape using user-defined criteria of random (a) or aggregated (b) distribution. Riparian zones are assigned to a ‘no management’ system. The small sample landscape in this figure belongs to a much larger landscape.

2.3. Vegetation dynamics

TELSA represents vegetation succession as changes in species composition and structural stages of stands, thus projecting future landscape conditions using information that is relevant for the analysis of wildlife habitat and other resource indicators. Each combination of species composition and structural stage defines a different successional class. These classes are then combined to create succession pathway diagrams (Fig. 6) for each broad ecological stratum. Pathway diagrams define the transition times and pathways between successional classes and, for each class, the probabilities and impacts of disturbance by insects, fire or other agents. These diagrams also define the impacts of forest management actions on stand structure and composition. Technically, the model uses a semi-Markovian concept in which transition from succession is time dependent, while transitions due to disturbances are based on probabilities.

The vegetation dynamics development tool (VDDT) (Beukema and Kurz, 1998) is used to develop and test such pathway diagrams. The process involves groups of ecologists, silviculturists, pathologists, entomologists, and fire ecologists that collectively define the successional pathways, disturbance probabilities, and the impacts of disturbance and management actions on changes in stand structure and composition. VDDT was originally developed for the Interior Columbia River Basin Project (Quigley and Arbelbide, 1997) and was used in many workshops to define pathway diagrams for forest and rangeland vegetation complexes. These rules were then used as input to the Columbia River Basin Succession Model (CRBSUM) (Keane et al., 1996). The ability of groups of experts to define realistic pathway diagrams has been confirmed through an independent analysis that compared VDDT predictions to those of a more detailed vegetation dynamics model (Stage

1997). VDDT has since been developed further and applied to a wide range of vegetation types. In applications where vegetation inventory data are limited and the definition of structural stages is not possible, successional classes have been defined simply by cover type and age-class combinations.

2.4. Other scenario assumptions

For each simulation scenario, the user can define various other assumptions. Since VDDT is a non-spatial model, TELSA requires additional information about the size-class distributions of the various disturbance types. In addition, the between-year variability for each disturbance type and any external trends that affect natural disturbances, e.g. climate change or suppression efforts, are defined and can be varied between scenarios. For example, two scenarios could contrast assumptions about future fire regimes and their impact on harvest levels and seral stage distributions in a landscape. Other non-spatial parameters that are defined for

