Spatial simulation of forest succession and timber harvesting using LANDIS

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Abstract: The LANDIS model simulates ecological dynamics, including forest succession, disturbance, seed dispersal and establishment, fire and wind disturbance, and their interactions. We describe the addition to LANDIS of capabilities to simulate forest vegetation management, including harvest. Stands (groups of cells) are prioritized for harvest using one of four ranking algorithms that use criteria related to forest management objectives. Cells within a selected stand are harvested according to the species and age cohort removal rules specified in a prescription. These flexible removal rules allow simulation of a wide range of prescriptions such as prescribed burning, thinning, single-tree selection, and clear-cutting. We present a case study of the application of LANDIS to a managed watershed in the Missouri (U.S.A.) Ozark Mountains to illustrate the utility of this approach to simulate succession as a response to forest management and other disturbance. The different cutting practices produced differences in species and size-class composition, average patch sizes (for patches defined by forest type or by size class), and amount of forest edge across the landscape. The capabilities of LANDIS provide a modeling tool to investigate questions of how timber management changes forest composition and spatial pattern, providing insight into ecological response to forest management.

Résumé : Le modèle LANDIS simule des dynamiques écologiques telles que les successions forestières, la dispersion et l'établissement des semences, les perturbations causées par le feu et le vent, ainsi que leurs interactions. Cet article décrit des ajouts faits au modèle LANDIS qui permettent la gestion de la végétation forestière, incluant la récolte. Les peuplements (groupes de cellules) sont priorisés pour la récolte en utilisant un des quatre algorithmes de classement qui utilisent des critères reliés aux objectifs d'aménagement forestier. Les cellules à l'intérieur d'un peuplement sélectionné sont récoltées par cohorte d'âge et d'espèce selon des règles de prélèvement spécifiées dans une prescription d'intervention. Ces règles souples de prélèvement permettent la simulation d'un large éventail de prescriptions telles que le brûlage dirigé, l'éclaircie, la coupe sélective et la coupe rase. L'utilisation de LANDIS est présentée à l'aide d'une étude de cas impliquant un bassin versant sous aménagement situé dans les montagnes Ozark du Missouri (États-Unis). L'étude de cas illustre l'utilité d'une telle approche pour simuler les successions écologiques en réponse à l'aménagement forestier et à d'autres types de perturbations. Les différents types de coupes ont généré des différences dans la composition des espèces et des classes de dimensions, la superficie moyenne des coupes (pour les coupes définies selon le type de forêt ou par classe de dimensions) et la quantité de bordures forestières sur l'ensemble du paysage. Ces capacités font de LANDIS un outil de modélisation pouvant servir à explorer de quelle façon l'aménagement forestier affecte la composition et la distribution des peuplements, ce qui permet en retour d'avoir un aperçu de la réaction écologique suite à l'aménagement forestier.

[Traduit par la Rédaction]

Introduction

Appreciation of the importance of disturbance in ecological systems, particularly temperate forest ecosystems, has become widespread during the second half of this century (Heinselman 1973; McIntosh 1985; Pickett and White 1985). This modified the earlier notion of Clements (1916) and others that long-term equilibrium and deterministic successional trajectories characterized most ecosystems. Forests have been shown to be broadly influenced by repeated events of fire (Heinselman 1981), wind (Canham and Loucks 1984), as well as insects and disease (Holling 1981).

Models of forest change have developed over the last several decades, initially emphasizing successional dynamics in small (~0.01–0.10 ha) plots ("gap" models; Botkin et al. 1972; Shugart 1984), or growth and yield (Munro 1974; Dale et al. 1985), without incorporating the dynamics of disturbance. Other models were more conceptual in nature, incorporating rule-based successional transitions and species characteristics that could result in altered and renewed successional trajectories (Cattelino et al. 1979; Noble and Slatyer 1980). Later versions of the forest gap models began

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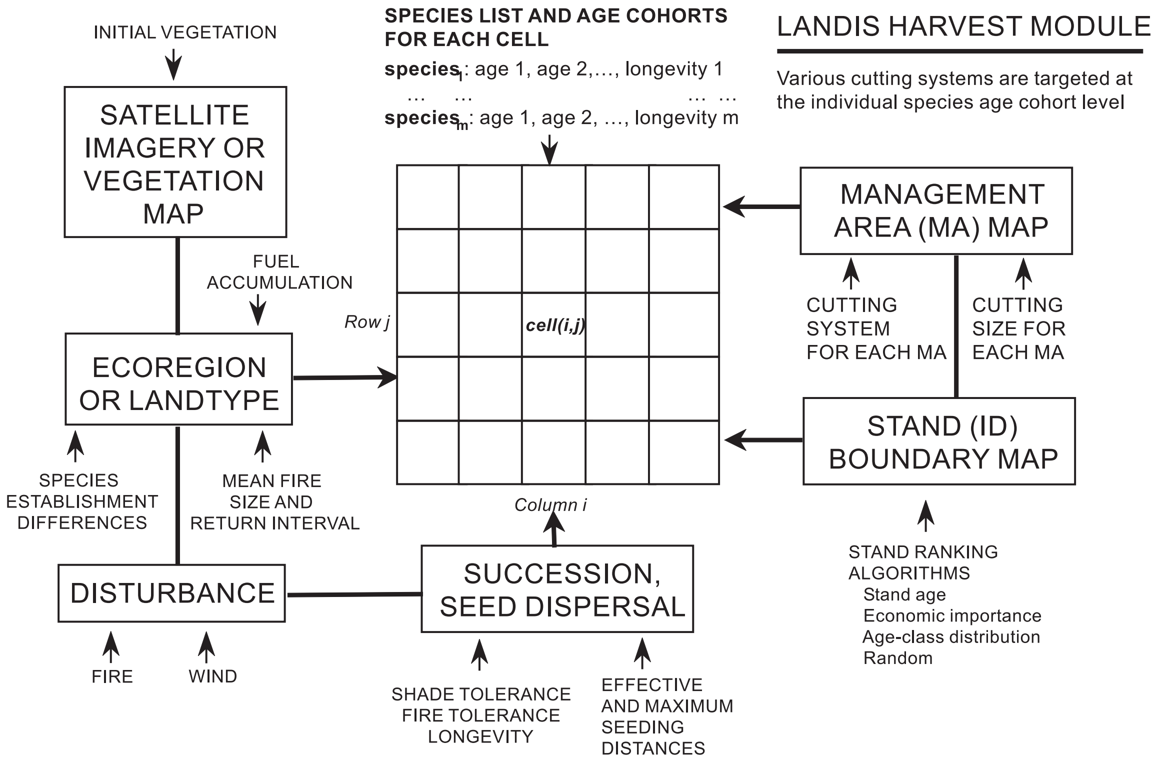
Fig. 1. LANDIS model design. A landscape can be conceptualized as a grid of equal-sized individual cells. For example, cells are stratified into environmentally homogeneous units as land types or ecoregions, and each cell (*i*, *j*) contains a unique species list and age cohorts of species. These species data change via establishment, succession, and seed dispersal and interact with disturbances. Each management area (MA) can be designated with a cutting system that allows harvest practices to be simulated at the species – age-cohort level. Spatial allocation is performed at stand level (stand map) with an appropriate stand ranking algorithm.



