Chapter 5 Using Landscape Disturbance and Succession Models to Support Forest Management

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Abstract

Managers of forested landscapes must account for multiple, interacting ecological processes operating at broad spatial and temporal scales. These interactions can be of such complexity that predictions of future forest ecosystem states are beyond the analytical capability of the human mind. Landscape disturbance and succession models (LDSM) are predictive and analytical tools that can integrate these processes and provide critical decision support information. We briefly review the state of the art of LDSMs and provide two case studies to illustrate the application and utility of one LDSM, LANDIS. We conclude that LDSMs are able to provide useful information to support management decisions for a number of reasons: (i) they operate at scale that is relevant to many forest management problems, (ii) they account for interactions among ecological and anthropogenic processes, (iii) they can produce objective and comparable projections of alternative management options or various global change scenarios, (iv) LDSMs are based on current ecological knowledge and theory, (v) LDSMs provide a vehicle for collaboration among decision-makers, resource experts and scientists, (vi) LDSMs are the only feasible research tool that can be used to investigate long-term, large area dynamics.

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5.1 Introduction

Forest managers must balance increasing demand for wood products and bioenergy feedstocks with the long-term maintenance of the integrity of the ecosystems that provide multiple valuable ecosystem services. Because forest ecosystems are characterized by many processes operating at multiple scales, interacting with each other and with the biotic and abiotic environment, a landscape perspective must be integrated into the thinking of land managers. Managing forests while considering only the stand scale will not achieve ecosystem sustainability objectives. Forests develop through the interplay of dynamic processes such as plant establishment, growth, competition and reproduction, and these are mediated by the abiotic environment (e.g., substrate, climate) and disturbances such as fire, herbivory and harvest. Interactions among these many processes can be complex; so much so that predictions of future forest ecosystem states are beyond the analytical capability of the human mind. Consequently, forest managers need computer-based tools to provide the predictive and analytical decision support information they require.

Decision support tools used by forest management agencies are typically non-spatial, non-ecological, non-process based models. For example, forest optimization models combine growth and yield with harvest scheduling to support timber-oriented forestry (e.g., Cogswell and Feunekes 1997). Such models are well suited for their intended purpose, but they lack integration with key ecological processes such as succession and natural disturbance, which limits their use when ecological sustainability is also a management goal (Fall et al. 2004). Habitat Suitability Index models rely on empirical relationships, but they rarely have a spatial component or a mechanistic basis. Forest management decision support tools may include an *ad-hoc* collection of non-spatial models, spreadsheet models, GIS analysis and expert opinion (Baskent and Keles 2005). Consequently, there is an urgent need for comprehensive spatial models that can (i) accommodate multiple management goals and actions, (ii) include multiple ecological processes and their interactions, (iii) include spatial interactions, (iv) evaluate large areas and (v) make holistic predictions about ecosystem properties. Because multiple global changes are affecting forest ecosystems, it is also desirable that the models can predict responses to novel conditions that have not been empirically observed before. In these situations, the only reliable way to project landscape change and estimate ecological sustainability is through modeling based on ecological processes rather than statistical relationships estimated under past conditions.

Comprehensive spatial models that can integrate multiple ecosystem processes are invaluable to decision makers because they provide information that cannot be derived from other tools. This includes projections of the spatial distribution of forest composition (species and age classes), carbon and nutrient cycling and disturbance regimes. Perhaps the most useful characteristic of modeling is the ability to objectively compare the response of the ecosystem to alternative management strategies or global change scenarios.

Dynamic landscape models combine the scientific knowledge accumulated in hundreds of disparate forestry and ecological studies to project how a forested ecosystem might be expected to respond to specific internal and external driving forces. These models are simply computational formulations of our human understanding of the components of complex ecological systems, and they are able to integrate these complex components in ways that the human mind simply cannot do.

This paper focuses on dynamic forest models that make projections of forest conditions over large areas (landscape scale) and long time periods by simulating forest succession and one or more forest disturbances. Such Landscape Disturbance and Succession Models (LDSM) have been constructed to achieve at least one of the following objectives. (i) Understand implications and interactions of scientific assumptions and hypotheses (i.e., if assumptions are correct, then model output represents how the system will behave.). (ii) Identify important processes for further study (sensitivity). (iii) Enhance understanding of complex ecological systems (heuristic). (iv) Integrate ecological and forestry issues for research and planning purposes. (v) Support an ecosystem approach to management. (vi) Account for spatial processes and spatial dynamics. (vii) Consider long temporal and large spatial scales. (viii) Account for interactions among ecological and management processes. (ix) Make projections about future forest ecosystem states — composition and pattern. (x) Conduct virtual landscape experiments and scenario analysis — to answer the "what if" questions.

5.2 Overview of landscape disturbance and succession models

One major component of LDSMs is the ability to simulate disturbance. Most disturbance simulators are process-based, simulating disturbance events (e.g., triggers, probabilities, location, size, intensity, spatial characteristics) and effects on species or community type (e.g., cohort mortality, biomass reduction, change to another type). Alternatively, a pattern-based approach places disturbance patches spatially and temporally on the landscape using mean disturbance regime properties. Disturbance effects depend on pre-disturbance site conditions and disturbance intensity. Disturbance is modeled as explicitly spatial processes, and these processes interact with the spatial pattern of vegetation and the environment.