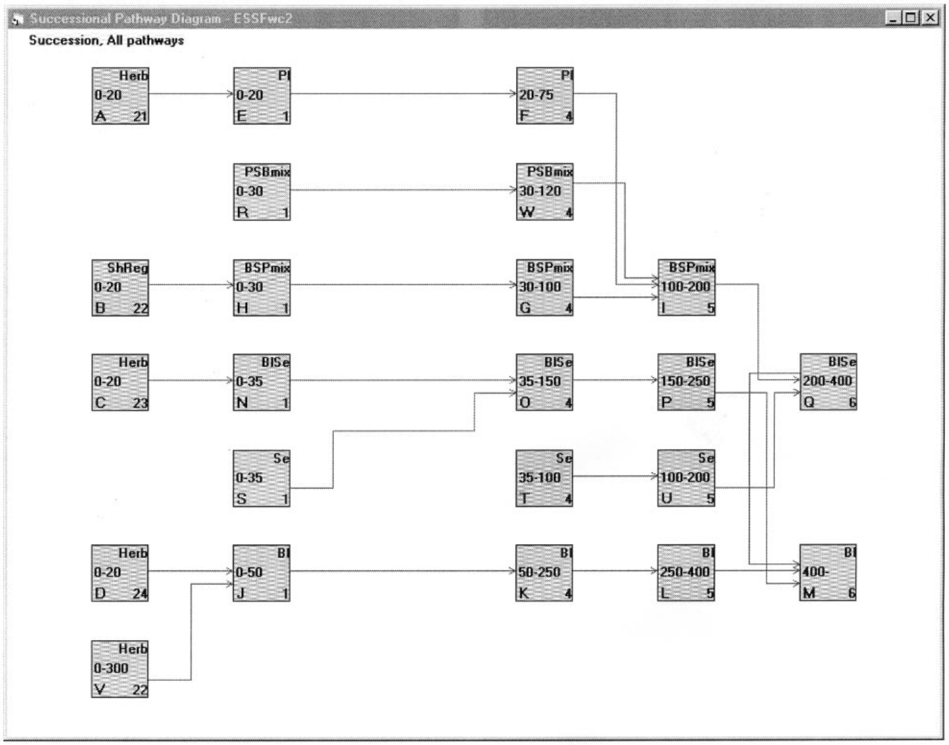

Fig. 6. Example of a successional pathway diagram developed with the Vegetation Dynamics Development Tool (VDDT). Each box represents a successional class with a unique combination of forest cover type and stand structural stage. In this example, only the succession pathways are shown. Disturbance probabilities are defined for each successional class. Other pathways define the impacts of disturbances and management actions.

each scenario are the timber salvage rules and the activity limits for each management activity. Because the model could implement a specific action in all eligible stands in a single year, users can define activity limits for management actions. These place an upper bound on the area that will be managed in a single year to represent constraints in the availability of various resources. Activity limits can also be used to temporarily suspend certain activities in a simulated scenario.

TELSA enables users to define scenarios with no management activities or with pre-suppression fire regimes, thus generating 'no action' or 'historic condition' reference scenarios. Users can also specify scenarios with only succession and management actions but no natural disturbances. Such scenarios may be useful to compare results to those obtained from other simulation models that do not represent natural disturbances. By simulating multiple Monte Carlo runs of historic scenarios, users can generate the historic range and variability of various landscape indicators. These provide a useful reference about landscape characteristics that were derived with the same model that is used for all other scenarios.

The assumptions for a specific simulation scenario define the disturbance probabilities for each successional class. While it is possible to predict that certain vegetation classes are more susceptible to specific disturbances than others, it is not possible to predict whether a specific year, some decades into the future, will have climatic conditions that will result in high or low disturbances. User-defined multipliers for between-year variability of each disturbance type provide the temporal pattern of future variability. Users are encouraged to simulate multiple Monte Carlo runs of those scenarios that include natural disturbances to assess the range and variability of future landscape conditions.

Two factors contribute to the differences between Monte Carlo runs of the same scenario: the location of natural disturbances in each year and the temporal sequence of disturbance multipliers. A natural disturbance can occur in any simulation polygon that, in the simulated time/step, contains a vegetation type that is susceptible to that disturbance (i.e. it has a disturbance probability greater than zero). Each Monte Carlo run represents a unique spatial realization of the assumptions defined in the scenario.

Once all scenarios are defined, users can specify which scenarios to simulate, how many Monte Carlo simulations of each scenario to execute, at which reporting interval to save the results for the entire landscape to the database, and which spatial analyses to conduct upon completion of the model simulations. The complete set of scenarios can then be executed with the simulation model and the results can be analyzed with the spatial analysis tool without further user interaction. Upon completion of the analyses, users can review the results and create additional scenarios.

2.5. The main model

The main component of TELSA is a spatially-explicit simulation model of vegetation succession, natural disturbances, and forest management activities. TELSA simulates succession, natural disturbances, and the appropriate management actions based on the current state of the landscape. The three processes interact through their effects on the stand and landscape conditions. For example, if a stand-replacing fire occurs, the burned area may become eligible for salvage logging if this is requested in the scenario and certain criteria (e.g. stand age, size of disturbance, etc.) are met. Either natural regeneration or management activities such as site preparation and planting will determine future vegetation characteristics of the burned area.

The sequence of simulation steps in each annual timestep is as follows. TELSA first simulates natural succession for every simulation polygon, except those identified as lakes, roads or other non-projectable areas. The pathway diagrams define the rate and direction of succession and the resulting polygon characteristics. After updating the current successional class for each polygon, TELSA simulates all natural disturbances that were defined for the current scenario. Disturbance types are processed in no particular order because the model treats disturbances generically and because there is no biological reason for ordering disturbance types within the annual simulation timestep.