to incorporate effects of disturbance (such as fire) on succession (Kercher and Axelrod 1984; Shugart 1984; Urban and Shugart 1992). However, these initial models all lacked spatially explicit dynamics that incorporate interactions between plots or stands (Mladenoff and Baker 1999*a*). The field of growth and yield models diverged from the more ecologically based models, evolving into forest management and planning tools that incorporated effects of harvesting on forest commodity production (Wycoff et al. 1982; Iverson and Alston 1986; Johnson et al. 1986; Miner at al 1988). These models were not designed to incorporate spatial interactions (Hoganson and Burke 1997).

There are a growing variety of approaches to spatial simulation of forest landscape dynamics (Mladenoff and Baker 1999*b*). Increasingly, we are faced with the need to understand complex ecological dynamics over large spatial scales and longer temporal domains. At the same time, forest management is under increasing pressure to incorporate new ecological knowledge, while protecting a variety of values and sustaining forest productivity (Aplet et al. 1993). Spatial simulation models allow us the opportunity to assess management scenarios and environmental change hypotheses at spatial and temporal scales that are otherwise difficult or impossible to evaluate.

The conceptual basis for simulation of harvest patterns at landscape scales can be traced back at least to the coarse-grid cutting model developed by Franklin and Forman (1987). Other similar pattern-generation models include LSPA (Li et al. 1993), CASCADE (Wallin et al. 1994, 1996), HARVEST (Gustafson and Crow 1994, 1996, 1999), and the DISPATCH model of Baker (1995) as modified to simulate disturbance by timber harvest. LSPA operates on an initially homogeneous map and was used to investigate theoretical relationships between cutting strategies and landscape pattern. HARVEST, CASCADE, and DISPATCH have each been successfully applied to investigate the effects of harvest patterns at the landscape scale, and each has some limitations when applied to simulate long-term change on real forested landscapes. These models do not model forest growth or succession other than the aging of stands. CASCADE and DISPATCH do not consider forest type; HARVEST recognizes only very general forest types. These models generally have inflexible and simple rules to select areas for harvest, and harvest activities are limited to canopy-removing harvest treatments, such as clearcuts, shelterwood cutting, and in the case of HARVEST, group selection. Harvest scheduling programs (e.g., FORPLAN (Johnson et al. 1986), SNAP (Sessions and Sessions 1991); Spectrum (Greer 1997), and STEPPS (Arthaud and Rose 1996)) were designed for tactical management planning, have much greater data requirements, and are not well suited to long-term landscape pattern research.

Here we describe the harvest simulation capabilities we have added to the spatially explicit LANDIS disturbance and succession model. LANDIS was designed to model the interactions of disturbance by fire, windthrow, and forest management on large ($>10^4$ ha) forest landscapes (Mladenoff et al. 1996; Mladenoff and He 1999). This paper provides a detailed description of the algorithms we have developed to implement the timber management module for LANDIS, providing flexibility to simulate a broad array of harvest activities. We present a case study of the application of LANDIS to a managed watershed in the Missouri (U.S.A.) Ozark Mountains to illustrate the utility of this approach in simulating forest change in response to harvest and other disturbance. Finally, we discuss the significance and utility of this approach as a tool to assist in the formulation of research hypotheses and to assess management alternatives.

LANDIS modeling design

The LANDIS model simulates ecological dynamics including forest succession, disturbance, seed dispersal, species establishment, and fire and wind disturbance and their interactions (Mladenoff et al. 1996; Mladenoff and He 1999) (Fig. 1). The purpose of LANDIS is to simulate long-term changes (>100 years) in patterns of forest vegetation across large landscapes while maintaining reasonable realism in important ecological processes and their spatial interactions. The model is not designed to simulate fine-scale resolution of processes operating within single stands or to develop operational plans for small groups of stands. Rather, LANDIS is a tool to examine the large-scale, long-term impacts of forest disturbance by wind, fire, and harvest across landscapes from several hundred to several hundred thousand hectares in extent. The model operates on a raster map or grid, where each cell contains information on the tree species and their 10-year age cohorts present (species–age list), but not information about the number or size of individual stems (Fig. 1). The model is suited for scales where landscapes can be represented by cells of 10 m × 10 m to 500 m × 500 m. The model time step is 10 years, also suggesting that appropriate use is for assessing long term change, not fine-scale dynamics that may be less predictable.

The model simulates differential reproduction, dispersal, and succession patterns by species and incorporates effects of disturbance and environmental heterogeneity across the landscape. Species establishment probabilities can be made to vary by user-defined land-type units that typically are defined to reflect site quality differences (He et al. 1996). There is feedback between disturbances and species response. For example, windthrow events may contribute to fuel accumulation on a site, consequently increasing the severity of subsequent fire events and altering the simulated species composition relative to sites without windthrow.