Succession is the other major component of LDSMs, and it is simulated in one of two ways in most LDSMs — pathway-based or process-based. In a pathway-based system, there is a well-defined successional trajectory, and communities transition from one successional stage to the next at a predefined temporal rate unless disturbance resets them to another stage. The number of pathways is often limited. In a process-based system, succession may have many possible endpoints, and it is simulated based on the life-history attributes of the species and conditions found at each site on the landscape. The suitability of each approach is quite dependent on the ecosystem. For systems that have fairly predictable successional trajectories, such as in the American West, the pathway approach can save considerable computing time. For ecosystems where multiple successional trajectories may occur somewhat stochastically, such as in temperate mixedwood forests, then a process-based approach may produce more realistic results. Pathway-or transition-based LDSMs include VDDT/TELSA (Merzenich et al. 1999), LANDSUM (Keane et al. 1997), SIMPPLLE (Chew 1997), BFOLDS (Perera et al. 2008) and RMLANDS (http://www.umass.edu/landeco/research/rmlands/rmlands.html), while the major process-based LDSMs are LANDIS (Mladenoff 2004; Scheller et al. 2007) and LANDSIM (Roberts and Betz 1999) (Table 5.1). See Scheller and Mladenoff (2007) and Messier et al. (2003) for excellent reviews of LDSMs.

Table 5.1 How succession is modeled by the major LDSMs.

Model	Succession trajectory	Succession process
VDDT/TELSA	Pathway	Deterministic
SIMPPLE	Pathway	Stochastic
LANDSUM	Pathway	Deterministic
BFOLDS	Pathway	Stochastic
RMLANDS	Pathway	Stochastic
LANDIS	Process	Stochastic
LANDSIM	Process	Stochastic
SELES	User-defined	User-defined

The primary distinctive of LDSMs is spatial interactions. A model is spatial if it represents system components in geographic space, and considers the spatial relationships between objects. A model is spatially dynamic if these spatially-referenced components can change, therefore changing the spatial pattern of the modeled system. Most LDSMs simulate: (i) establishment and growth of tree species or communities, (ii) modification of species or communities by disturbance, and (iii) a fairly large spatial domain (100 to >10,000 km^2). Many LDSMs model ecological communities, which are assemblages of species, and in some models, these communities are composed of specific species and there are no compositional dynamics within them. In others, individual species or guilds are modeled, and communities are therefore dynamic and become an emergent property of the simulations. One LDSM (SELES, Fall and Fall 2001) is actually a declarative modeling language with a library of routines and functions that allows users to model spatial, landscape-level processes on raster map layers. This approach allows users to customize the way succession and disturbance is simulated.

The strengths and limitations of the various LDSMs are directly determined by the objective for their use and the ecosystem to which they are applied. A good rule of thumb is to use the simplest model that allows the question at hand to be answered. Complexity can increase uncertainty by adding parameterization and specification error. On the other hand, if a process has an important effect on landscape conditions and dynamics, its omission also increases prediction error. LDSMs have the capability to model most major disturbance processes, and in some cases, specific disturbances can be turned on or off, depending on the question (Table 5.2). LDSMs vary considerably in the amount of spatial dynamism that can result from the simulated processes. Spatial dynamism refers to the ability of the spatial pattern of the landscape (e.g., forest type, age classes, fuels) to change in response to the simulated processes. The algorithms used to simulate processes must be consistent with the way each process works in the ecosystem being studied. It is advisable to match the question and the level of detail for the ecosystem processes that are to be modeled to the modeling approach of a specific LDSM. The reason many LDSMs are in use is because each fills an important modeling niche. In this chapter we describe two applications of the LANDIS LDSM that provide examples of matching the model to the question, and illustrate ways that LDSM simulation results can be useful for decision support at landscape scales.

Table 5.2 Disturbance processes modeled by the major LDSMs.

Model	Fire	Insects	Disease	Wind	Harvest	Climate Change
VDDT/TELSA	X	X	X		X	
SIMPPLLE	X	X	X		X	
LANDSUM	X		X		X	
BFOLDS	X					X
RMLANDS	X	X	X		X	X
LANDIS	X	X	X	X	X	X
SELES	X	X	X	X	X	

5.3 Case studies

In this chapter we describe two applications of the LANDIS LDSM that provide examples of matching the model to the question, and illustrate ways that LDSM simulation results can be useful for decision support at landscape scales.

5.3.1 Reducing landscape-level wildfire risk on the Chequamegon-Nicolet National Forest

The first case study used the LANDIS LDSM (Mladenoff 2004) to address a strategic question at a landscape scale, being aimed at determining which of several strategies is most effective to reduce the landscape-scale risk of wildfire. Fire mitigation is especially problematic for managers of large public forests in the United States because public lands are surrounded by land over which agency managers have no control. Wildfire in fire-prone ecosystems is a landscape-scale phenomenon, so management strategies to mitigate landscape-level fire risk are exceptionally difficult to develop when much of the land base is outside of the manager's control. LANDIS is well suited for evaluating alternative potential solutions to such a complex management problem.