In each simulated year, TELSA calculates the expected area affected for every disturbance type. This calculation considers four factors: the current distribution of successional classes in the landscape, the user-defined disturbance probabilities for each successional class, the between-year variability of disturbances, and the long-term trend. Based on the condition of the study area in the current timestep, TELSA first determines which polygons are in a successional class for which a non-zero probability of disturbance has been defined. The sum of products of the disturbance probability times the area of each polygon yields the base estimate of the area affected by each disturbance type. Two user-defined multipliers calibrated to local conditions or scenario objectives are then applied to this area: the first multiplier represents the between-year variability, the second any long-term trend (e.g. due to global warming or improved protection). For every disturbance type, user-defined size–class distributions of disturbance events are used to distribute the area disturbed per year to individual events. For example, regional fire statistics typically report the area burned in different fire-size classes.

Once the total area to be disturbed and the desired size-class distribution of the disturbance events are known, the disturbance events can be applied to the simulation polygons in the landscape. First, a target size for an event is drawn from the user-defined size-class distribution. Next, the event is initiated in a polygon picked at random from a list of eligible simulation polygons. The disturbance is then spread to the eligible neighbors of the polygon. If there are sufficient contiguous and eligible simulation polygons to implement the disturbance event with the target area, the model will do so. If there is insufficient area in contiguous eligible simulation polygons, an event smaller than the initial target is simulated. In either case, the actual size of the disturbance event is recorded. TELSA then draws the next target size from the size-class distribution and attempts to implement an event with the new target size. In a single timestep, the simulations for a single disturbance type are complete when the expected area to be disturbed has been reached. The user-defined size-class distribution of disturbance events can be achieved if the landscape contains sufficient area of contiguous polygons that can be affected by the disturbance type. If the landscape is fragmented, thus reducing the likelihood of large disturbance events, the simulated size-class distribution of disturbances can differ from that defined by the user. This approach provides feedback between the current landscape condition and the simulated natural disturbances.

Following natural disturbances salvage logging is simulated, if it is requested in the scenario descriptions. Users can define the natural disturbance types after which stands can be salvage logged, the maximum length of time after the disturbance within which salvage must occur, the minimum age of the stand that will be salvaged, and the minimum size of the disturbance event that will be salvaged.

After succession and natural disturbances have both been simulated, TELSA determines which management actions will occur in the timestep, based on the conditions of the landscape and the management assumptions specified in the activity schedules of the various management systems. As stated previously, users do have the option to simulate scenarios with no management activities. When management is simulated, TELSA evaluates the current condition of the landscape and generates, for each management activity, a list of eligible management units. Every management unit has been assigned to a management system for which a list of activities was defined by the user. TELSA identifies those management units for which a management activity is scheduled based on their current vegetation state. In some planning zones, the eligibility of a management unit is affected by the condition of adjacent units. For example, green-up constraints may specify that a management unit not be logged until the vegetation in the adjacent management unit reaches a certain state or age. In addition, activities will only be implemented if a management impact pathway was defined for the current successional class of the polygon. For example, natural succession following clearcutting of a simulation polygon could result in cover type A (pure conifer) or B (a conifer and deciduous mix). The management system could specify a thinning between age 15 and 20 in which the deciduous component is removed. The pathway diagram applicable to the simulation polygon defines the thinning pathway for the successional class that contain cover type B but contains no thinning pathway for cover type A. Consequently, thinning to remove the deciduous component will only be implemented in those simulation polygons in which succession has resulted in cover type B, the mixed conifer and deciduous stand.

The list of eligible management units is then sorted to determine the sequence of operation within a timestep. Sort criteria can include an operating unit priority and age (or in some cases stand volume). The management activities are then implemented in all eligible management units until the activity limit for the year has been reached or until all eligible units have been managed. Once management units are defined during the setup phase, there is no further stochastic component to management, except through the feedback from stochastic natural disturbances. Thus, if natural disturbances are not included, the simulation of a scenario is deterministic, i.e. it will produce the same results in every run of a specific scenario without natural disturbances.

2.6. Model output

TELSA records in the Access database, for every year of the simulation, which polygons were managed or disturbed. At user-defined reporting intervals (e.g. every 25 years), the model saves the information on the state of every polygon in the landscape for further post-processing or mapping. The maps saved at the reporting intervals can be further analyzed with the spatial analysis tool of TELSA. This tool calculates various spatial statistics for the landscape, including the count, size, and area distribution of patches and interior forest habitat according to user-defined age classes, and the length of edge between different patches. The results of these spatial analyses are recorded in the Access database. Users can review the results through interfaces that create graphs, tables, summary statistics, or maps of the results. Users can select the results from one or more scenarios or Monte Carlo simulations, can select a variety of indicators (Fig. 2) and show results by one or more ecological strata or planning zones as well as for the entire landscape.