Species seed dispersal is based on dispersal curves for each tree species derived from the literature (Burns and Honkala 1990; Loehle 1988). Seed can theoretically disperse from any cell on the map that contains sexually mature age-classes. Whether the seed will successfully establish on a different cell depends on distance from seed source, the characteristics of trees already at the site, the shade tolerance of the dispersing species, the land type, and a random probability. Model design and behavior, as well as model test results, are described elsewhere (He et al. 1999*a*; He and Mladenoff 1999; Mladenoff and He 1999).

The LANDIS model simulates wind and fire disturbance regimes based on user-specified return intervals for wind and fire events. These return intervals are spatially implemented on the landscape using a stochastic algorithm that approximates the desired return interval on the landscape over a long-term (e.g., ≥100 years) simulation (He and Mladenoff 1999). LANDIS disturbance and harvest modules can be turned on or off prior to the model run. If all are turned on, LANDIS sequentially simulates windthrow, fire, harvesting, and forest succession at each time step. Further details of the LANDIS model can be found in the literature: overall model design and behavior (Mladenoff et al. 1996; Mladenoff and He 1999); descriptions of the fire object (He and Mladenoff 1999); representation of species and age-list objects (He et al. 1999*b*); model parameterization (He et al. 1996); and model verification and calibration (He and Mladenoff 1999).

We have added a timber-management module to LANDIS to allow simulation of disturbance by timber-management activity in managed forests. The LANDIS data structure is rich in site information, allowing the heterogeneity of stands to be expressed as heterogeneity both within cells and among the cells that make up a stand. This structure allows flexible simulation of a wide range of management activities. Our approach permits the user to specify the details about how timber-management activities selectively remove age cohorts of each species on harvested cells. The order in which stands are selected for harvest is based on ranking algorithms that can be related to specific management goals. These features provide the ability to simulate an almost unlimited variety of vegetation-management activities that might be proposed to achieve various management goals. Because LANDIS records species information as 10-year age-cohort presence–absence for each cell, forest succession dynamics within LANDIS represent a synthesis of those simulated in a physiological model (Mladenoff and He 1999). Succession on harvested cells is simulated based on the residual species and age-classes both on the cell and on dispersal from other cells. Because individual trees are not tracked, residual stand volume and density after a harvest treatment is not simulated in LANDIS. However, estimates can be derived based on an existing age-class and timber-volume relationship for a given study area (e.g., Jenkins and Parker 1997; Shifley et al. in press).

LANDIS verification and calibration

A validation approach for the LANDIS model has been proposed and tested (He and Mladenoff 1999). This approach allows verification and calibration of natural disturbance through an iterative process, adjusting parameters to achieve the disturbance return interval and size on each land type that is expected based on empirical data. Successional processes in LANDIS are described and tested in detail elsewhere (He et al. 1996; Mladenoff et al. 1996; Mladenoff and He 1999). The harvest module is currently being extensively tested. Similar algorithms in another model (HARVEST) have been shown to reproduce statistically similar spatial patterns to those produced by management activity on the Hoosier National Forest (Gustafson and Crow 1999).

Description of the harvest module

Overview

Harvest activities are applied in the context of management areas. Management areas are spatial zones (not necessarily

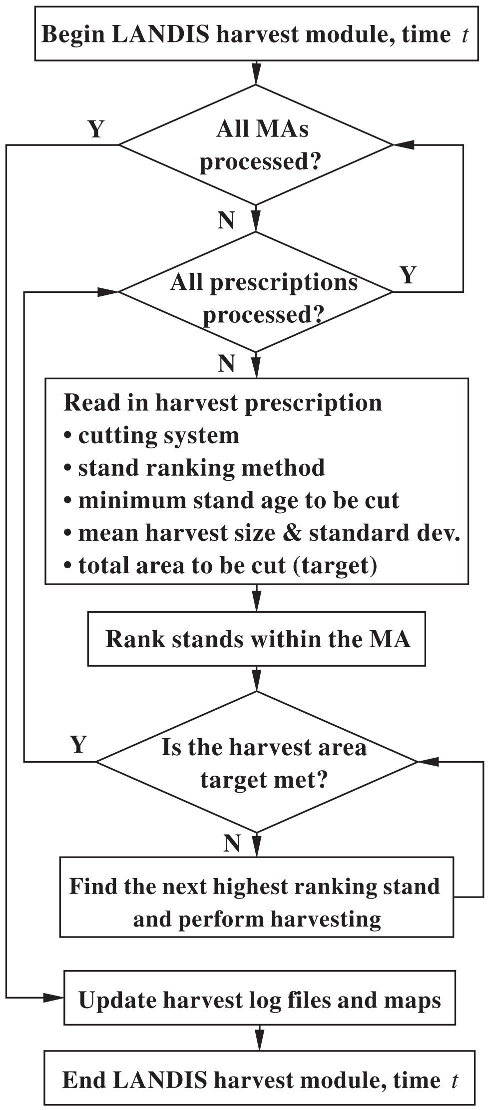


Fig. 2. Flow chart of the LANDIS harvest module.

contiguous) with specific management objectives (e.g., maximize volume production, maintain closed-canopy forest, enhance wildlife habitat). For each management area, the user develops any number of management (harvest) prescriptions to achieve these objectives. For example, one management area may be dedicated to fiber production and feature primarily a clear-cutting prescription, while another dedicated to quality sawtimber production might prescribe both single-tree and group-selection harvests (i.e., removal of groups of trees, 0.1–0.8 ha in size). In the latter case, only one prescription is applied to any individual stand, but both prescriptions are applied within the management area. Within each management area, the landscape is divided into stands whose boundaries remain fixed. Stands are represented by contiguous grid cells having a common stand identifier. LANDIS implements prescriptions by selecting stands for treatment, visiting cells within the stand, and removing selected age cohorts of selected tree species from the cell. The order in which stands are treated is determined by one of four ranking algorithms that prioritize stands by criteria, such as stand age or economic value. The age cohorts to be removed are specified by species and age class in the prescription. Prescriptions may specify harvest size distribution, allowing a single harvest event to cut a portion of a stand or multiple stands.