In this case study (Sturtevant et al. in press), LANDIS 4.0 (He et al. 2005) was applied to evaluating the relative effectiveness of four alternative fire mitigation strategies on the Chequamegon-Nicolet National Forest (CNNF) in Wisconsin (USA), where fire-dependent pine and oak systems overlap with a rapidly developing wildland urban interface (WUI). Much of northern Wisconsin is dominated by fire-resistant hardwood forests, but in places there are significant areas of pine and oak forests associated with sandy glacial landforms that are prone to high intensity fires and dependent on frequent fire for long-term persistence (Radeloff et al. 2000). Fire-dependent ecosystems are currently in decline in Wisconsin because of aggressive fire suppression policies (Radeloff et al. 2000). Human populations are rapidly encroaching on forested areas in the region primarily for quality-of-life reasons. Consequently, human-caused fire ignitions are increasing (Cardille and Ventura 2001) and there are more homes to be destroyed by wildfires.

LANDIS represents landscapes as a grid of interacting cells. Each cell may contain multiple species and each species can be represented by one or many age cohorts. Each cohort will establish and respond to disturbance as a function of its life history attributes (e.g., shade tolerance) and, in the case of disturbance, its age. The succession and disturbance processes act on the cohorts found on cells, and their interactions emerge as a consequence of the changes each imposes on landscape cells. Spatial inputs for LANDIS take the form of raster maps and include the land types (ecoregions), tree species cohorts initially found on each cell, and timber harvest management areas. Model output primarily consists of maps.

The 780 km^2 study area is defined by the outer boundary of the Lakewood subdistrict of the CNNF, located in northeastern Wisconsin (Fig. 5.1). Seventy-four percent of the land area is owned by the CNNF, and the remainder is privately owned. The majority of private land in the study area contains low density housing, but there are several locations where housing density exceeds 6.17 houses per km^2. Land cover is dominated by forest (81%), with some agricultural and hay fields (4.5%) and open wetlands (12.5%). Forested ecosystems in the study area are strongly influenced by glacial landforms that create a sharp soil moisture gradient from west (mesic and nutrient-rich, northern hardwoods) to east (xeric and nutrient-poor, pine and oak). An extensive unimproved road network is maintained to provide access for both harvest and fire suppression activities, linked by improved county and state roads (Fig. 5.1). The research team (Sturtevant et al. in press) assisted the CNNF in developing and evaluating alternative fire and fuel mitigation strategies for the study area.

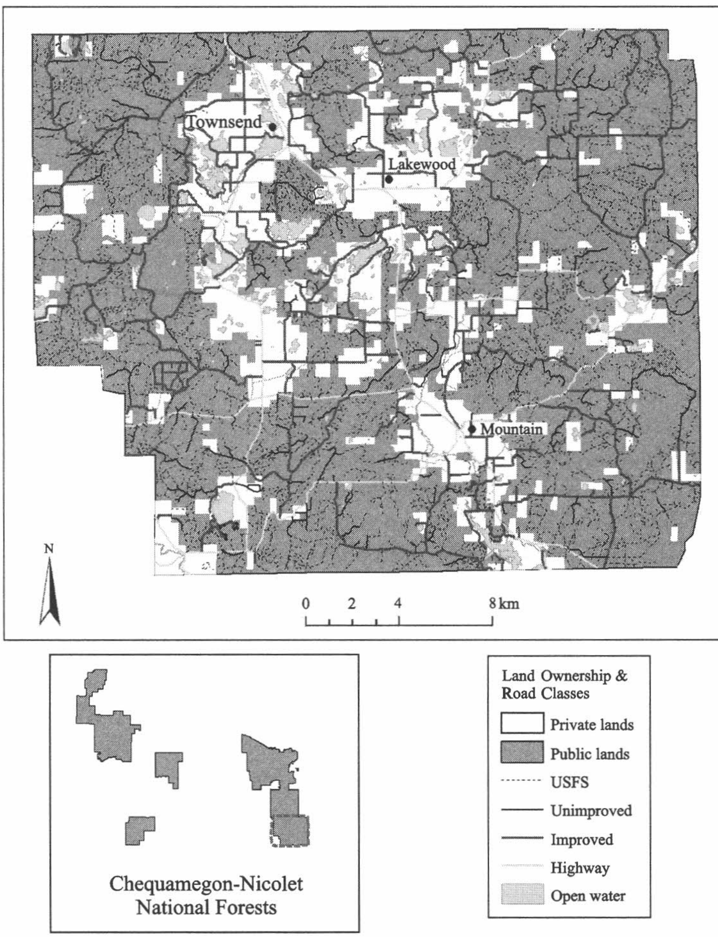


Fig. 5.1 Study area on the Chequamegon-Nicolet National Forest in Wisconsin, USA.

The alternative strategies were (i) placement of permanent firebreaks within fire-prone land types (FIREBREAK), (ii) redistribution of "risky" management treatments (i.e., those establishing pine or oak) to zones with low housing density (ZONE), (iii) reducing fire ignitions by 25% by banning local debris-burning practices (DEBRIS) and (iv) reducing fire ignition rates along roads by roadside vegetation management on federal lands (ROAD). The alternatives were evaluated by comparing a simulation of each alternative strategy to a base scenario representing current natural and anthropogenic disturbance processes of fire (including human ignitions and suppression), wind and timber harvest. The details of model parameterization can be found in Sturtevant et al. (in press) A 4×2 factorial experiment was designed with three replicates of each combination. Simulations were run for 250 years. Response variables were the cumulative area burned both inside and outside WUI areas during the 250-year time period. MANOVA was used to evaluate the null global hypothesis that neither treatments nor their interactions had significant effects on the response variables. The treatments were evaluated to determine if they had unintended consequences on ecological goals by comparing ecological indicators with targets outlined in the CNNF forest plan. Spatial maps of fire risk were estimated as the cell-scale probability of burning during 100 replicate simulations.