2.7. Run time requirements

The performance of various components of the TELSA toolbox is dependent on the computing hardware, the available memory, the size of the analysis area and on the complexity of the scenarios. For general guidance only, we provide the following statistics, which were obtained with a 266 MHz Pentium II processor, Windows NT 4.0 operating system, and 128 MB RAM. The most CPU time-intensive process is the spatial set-up phase. A landscape of 116 000 ha area requires a total of about 24 h of computing time to perform the tessellation of some 35 000 simulation polygons and the assembly of some 7300 management units. Once these steps are completed different scenarios can be simulated. A 100-year simulation in annual timesteps requires approximately 30 min for scenarios that simulate management only, and about 60 min for those with management plus disturbances. The automated spatial analysis of patch size distribution, interior old-growth habitat, and border length requires about 45 min for every map (i.e. reporting timestep) that is analyzed. The model can be set up to execute a series of scenarios, Monte Carlo runs of each scenario, and spatial analyses of user-selected maps. These runs can be executed overnight and results can be reviewed upon completion.

3. Discussion

TELSA is designed as a tool for adaptive management, following many of the original concepts that require an open and transparent model development process (Holling, 1978; Walters, 1986). Given the complexity of forest ecosystem dynamics and the wide range of information requirements for landscape-unit planning, our approach emphasizes the cooperation between different groups of experts and stakeholders. For example, the successional pathway diagrams that describe vegetation dynamics can be developed by one group of experts who are familiar with the ecology of the landscape unit. Other groups can define the details of management systems, planning zones, and other aspects of the simulated scenarios. Planning teams and stakeholders can then easily review and compare the results of the various scenarios and explore the impacts of the assumptions on various indicators of interest.

Forest ecosystem management requires the ability to assess the consequences of the interactions of vegetation succession, natural disturbances, and management actions on the structure and composition of large landscape units over long time scales. TELSA provides planners and other stakeholders in the management process with a tool to assess the consequences of alternative management scenarios on several indicators relevant to the planning process.

The automated design of management units employed during the initial setup phase allows users to explore and assess the effects of management unit size ranges, the mixture of various management systems, and their spatial arrangement. While this approach offers great flexibility during strategic explorations, the resulting cutblocks are not suitable for implementation at the operational level without further review and modification by forest engineers. The results of the strategic analysis can, however, be used as guidelines for the operational layout of management units, their size range and the adjacency constraints that should be considered to achieve the landscape management objectives.

TELSA's approach to succession modeling is simple but effective and minimizes the need for detailed inventory information for each polygon in the landscape. Approaches to representing stand dynamics that are more data intensive (e.g. detailed growth and yield models), are not suitable to the scale of analysis and the large number of simulation polygons included in the approach described here. Moreover, detailed inventory information is typically not available for parks and other areas that are not managed for timber. TELSA is therefore suited to assist park managers in evaluating the effects of fire suppression or prescribed burning on vegetation dynamics and landscape characteristics.

TELSA incorporates feedback between landscape conditions and the area affected by natural disturbances by defining disturbance probabilities as a function of the successional class of the polygons. This feedback is achieved through changes in the amount of forest area that is in different successional classes. For example, simulating fire suppression and a reduction in wildfire activity may result in a larger proportion of the landscape in older seral stages. If these successional classes have higher probabilities of insect disturbance, fire suppression will lead to increased insect activity in the landscape. Second order effects, such as increased probabilities of bark beetle outbreaks in a stand surrounded by other highly-susceptible stands are currently not represented. There is little quantitative information about such second-order effects.

TELSA is not an optimization tool. Instead it assesses the consequences of the interaction between management plans and assumptions about succession and natural disturbances. Some planners may prefer to use decision support tools that define the 'optimum solution' even if these tools require the assumption that natural disturbances do not have a significant effect on landscape structure and composition. While this assumption may be justified in some ecological systems (e.g. Gustafson, 1996), in the dry interior of British Columbia and in many other ecosystems, broad scale stand-replacing wildfires and bark beetles are examples of agents with significant impacts on landscape characteristics. Moreover, forest management guidelines in British Columbia include definitions of seral stage distributions, patch size distribution, and the amount of interior old-growth habitat, all of which will be affected by the interactions between forest management and natural disturbances. Forest management plans based on the assumption that natural disturbances will not occur will yield projected future conditions that are of little relevance to many stakeholders in the planning process.