Forest management is implemented in LANDIS as a series of nested processing loops (Fig. 2). In the outer loop, LANDIS sequentially visits each management area. Within this loop, each harvest prescription specified for the management area is applied. For each prescription, a list is generated of stands within the management area that meet harvest-eligibility requirements. Eligibility criteria are stand age (must be greater than minimum age specified in the prescription) and adjacency (user defines how conditions on adjacent stands (e.g., when last cut) affect eligibility). The specific stands to be treated by the prescription are selected from the list of eligible stands using the ranking algorithm specified in the harvest prescription. The algorithm ranks all the eligible stands in the management area for harvest priority, and stands are harvested in rank order until the target area has been harvested. Cells within a selected stand are visited using a random spread algorithm and harvest is simulated by removing the species and age cohorts specified in the prescription. These rules together define a harvest event that is implemented using object-oriented programming techniques. Complete user control over the species and age cohorts removed in each harvest operation and over the spatial distribution of harvested cells within a stand allow simulation of a wide range of management prescriptions including thinning, single-tree selection, clear-cutting, or even prescribed burning.

This flexibility comes at the price of added complexity in the specification of model runs. Each prescription for each management area must specify the species and age cohorts to be removed, the proportion of cells to be treated, a minimum age, and other information described below. However, because LANDIS reads harvest parameters from an input file, once this file is created, it can readily be modified to generate new harvest scenarios.

Harvest prescriptions

Harvest prescriptions are implemented by LANDIS at the stand level, and have a spatial, a temporal, and a cohort-removal component. The spatial component determines how simulated harvest activity responds to stand boundaries and allows LANDIS to create user-specified, harvest-size distributions. In stand-constrained harvests, every cell in a single stand is treated, and the harvest size is equal to the stand size. In area-constrained harvests, harvests spread out around an initial cell chosen at random from within the stand, and this spread (to adjacent cells) stops when a target harvest size is reached. The target size is randomly drawn from a normal distribution having a mean and standard deviation specified by the user in the prescription. The sizes of area-constrained harvests are independent of stand sizes; in some cases, harvests may be smaller than the stand, and in others, they may be much larger than a single stand. If, as these harvests spread, they fill the initial stand without reaching the target size, the harvest spills into the highest ranked adjacent stand, and the harvest begins to fill that stand. This process continues until the specified harvest size is reached. In the event that no adjacent stands are eligible for harvest during

Table 1. Silvicultural activities simulated by the six spatiotemporal cutting systems available in LANDIS.

	Area constrained	Stand constrained
One entry	Change patch sizes, e.g., clearcut	Maintain patch sizes, e.g., clearcut
Two entry	Change patch sizes, e.g., shelterwood, seed tree	Maintain patch sizes, e.g., shelterwood, seed tree
Periodic entry	Change patch sizes, e.g., group selection, patch cutting, single-tree selection	Maintain patch sizes, e.g., single-tree selection, strict rotation forestry

this process, the expansion of that harvest unit is truncated. This capability allows investigation of how the scale of patchiness might be modified by management activity. An additional specialized spatial harvest pattern is patch cutting, where disjunct openings are scattered randomly throughout a single stand. This feature was developed primarily to model group-selection harvests and requires an input map with cell size less than or equal to the smallest opening to be simulated.

The temporal component of the harvest prescription allows simulation of multiple-entry silvicultural treatments. A prescription may be implemented as a single-entry, two-entry, or periodic-entry prescription. A single-entry prescription is applied at a single time step. Two-entry prescriptions involve an initial treatment followed by a second treatment at some specific time interval following the first. Species and age cohorts to be removed can be specified separately for each entry. This allows simulation of common silvicultural treatments such as seed tree and shelterwood cutting systems where some of the trees are harvested in the first entry, and the remainder is removed in a later entry. A periodic-entry prescription involves a treatment that is repeated at a specific time interval. This feature allows simulation of harvests on a strict rotation or of group selection harvests where a stand is revisited on a fixed interval to harvest relatively small patches of trees. The combination of the spatial and temporal components result in six spatiotemporal cutting systems (Table 1). At each time step the scheduled harvest re-entries required by two-entry harvest prescriptions are implemented prior to ranking stands for new harvests.

The cohort removal component of harvest prescriptions specifies the age cohorts of each species that will be removed in each harvest operation. Removal is specified uniquely for each prescription. For example, a simulated prescribed burning might specify that the youngest cohort of all species be removed. A simulated clear-cutting might specify that all cohorts of commercially valuable species be removed. A simulated shelterwood might specify that all but the older cohorts of one or two species be removed during the first entry, and that the older cohorts be removed during the second entry. A simulated single-tree selection harvest might specify the removal of only those cohorts older than 100 years.

An almost infinite variety of harvest prescriptions can be specified using different combinations of the spatial, temporal, and species- or cohort-removal components of harvest specification. Prescriptions can be tailored to the characteristics of the species found on the landscape and to local silvicultural practice. This flexibility is important to allow the use of LANDIS to explore research questions involving nontraditional management strategies and to allow comparison of the consequences of specific management alternatives in a decision-making environment.

Ranking algorithms

Within a management area, stands to be harvested under a given prescription are selected at each time step using one of four ranking algorithms chosen by the user. Ranking may be based on stand age (oldest stands first), economic importance (most valuable stands first), age-class distribution (attempts to produce an even distribution of age-classes), or random order. A value is calculated for each stand in the management area based on the criteria of the ranking algorithm, and this value is used as a rank. Because stands are ranked independently for each prescription, different ranking algorithms can be applied to different prescriptions within a management area. Prescriptions are applied to stands in rank order until the target harvest area for the prescription is reached. The process repeats for every prescription in every management area. Ranking algorithms are implemented as separate modules, allowing addition of other algorithms in the future.

The economic importance algorithm requires the user to supply a relative value and age of silvicultural maturity for each species. The economic value (V) of a stand is calculated by summing the value of each species (i) on each cell (c) in the stand using the formula

$$V = \sum_{c} \sum_{i} \sum_{a \geq l} \left(\frac{p_i}{m_i} \times a \right) \qquad \forall a \text{ that exist for species } i \text{ on cell } c$$

where p_i is the value per unit weight of species i, m_i is the age at which species i becomes merchantable, a is the age of the cohort in decades, and l is the minimum age for harvest.