Results indicated that eliminating debris fires as an ignition source had the greatest influence on the area burned, decreasing the cumulative area burned relative to the base scenario by 35% (Fig. 5.2). This response was consistent both within and outside WUI areas. The ZONE treatment had the next largest influence on area burned, though the magnitude of change was small relative to the DEBRIS treatment. The ZONE treatment decreased the area burned inside the WUI by about 15%, but slightly increased the area burned outside the WUI, though the latter was not significant ($p > 0.05$) (Fig. 5.2). The ROAD treatment had marginal influence on area burned, and the FIREBREAK treatment had virtually no effect. No interaction terms were significant and were therefore removed from the analysis. Simulated mitigation treatments had little influence on either landscape-scale forest composition or the ecological goals of the CNNF.

Fire mitigation strategies may hold promise for coexistence of human and fire-dependent forest types. The simulated ban on debris-burning practices substantially decreased fire risk, suggesting that fire prevention and education is an important strategy for reducing fire risk within the Lakewood area. The simulations also showed that landscape-scale forest management strategies, such as the redistribution of fire-dependent forest types away from human ignition sources, can offer viable solutions for mitigating long-term fire risk and reducing land-use conflict in multi-ownership landscapes. However, because the legacy of previous forest composition is typically a prerequisite for the reestablishment and long-term maintenance of fire-dependent forest types, strategic planning will be essential for identifying opportunities for ecosystem restoration while minimizing fire risk. Landscape simulations, such as those presented here, can help guide the planning process by exploring the conse-

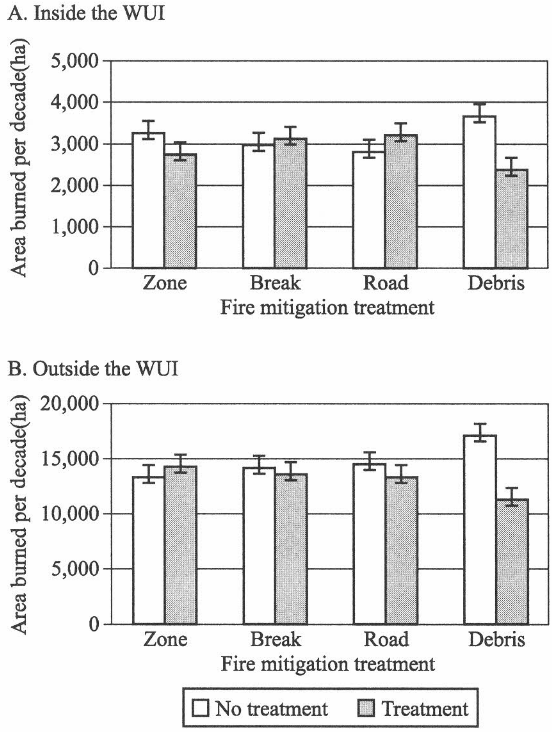


Fig. 5.2 Mean area burned per decade. A, inside the WUI, and B, outside the WUI, in response to the four main fire mitigation treatments. Error bars correspond to standard errors of the mean (Sturtevant et al. in press).

quences of different management options in a spatial context. Such exploration is critical before long-term management investments are made. For example, fire breaks can have unintended influence on fire risk due to the spatial interaction between human activities and human-caused ignition patterns. Given the declining trend of fire-dependent communities and the increasing trend of rural development, public land managers are poised to play an essential role in long-term conservation and maintenance of these key communities — but only if the conflict between fire disturbance and human safety can be resolved.

To that end, the results of the study were presented by Sturtevant to forest and fire management personnel in the region. Reactions to the results ranged from affirmation of their own perception of key relationships to surprise. Many were relieved to see patterns they intuitively understood but had difficulty expressing to decision-makers at higher levels. For example, much of fire research and resulting policies in the United States come from the western states. The idea that fire suppression can lead to reduced fire risk can be foreign to those with a "western" perspective. The reality of decline in fire-dependent ecosystems was another issue they were well acquainted with, but this fact is not well appreciated at higher organizational levels. The simulations clearly showed a long-term loss of fire-dependent tree species. By contrast, some (but not all) participants were surprised that fire breaks did not significantly reduce fire risk. Construction of fire breaks is another fire mitigation strategy common to the western US that may not transfer well to more settled areas of the upper Midwest, where fires are generally smaller and existing fire breaks, including a dense road network, are already in place (Malamud et al. 2005). The simulation results showed that fire breaks can have a strong local effect, but the effect is not significant at the landscape scale. Finally, the results affirm the current policy of the State of Wisconsin to control where and when debris burning is allowed through a simple, no-cost permit system (http://dnr.wi.gov/forestry/fire/burning-rp.htm). In each case, the simulation results provided objective evidence to help land managers communicate the rationale for their management priorities and to allocate limited resources for fire risk reduction.