TELSA reports the area affected by management in each timestep, and the characteristics of each polygon that is harvested in terms of its cover type, structural stage, and age. Recent model development has added timber volume to the area-based indicators of timber harvest. Future development will add slope, aspect and elevation of each simulation polygon to the database, which will permit further refinements in the scheduling and application of management activities, as well as improved representation of succession and natural disturbances.

Any map displaying future landscape conditions for scenarios that include natural disturbances represents only one possible realization of the scenario assumption. TELSA can generate maps that summarize, across multiple Monte Carlo simulations of the same scenario, the disturbance probability for each polygon. Such maps can demonstrate whether certain parts of the landscape are more likely to be affected by natural disturbances. For example, certain insect outbreaks are more likely to occur in those parts of a landscape that contain susceptible vegetation. Parts of a landscape that are highly fragmented by roads, wetlands or lakes may have lower probability of burning than other parts with the same vegetation types.

TELSA is currently being applied to case studies in the southern interior of British Columbia (e.g. Klenner et al., 2000), in northwestern British Columbia, and in northern Alberta. Additional case studies have been started in the western United States. The modeling framework can be applied to other regions and vegetation types where users have data on vegetation dynamics and natural disturbances.

Acknowledgements

The development of TELSA was supported by funding from Forest Renewal BC through a grant administered by the Science Council of British Columbia. We thank the members of the scientific review committee (Bob Helfrich, Fred Bunnell, Marvin Eng, John Nelson, Glenn Sutherland, and Carl Walters) and the many participants for their input during the model design and review workshops. We thank two anonymous reviewers for their constructive comments on an earlier draft.

References

BC Ministry of Forests and Ministry of Environment, Lands and Parks, 1999. Landscape Unit Planning Guide, Forest Practices Code of British Columbia. BC Ministry of Forests and Ministry of Environment, Lands and Parks, Victoria, BC.

Beukema, S.J., Kurz, W.A., 1998. Vegetation Dynamics Development Tool User's Guide, Version 3.0. ESSA Technologies, Vancouver, BC document available at www.essa.com/forestry.

Gustafson, E.J., 1996. Expanding the scale of forest management: allocating timber harvests in time and space. Forest Ecol. Manage. 87, 27–39.

Holling, C.S. (Ed.), 1978. Adaptive Environmental Assessment and Management. Wiley, New York.

Keane, R.E., Long, D.G., Menakis, J.P., Hann, W.J., Bevins, C.D., 1996. Simulating Coarse-Scale Vegetation Dynamics Using the Columbia River Basin Succession Model — CRBSUM. U.S. Department of Agriculture Forest Service, Intermountain Research Station General Technical Report INT-GTR-340.

Klenner, W., Kurz, W.A., Beukema, S.J., 2000. Habitat patterns in forested landscapes: management practices and the uncertainty associated with natural disturbances. Comput. Electronics Agric. 27, 243–262.

Okabe, A., Boots, B., Sugihara, K., 1992. Spatial Tessellations: Concepts and Applications of Voronoi Diagrams. Wiley, New York.

Pojar, J., Klinka, K., Meidinger, D., 1987. Biogeoclimatic ecosystem classification in British Columbia. Forest Ecol. Manage. 22, 119–154.

Quigley, T.M., Arbelbide, S.J. (Eds.), 1997. An Assessment of Ecosystem Components in the Interior Columbia Basin and Portions of the Klamath and Great Basins, vol. 11. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station and US Department of the Interior Bureau of Land Management General Technical Report PNW-GTR-405.

Stage, A.R., 1997. Using FVS to provide structural class attributes to a forest succession model (CRBSUM). In: Teck, R., Moeur, M., Adams, J. (Eds.), Proceedings: Forest Vegetation Simulator Conference, 1997. Fort Collins, CO. U.S. Department of Agriculture Forest Service, Intermountain Research Station, Ogden, UT, pp. 139–147 General Technical Report INT-GTR-373.

Walters, C., 1986. Adaptive Management of Renewable Resources. Macmillan, New York.