The age-class distribution algorithm is based on the frequency distribution of stand ages across the management area. The objective of the algorithm is to increase the likelihood of cutting stands of ages that are over-represented in the frequency distribution while also favoring harvest of the oldest stands. The algorithm requires that the frequency distribution of stand ages (a, defined as age of oldest cohort within stand) be tabulated in a vector (**freq**). Relative rank (R_j) for stand j is calculated by

$$R_j = \frac{e^j \mathbf{freq}(j)}{\sum e^a \mathbf{freq}(a)} \quad \forall a \geq \text{minimum age for harvest}$$

where j represents the age of oldest cohort of the current stand, a indexes the ages of all stands in the management area, and e is the base of the natural logarithm.

Table 2. Summary of the three harvest and natural disturbance regimes compared using LANDIS.

	Harvest regime		
Criteria	No harvest	Even aged	Uneven aged
Method of harvest	na	Clearcut entire stands	Group selection applied to all stands; opening size 0.2 ± 0.33 ha (mean ± SD)
Area harvested per decade	0	10% of landscape	8% of each stand
Minimum harvest age (years)	na	20	20
Stand selection criteria	na	Oldest first	All stands
Mean interval between repeat fire damage (years)	300	300	300
Mean interval between repeat wind damage (years)	800	800	800

Note: na, not applicable.

Because stand age is calculated by averaging the age of the oldest cohorts in each cell within the stand, the ranking algorithms that use age work generally well when forests are even aged. For management areas composed of primarily uneven-aged stands, ranking algorithms that do not use stand age may be preferred.

Specification of prescriptions

The design of the algorithms to simulate harvest activity allows the user to explicitly control most of the details of forest management. The user may specify any number of harvest prescriptions to be applied to the landscape. In each prescription the user specifies the management area where it will be applied, the total number of cells (or proportion) to be treated, the size distribution of harvests (for area-constrained harvests), the cutting system (e.g., single entry), the ranking algorithm to be used, the species and age cohorts to be removed, the time steps in which the harvests will be implemented, the time interval for any re-entries, and the number of decades until adjacent stands can be harvested. When multiple stands have the same rank, the tied stands are harvested in the order of their stand identifier value. These identifiers need not be assigned based on the spatial location of a stand. For example, if the list of sequential numbers is assigned to stands at random, tied stands will be selected at random with respect to spatial location.

Performance

The performance of LANDIS harvest makes it feasible to simulate management activity over long time periods on a large land base. For example, simulations spanning 10 decades of even-aged stand management for our 837-ha case study (0.09-ha pixel size and 136 stands) required approximately 1.3 min on a Unix workstation (233 MHz). A comparable simulation for a 129 000 - ha landscape (0.09-ha pixel size and 18 848 stands) requires about 3.5 h of computer time. In a separate test of the model we simulated management of 25 143 stands on a map representing 262 080 ha (60-m cell, 728 000 cells). We carried 23 tree species within the model, and when we applied six prescriptions to six management areas within this landscape, a simulation of 500 years (50 time steps) took about 6 h using a 450-MHz Pentium processor. Significant performance improvements can be realized by carrying fewer species in the model.

Case study

Methods

We demonstrated application of the LANDIS harvest module by simulating three harvest disturbance scenarios on a southeastern Missouri (U.S.A.) landscape. The landscape was previously mapped and inventoried as part of the Missouri Ozark Forest Ecosystem Project (MOFEP) (Brookshire and Hauser 1993; Brookshire and Shifley 1997). This landscape consists of 836 ha that correspond to compartments 7 and 8 of the MOFEP study (Brookshire et al. 1997). The most common ecological land types (Miller 1981) are southwest-facing side slopes (35% of the area), northeast-facing side slopes (26%), ridgetops (15%), and upland drainages (8%). The area was previously mapped into stands for management, and stand boundaries were delineated so that they did not cross ecological land-type boundaries. This landscape is forested with mature, upland mixed oak forest in the 60- to 90-year age-classes. The area has been largely undisturbed by harvest and fire for the last 40 years. Basal area averages 21 m^2/ha. Three fourths of the basal area is in a mixture of black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus coccinea* Muenchh.), white oak (*Quercus alba* L.), and post oak (*Quercus stellata* Wangenh.). Shortleaf pine (*Pinus echinata* Mill.) represents an additional 6–10% of the basal area. Red maple (*Acer rubrum* L.) and sugar maple (*Acer saccharum* Marsh.) account for less than 1% of the basal area.

We used LANDIS to simulate three harvest scenarios for this landscape over a 100-year period (Table 2). The first scenario simulated no timber harvest on the landscape. The second simulated even-aged management by clear-cutting across the entire landscape. Ten percent of the area was harvested each decade, and stands were ranked for harvest so that the oldest stands were harvested first. The third scenario simulated uneven-aged management by group selection over the entire landscape. Group openings covered 8% of the area each decade, and group opening sizes averaged 0.2 ha. We parameterized the model to have severe wind disturbances occur with an 800-year return interval. We simulated fire with a 300-year mean return interval and low severity; these conditions are characteristic of the Ozarks during the last 20 years (Westin 1992; Guyette 1995). We adjusted fire-severity parameters so that forests less than 30 years and greater than 150 years in age had greater fire damage, because we expected those forests to have relatively high volumes of downed wood (Jenkins and Parker 1997; Shifley et al. 1997).

Four maps were required to initialize the simulations: management areas, land-type units, stands, and initial vegetation conditions. All maps were based on a 30 × 30 m cell (i.e., pixel size). We placed the entire landscape in a single management area for this example. Note, however, that it is possible to specify multiple management areas on a landscape and have them receive different harvest treatments during a single simulation run. We used the previously mapped ecological land types to define eight land units, and we used the existing stand boundary maps. We represented the forest vegetation with four species groups during the simulation: black oak (included black and red oak), white oak (included white and post oak), shortleaf pine, and maple (included red and sugar maple). For each cell within each stand (i.e., for each 30 m × 30 m pixel) we assigned one of these four species groups. Species groups were randomly assigned to individual cells within each stand subject to the constraint that the total abundance of each species group within a stand be proportional to abundance of that species group as inventoried in 1992. The oaks were initialized in the 80-year age-class, and shortleaf pine was initiated in the 90-year age-class. Maple cells were initialized in the 20-year age-class with an overtopping black oak in the 80-year age-class.