5.3.2 Global change effects in Siberia

The second case study used LANDIS-II to address a policy-relevant question at the national scale, and focused on how multiple, overlapping global changes will affect the forests of south-central Siberia (Russia). Some of the authors are part of the team that re-engineered the LANDIS model using modern software development techniques (Scheller et al. in press) to create LANDIS-II (Scheller et al. 2007). LANDIS-II consists of a core collection of libraries (Scheller and Domingo 2006) and a collection of optional extensions that represent the ecological processes of interest (described below). LANDIS-II was specifically designed to address climate change effects on forested ecosystems (Xu et al. 2007; Scheller and Mladenoff 2008; Xu et al. 2009), by linking to the outputs of global circulation models (GCMs) to allow climate change to interact with landscape processes in the simulation environment.

The forested regions of Siberian Russia are vast and contain about a quarter of the unexploited forests worldwide (Dirk et al. 1997). However, many Siberian forests are facing twin pressures of rapidly changing climate and increasing timber harvest activity. Mean temperatures have risen significantly over the past 40 years, and this trend is expected to continue, while precipitation trends are variable (IPCC 2007). The combination of altered climate and altered species interactions will eventually produce altered disturbance regimes. The incidence and severity of fires is likely to increase (Litkina 2003; Goldammer et al. 2004; Efremov and Shvidenko 2004). A moderation of the harsh Siberian winters may allow insect pests to become more widespread. The frontier of timber harvest activity is pushing into previously inaccessible areas. New forest openings will increase fragmentation, and the building of roads may increase human access and fire ignition rates. Forest policy and management systems must take into account changing conditions and multiple interacting processes in order to achieve sustainable forest use in the future and to avoid unintended consequences.

The 3,165 km^2 study area is situated in the north-eastern part of the *Severny leshoz* (i.e. Northern forest enterprise) near the city of Ust-Ilimsk (Fig. 5.3). The forests of the study area are comprised of seven dominant species (*Picea obovata, Abies sibirica, Larix sibirica, Pinus sylvestris, Pinus sibirica, Betula pendula* and *Populus tremula*). The major natural disturbances are wildfire and windthrow. The study area is remote, but was recently opened to timber production and a warming climate may allow outbreaks of a major insect defoliator (Siberian silk moth, *Dendrolimus sibiricus superanse*) to become more common (Kondakov 1974).

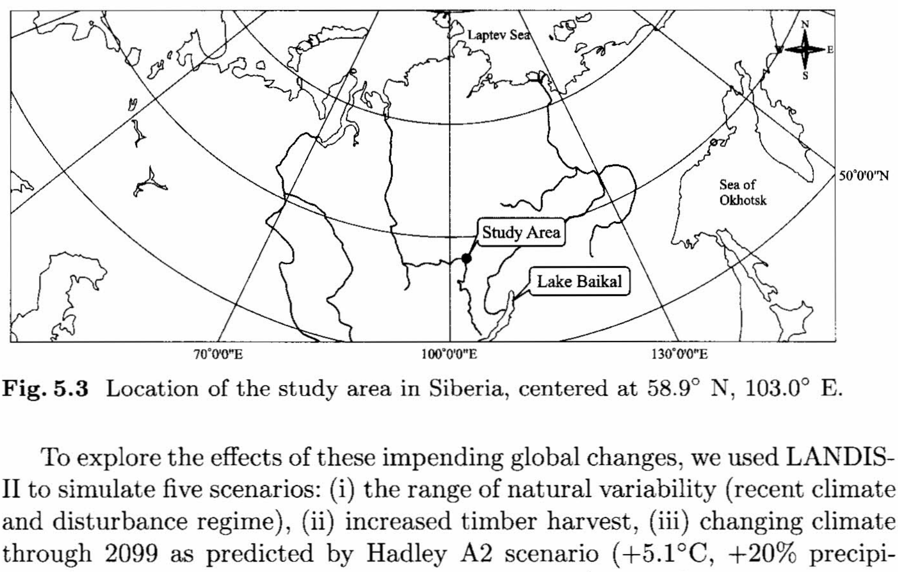


Fig. 5.3 Location of the study area in Siberia, centered at 58.9° N, 103.0° E.

To explore the effects of these impending global changes, we used LANDIS-II to simulate five scenarios: (i) the range of natural variability (recent climate and disturbance regime), (ii) increased timber harvest, (iii) changing climate through 2099 as predicted by Hadley A2 scenario (+5.1°C, +20% precipitation), which resulted in an altered fire regime (longer fire season, altered weather), (iv) Siberian silk moth outbreaks (with warmer climate) and (v) all changes combined (climate, harvest and insects). We used the simulation parameters described in Gustafson et al. (in review). Response variables were measures of forest composition, forest biomass and the landscape pattern of the forest.

Forest composition was influenced most strongly by timber harvest and insects (Fig. 5.4 and Fig. 5.5). The effect of the expected future climate treatment was significant, but its effect was minor compared to harvest and insects, excepting the abundance of Scot's pine. Climate did have a modest effect on the fire regime (Fig. 5.6). The total area burned per decade and mean severity of fires was projected to be slightly increased, with higher variability under the future scenario. However, both the area burned and fire severity were lower by year 300 under the future climate scenario because of changes in the species composition of the forest (Fig. 5.5). The amount of live aboveground biomass and the level of forest fragmentation were related to the amount of disturbance associated with each scenario (Fig. 5.7). Biomass increased during the last 100 years of the simulations under the insect scenario because insects favor tree species with higher growth rates. Harvest scenarios show a similar trend for similar reasons.