Maps produced at each decade in the simulation show fire disturbance, wind disturbance, type of harvest, forest age, and species presence for each 30 m × 30 m cell. To facilitate interpretation of results we also created maps of forest type (i.e., mixed–white oak, black–scarlet oak, pine, oak–pine, or maple) and forest size or structure classes recognized by local managers (i.e., seedling, age 0–9 years; sapling, age 10–29 years; pole, age 30–59 years; sawlog, age ≥ 60 years; uneven, ages span three or more size classes). A cell is assigned to the size class represented by at least 80% of the cohorts of all species. When 80% of the cohorts fall in two consecutive size classes, the class with the larger proportion is assigned. When no two consecutive size classes include at least 80% of the cohorts, the cell is called uneven aged. We further analyzed some of these maps to obtain spatial statistics. The LANDIS simulations have the capacity to create a prodigious quantity of output. Most simulation results can be displayed as maps or summarized as spatial statistics. Geographic information systems provide a ready means to reclassify results into broader age-classes or forest size–structure classes. Such reclassifications often make it easier to interpret temporal trends and spatial patterns across large landscapes or to summarize results in terms that are familiar to resource managers.

Results

Some of the most striking differences among the management alternatives are visible in maps of the simulated vegetation age structure of the landscapes under different harvesting practices (Fig. 3). For the scenario with no harvesting, the variation in the forest age was caused by stochastic fire and wind events. Based on our parameterization of the model, fire was expected to affect about one third of the landscape over the course of a 100-year simulation. Spatial patterns of fires are reflected in the spatial patterns of the vegetation under all three scenarios (Figs. 3 and 4). The effects of harvest are clearly visible in the two harvested landscapes. The even-aged harvest scenario resulted in a patchwork of age-classes that generally followed stand boundaries. The scenario for uneven-aged management by group selection resulted in a landscape characterized by small (e.g., 0.1–0.3 ha) clusters of forest vegetation of differing ages. Wind and fire disturbances maintained 1–3% of the no-harvest landscape in the seedling, sapling, and pole size classes.

The spatially explicit simulation approach permits comparison of many landscape characteristics among scenarios (Table 3). The different cutting practices resulted in some variation in the predicted species composition across the landscape. Compared with the harvested landscapes, the no-harvest scenario resulted in more mixed oak (which is composed of the relatively long-lived white oak species), more shortleaf pine, and less oak–pine. Oak–pine sites occur when oak and pine become established on the same cells. This occurred on up to 14% of cells on the harvested landscapes. As anticipated, uneven-aged management produced the greatest number of patches by size class. As used here, a patch is a contiguous group of cells (pixels) that touch on one side or one corner and have the same value for a characteristic of interest (e.g., same age, same forest species type, or same forest size class as defined in the Methods). With 1560 patches averaging 0.5 ha in size, the uneven-aged scenario created nearly four times as many patches as the no-harvest and the even-aged harvest scenarios. The no-harvest scenario had the largest mean patch size at 2.1 ha, predominantly because of the large extent of the sawlog size class. On average, the mean patch size for the even-aged scenario was almost as large as that of the no-harvest scenario. (Table 3). The simulated clearcuts under the even-aged scenario had the effect of resetting all pixels in each harvested stand to the same size class and creating relatively uniform patch sizes. For most size classes the uneven-aged scenario also produced from 4 to 10 times as much edge habitat as the other harvest scenarios (Table 3).

At the end of the 100-year simulations, the harvest treatments had been implemented across nearly the entire landscape, and the overall pattern of size classes would change little if the management practices were continued through additional decades of simulation. However, the process of change from the initial 80-year-old undisturbed forest landscape to an intensively managed forest results in decades of transition where part of the landscape has been harvested and part has not (Fig. 3). These landscapes provide various mixtures of old forest and newly regenerated forest.

Expressed as a percentage of the mean acres disturbed, variation across decades was much greater for wind and fire events than for harvests (Table 4). Although wind disturbance was small, fires disturbed one third to one half of the area disturbed by harvest each decade. Because we had specified that forests less than 30 years of age and greater than 150 years of age would have greater fuel loads and be most susceptible to fire damage, the even-aged and the uneven-aged harvest scenarios resulted in greater fire damage. On average, they had more hectares in susceptible categories

Fig. 3. Missouri study area landscape under three different harvest practices. Landscape is 836 ha with pixel size of 0.09 ha (30 × 30 m). The panels illustrate initial forest age-classes for all simulations; final age-classes after 100 years with no harvest; and forest age-classes at years 20, 40, 60, 80, and 100 from the start of the simulation showing how the landscape changes over time with the implementation of the even-aged and uneven-aged harvest scenarios.