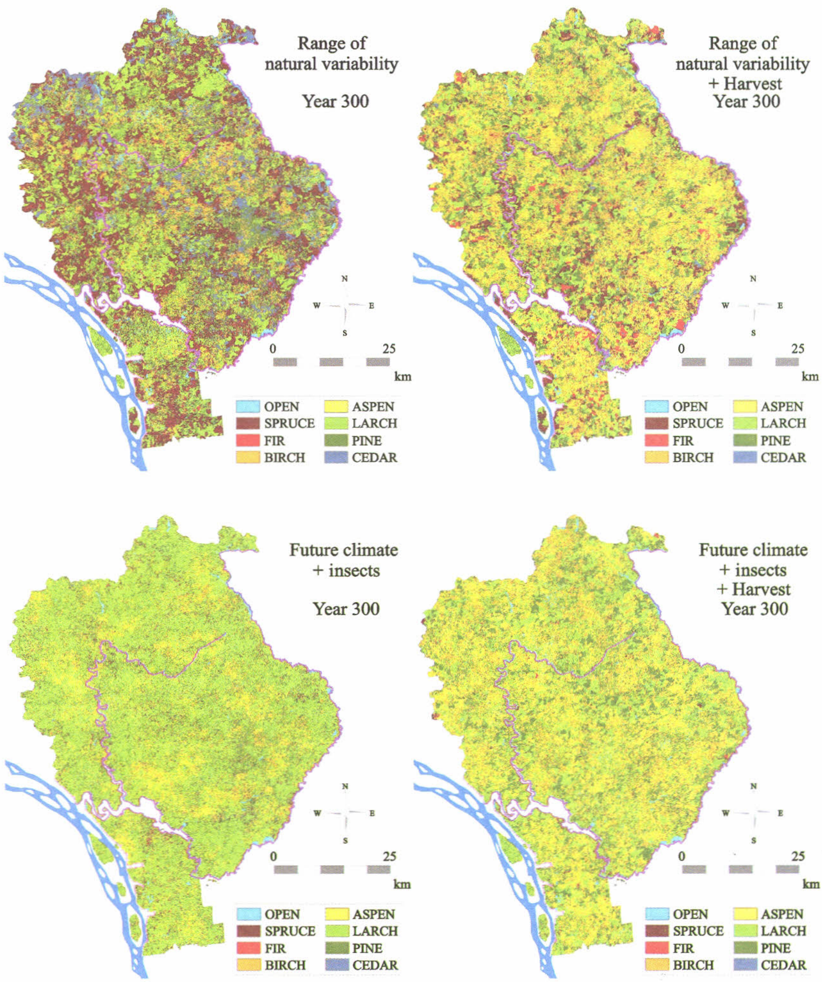


Fig. 5.4 Maps of forest composition at year 300 under four different scenarios.

Based on a comparison of these scenarios and on the results of simulation experiments by Gustafson et al. (in review), the following conclusions relevant to forest policy in the study area can be drawn. (i) The direct effects of climate change in the study area are not as significant as the exploitation of virgin forest by timber harvest and the potential increase in outbreaks of the Siberian silk moth. (ii) Global change is likely to significantly change

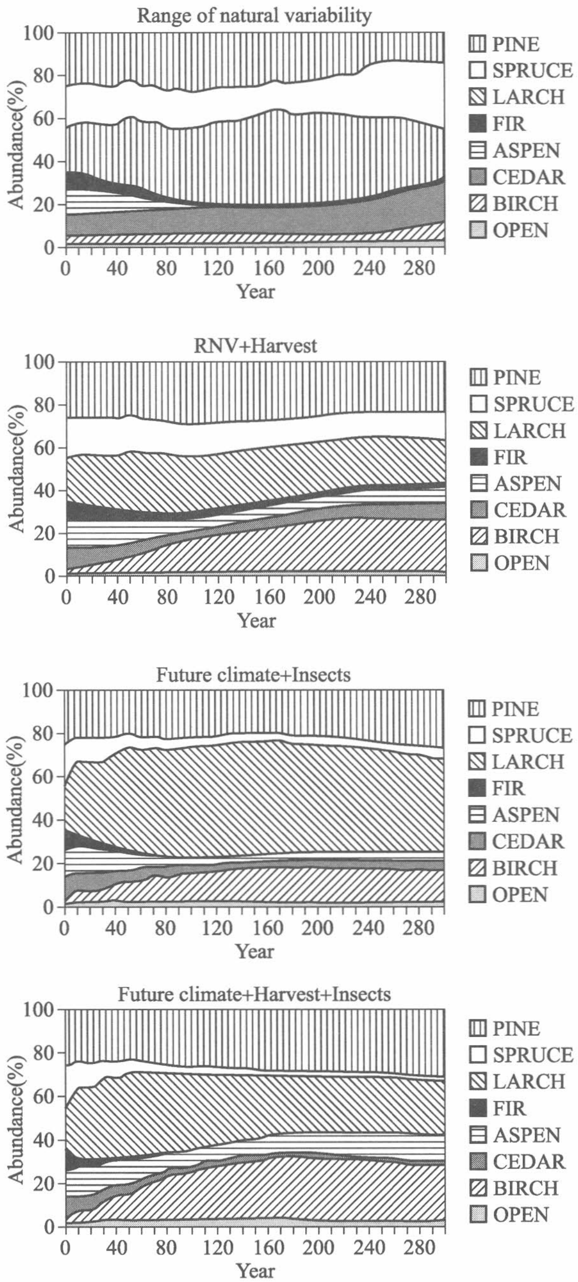


Fig. 5.5 Abundance of forest types defined by dominant species through time for four scenarios.

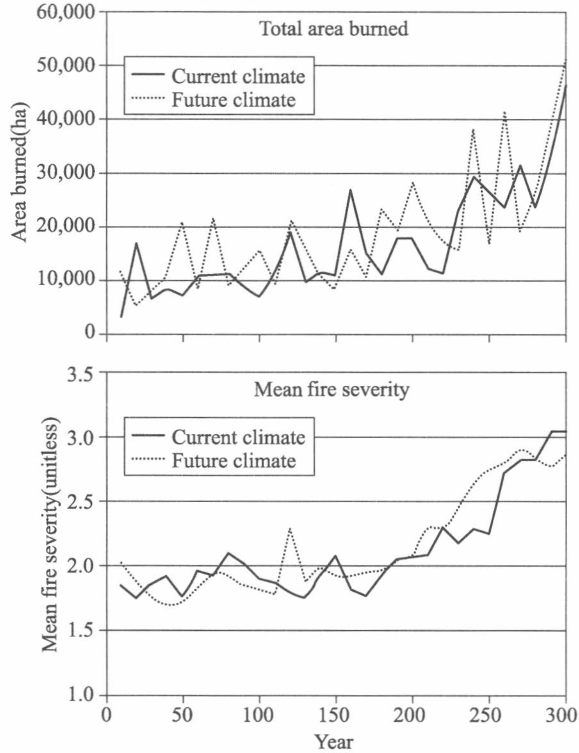
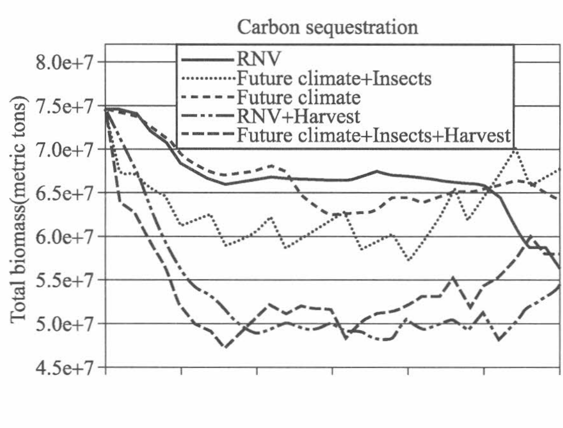


Fig. 5.6 Comparison of total area burned per decade and mean fire severity between current and future climate scenarios in the absence of harvest and insect disturbance.

forest composition of central Siberian landscapes, with some changes taking ecosystems outside the historic range of variability. (iii) Novel disturbance by timber harvest and insect outbreaks may greatly reduce the ability of Siberian forests to sequester carbon, and may significantly alter ecosystem dynamics and wildlife populations by increasing forest fragmentation.



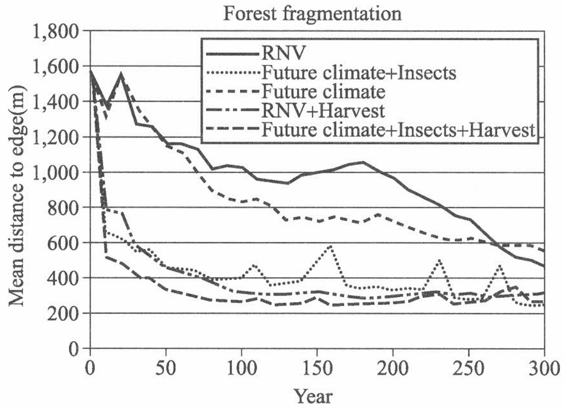


Fig. 5.7 Comparison of carbon sequestration and forest fragmentation through time among scenarios.

The results also suggest some forest management strategies that may help the forests in the region adapt to global change. (i) Encourage the regeneration of species that will be more productive under future climate (e.g., pine and birch) or able to tolerate increased fire (e.g., larch). (ii) Silk moth will have a negative impact on all conifers except larch. A potential strategy to mitigate insect losses is to begin to reduce landscape concentrations of spruce and fir, since these are major hosts for the silk moth.