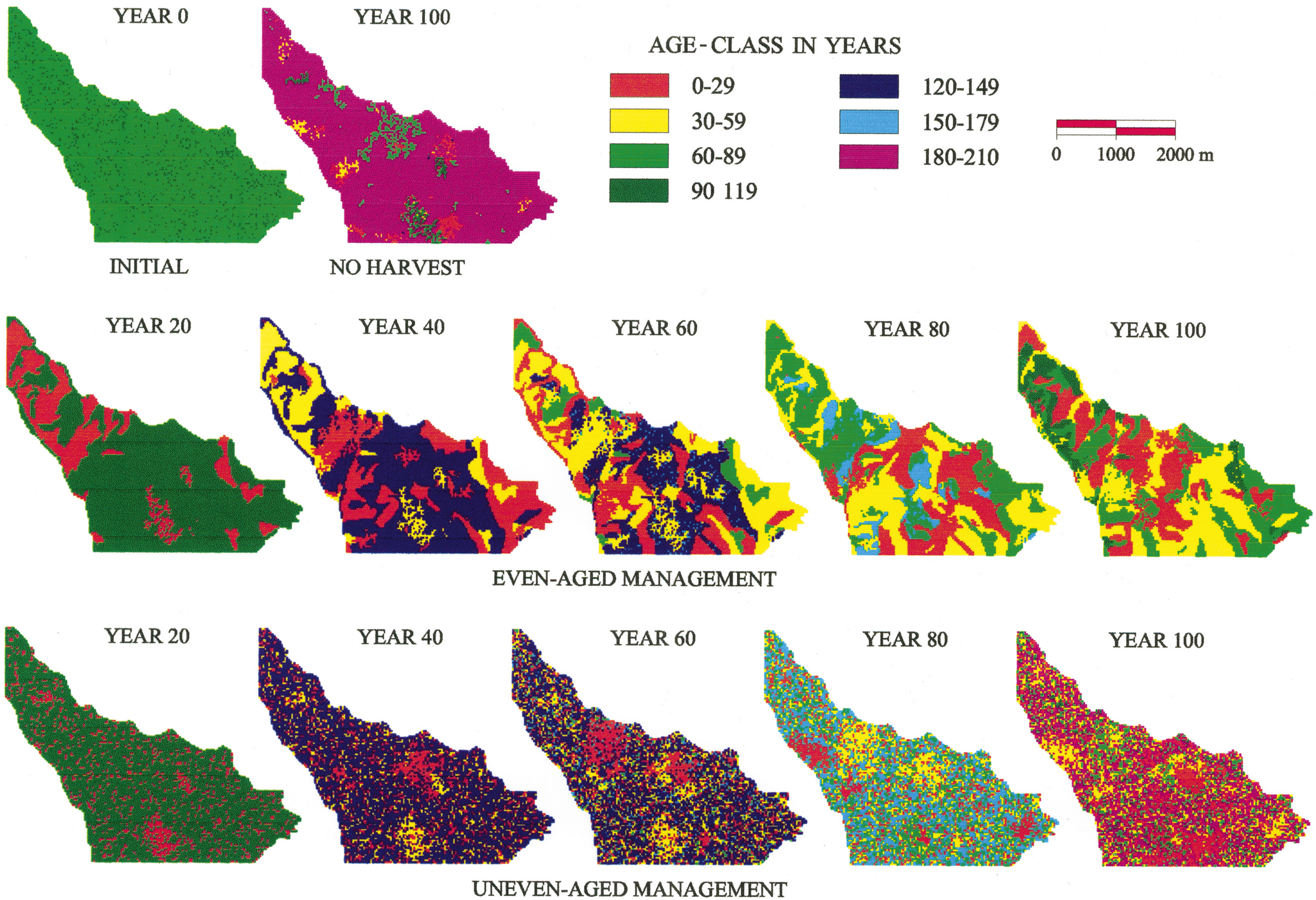
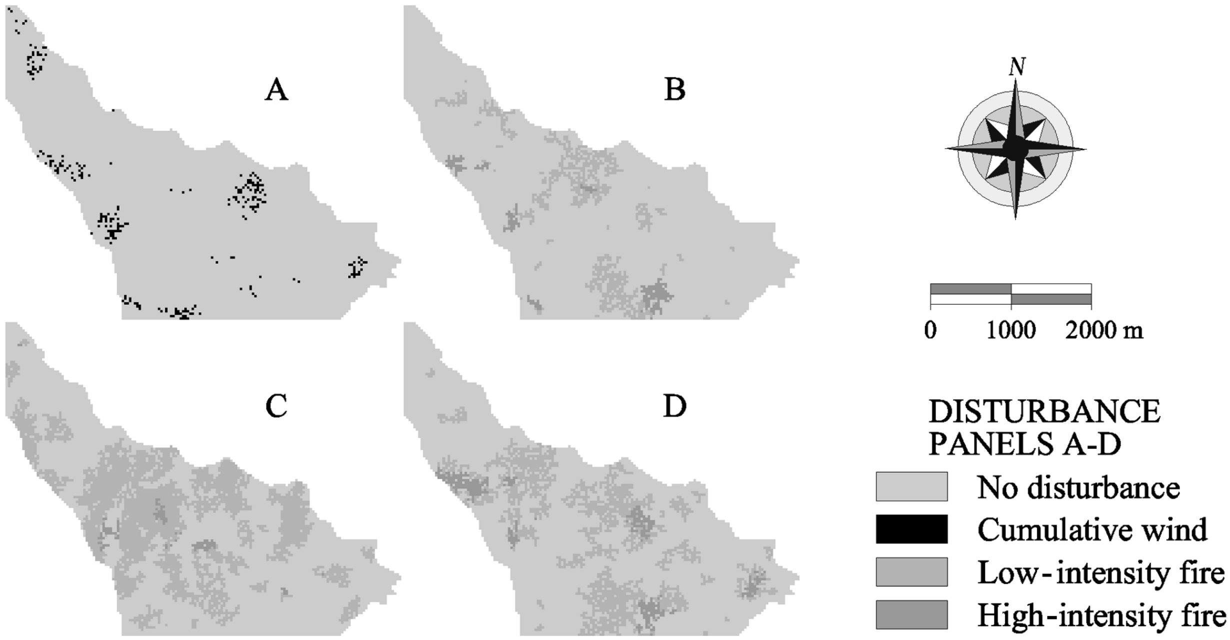


Fig. 4. Missouri study area landscape under three different harvest practices showing (A) Cumulative wind disturbance over 100 years under the no-harvest scenario. (B) Cumulative fire disturbance over 100 years, no-harvest scenario. (C) Cumulative fire disturbance over 100 years, even-aged harvest scenario. (D) Cumulative fire disturbance over 100 years, uneven-aged harvest scenario. The effects of fire disturbance are visible in the age-class patterns of the managed and the unmanaged landscapes shown in Fig. 3. Location of individual wind and fire events is randomly determined subject to user-specified constraints on disturbance size and severity. Consequently, multiple simulation runs for a given landscape will result in different spatial patterns but comparable total impact.



than did the no-harvest simulation. Toward the end of the simulation period, however, the majority of the no-harvest landscape moved into the higher (>150 years) age-classes and increased in susceptibility to fire damage.

Discussion

The model framework invites evaluation and comparison of management alternatives. Interesting alternatives for this landscape would include retention of larger areas with old-forest characteristics by restricting harvest activities in portions of the landscape. In the presentation of these examples, we focused on comparison of forest size classes. Maps and related statistics can also be produced for species composition, forest type, forest age, or harvested openings. The spatially explicit modeling approach also provides opportunities to link other resource values to the landscape, such as wildlife habitat quality for selected species, distance of harvested stands from roads, or visual quality. One of the strengths of this modeling technique is the ability to both visually and analytically monitor changes in the landscapes over time and observe changes by decade. In addition to providing the basis for spatial analyses, the maps provide an important medium through which resource managers and the public can view and discuss patterns of landscape change over time.

The capabilities of LANDIS now provide a tool to more fully investigate ecological response to forest management than was possible with other harvest simulation models. Because LANDIS does not simulate individual trees and lacks stand-density information, it is not a project-level harvest scheduling tool, but it does provide important insight into the spatial and compositional impacts of forest-management alternatives. Previous harvest-simulation models have a limited suite of harvest treatments that can be applied to a landscape, and the treatments are relatively inflexible. These models have limited ability to implement alternative decision rules to determine how harvests are allocated on the landscape. Nevertheless, because these models have limited data requirements they are suited to broad, strategic management questions related primarily to spatial pattern of openings. LANDIS now incorporates much more detail about stand structure and composition in the algorithms for allocating harvests, making LANDIS well suited for exploring more detailed questions about the interaction through time of current stand conditions, economic forces, and management strategies. Furthermore, LANDIS is able to simulate succession as a consequence of disturbance by vegetation management, providing insight into changes in both spatial pattern and forest composition produced by management alternatives.

The algorithms we have developed for modeling forest management in LANDIS include a number of novel approaches that enhance flexibility and allow additional or modified capabilities to be added with minimal code changes or system redesign. The use of independent ranking algorithms to select stands for harvest allows new ranking algorithms to be developed to allow other management goals to be incorporated into LANDIS. Because the timing, the spatial arrangement, and the cohorts to be removed can all be specified independently, a large number of harvest prescriptions can be designed to implement specific management scenarios.

We have identified some future enhancements to the harvest algorithms in LANDIS. The rules for removal of species and

Table 3. Initial and final landscape characteristics for three management scenarios applied to an 836-ha landscape in southeastern Missouri.

Landscape characteristic	Initial for all simulations	Management scenario: No harvest after 100 years	Even aged after 100 years	Uneven aged after 100 years
Forest composition (%)				
Black–scarlet oak	56.2	52.3	63.9	60.5
Mixed oak	33.3	34.1	16.7	23.9
Oak–pine	0.0	1.4	13.7	8.6
Shortleaf pine	10.5	12.0	5.7	7.0
Maple*	0.0	0.2	0.0	0.0
Size class (%)				
Seedling	0.0	1.3	16.8	14.2
Sapling	0.0	3.2	27.1	18.2
Pole	0.0	1.2	18.4	10.5
Sawlog	98.8	91.6	37.6	55.7
Uneven	1.2	2.7	0.1	1.4
No. of patches				
Seedling	0	50	147	494
Sapling	0	68	84	476
Pole	0	61	123	415
Sawlog	1	4	48	60
Uneven	110	215	8	115
All	111	398	410	1560
Mean patch size (ha)				
Seedling	0.0	0.2	1.0	0.2
Sapling	0.0	0.4	2.7	0.3
Pole	0.0	0.2	1.3	0.2
Sawlog	832.4	192.9	6.6	7.8
Uneven	0.1	0.1	0.1	0.1
All	7.6	2.1	2.0	0.5
Mean patch size (ha)				
Black–scarlet oak	17.5	8.6	20.7	26.8
Mixed oak	0.7	0.8	0.2	0.3
Oak–pine	0.0	0.1	0.2	0.1
Shortleaf pine	0.2	0.2	1.1	0.1
Maple	0.0	0.1	0.0	0.1
All	0.8	0.8	0.6	0.5
Length of edge (km)				
Seedling	0.0	10.2	66.6	108.5
Sapling	0.0	21.8	92.6	132.0
Pole	0.0	11.1	71.3	87.1
Sawlog	12.8	63.7	79.3	226.7
Uneven	12.8	28.7	1.0	14.3

Note: Age-classes were grouped into broad forest size classes for these summaries: seedling, 0–9 years; sapling, 10–29 years; pole, 30–59 years; sawlog, ≥60 years; uneven, ages span three or more size classes (e.g., sapling and sawlog).

*Species composition is based on the dominant species group for each cell. Although maples were present on the initial landscape, they always occurred beneath older oaks. Hence, no maples are reported in the forest composition summary for the initial landscape.

age cohorts are not dependent on the species and cohorts actually present on the cell. In reality, a forester making decisions about what to cut on a site, looks at the composition present and chooses what to remove based on what is there. We envision rules that will function in a similar way, using algorithms to specify the removal rules on a cell by cell basis, implementing the prescription in a dynamic way.

Harvest prescriptions are now static, and prescriptions may be applied when they are not appropriate, given conditions within a management area. Perhaps dynamic rules can be developed to trigger (prescribe) harvest events when certain conditions within the management area are true. These capabilities would allow study of the interaction of landscape conditions and the behavior of managers (rules) and perhaps provide more realistic simulation of vegetation management. However, for many immediate research needs,

Table 4. Simulated disturbances by harvest, wind, and fire for three management scenarios.

	Management scenario		
Disturbance type	No harvest	Even aged	Uneven aged
Harvest (ha/decade)	0	88 (3)	66 (0.4)
Fire (ha/decade)	11 (10)	31 (22)	25 (18)
Wind (ha/decade)	2 (3)	1 (0.4)	1 (1)

Note: Values are mean per decade over a 100-year simulation, with SD given in parentheses.

LANDIS provides the generality necessary to answer questions related to timber management and the resulting changes in forest composition and spatial pattern.

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