5.4 General conclusions

LDSMs are able to provide useful information to support management decisions for a number of reasons. (i) They operate at a scale that is relevant to many forest management problems. A landscape perspective and long-time horizons are critical to understand most forest ecosystem dynamics and to make predictions about biodiversity and sustainability. Furthermore, many ecological processes have an important spatial component that cannot be ignored. (ii) LDSMs account for interactions among ecological and anthropogenic processes. These interactions are often complex and nonlinear, and are therefore difficult to predict without modeling tools. (iii) LDSMs produce objective and comparable projections of alternative management options or various global change scenarios. Results are reproducible, in a scientific sense, and can be peer-reviewed. This provides a level of objectivity, transparency and defensibility that managers need. (iv) LDSMs are based on current ecological knowledge and theory. This is both a blessing and a curse. The models are reliable when they have robustly encapsulated the conceptual models derived from ecological theory (Scheller et al. in press), and therefore their use carries significant stature. However, current theory and knowledge is subject to falsification as the scientific enterprise pushes back the frontiers of ignorance. Models (or model building platforms) that easily allow new knowledge to be inserted and the flexibility to eliminate processes irrelevant to the question at hand are often the most useful and enduring (Fall and Fall 2001; Scheller et al. in press). Equally important is recognizing the appropriate domain of each LDSM to ensure that an appropriate model is selected for the system being modeled and question being asked. (v) LDSMs provide a vehicle for collaboration among decision-makers, resource experts and scientists. When LDSMs are applied for decision support purposes, the most positive results accrue when modelers and managers collaborate in an iterative process focused on outcomes rather than the tools (Gustafson et al. 2006). Collaboration ensures that both modeling expertise and local ecological knowledge are brought to bear equally on the problem to be solved. One approach that our research group has found effective is the collaborative, iterative approach (Gustafson et al. 2006). Rather than expecting managers to learn to independently use the complex LANDIS model, we collaborate on decision support projects. We scientists provide the technical modeling expertise, the decision maker frames the question and defines the information needed, and local resources experts provide the ecological knowledge needed to ensure that the model behavior conforms to reality. Because the model and its results are described and discussed at some length as an integral part of the iterative process, the managers become educated about the technology, and the model is much less likely to be perceived as a mysterious "black box." (vi) LDSMs are the only research tool that can be used to investigate long-term, large area dynamics. Replicated, manipulative experiments are not feasible at landscape scales and temporal scales of decades or centuries. Yet LDSMs can provide useful insights into our understanding of ecological processes and dynamics at these scales.

We have described the application of the LANDIS LDSM to forest management questions, which illustrates several specific strengths of the LANDIS model. (i) LANDIS uses a process-based approach (spatial and non–spatial) to account for interactions among disturbances and succession to predict future forest ecosystem states. It is among the few LDSMs in which tree species respond individually to different disturbance processes (Keane et al. 2004; Scheller et al. 2007). This design allows vegetation patterns to emerge from the interplay between multiple disturbances, environmental drivers and species life history traits so that succession is not deterministic. (ii) LANDIS is flexible enough to allow application to varied problems, ecosystems and decision support needs. Our case studies illustrate this flexibility, being applied in temperate North America and boreal Russia. (iii) LANDIS can be updated to reflect new knowledge. Most ecological knowledge is input to the model in parameter files, although some is implicit in model design. Parameters can easily be changed as new knowledge is gained. (iv) If assumptions and relationships that are coded into extensions need to be changed, the LANDIS-II open-source extensions are readily modified and plugged into the model core.

LANDIS-II is one of only a few open source LDSMs, and this increases the transparency and verifiability of the model, which should increase confidence of model users.

5.5 Future of LDSMs in decision-making

Most LDSMs require detailed information about various ecosystem properties (e.g., species and age classes, fuel loading) at relatively high spatial resolution (at least 30 m) and extent (across an entire landscape). Data about age classes and specific species present are almost never available at high resolution, and so are estimated using various techniques. While these initial condition estimation techniques may be statistically accurate at landscape scales, they do introduce uncertainty and error at the cell scale, which persists for some time until the model itself produces new landscape patterns, a process that usually takes 50-100 simulation years. However, many management questions are focused on specific locations with a time horizon of less than 50 years, which is where uncertainty is highest. Methods to create input maps directly from remotely sensed data or broad-scale inventory data would reduce the uncertainty and error in the initial conditions. Methods to reduce the uncertainty of input parameter values are also needed. LDSM simulations can be used to identify the parameters to which the results are most sensitive, prompting new research to reduce the uncertainty of key parameters.

Most LDSMs were initially developed as scientific research tools, and their application for decision support is often secondary, in reality (King and Perera 2006). Explicit design and development of a user interface and application protocols are rarely done because of the expense, and therefore LDSMs are difficult for non-modelers to use. This situation presents a significant barrier to the adoption of LDSM technology. To bring the power of LDSMs to bear on the forest management questions of our time, these barriers must be removed. Investments must be made to design and implement systems that give non-modelers reasonable access to the technology. Alternatively a well designed user interface can automate input data generation, help the user specify parameters and model runs, conduct automated error checking of inputs, and provide some analytical tools to evaluate model output. For example, an exceptional interface has greatly expanded the use of FVS, a stand-scale model (http://www.fs.fed.us/fmsc/fvs/index.shtml). Such a system would make LDSMs much more attractive for adoption as a routine decision support tool by lowering the investment in training specialists to use the technology.

Reliability, scientific credibility and longevity are important for decision-makers. Most managers of public forests expect their decisions to be legally challenged, and they must be confident that decision support from models would be defensible in a court of law. Furthermore, if they commit to a modeling tool for decision support, there is often the expectation that the tool will also be used for future decisions. Therefore, they must have some confidence that the tool will be maintained, and that it will always reflect the most current scientific knowledge. Unfortunately, most ecological models are developed and maintained in an *ad hoc* manner, and their reliability often decreases with time. The application of modern software engineering techniques may greatly improve the reliability of LDSMs and make it easier to keep them current with scientific advances (Scheller et al. in press).

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