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Influence of forest planning alternatives on landscape pattern and ecosystem processes in northern Wisconsin, USA

Patrick A. Zollner[a,*], L. Jay Roberts[b], Eric J. Gustafson[c], Hong S. He[d], Volker Radeloff[e]

[a] Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN 47906, United States
[b] Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48824, United States
[c] USDA Forest Service, Northern Research Station, 5985 Highway K, Rhinelander, WI 54501, United States
[d] Department of Forestry, University of Missouri, Columbia, MO 65211, United States
[e] Department of Forest Ecology and Management, University of Wisconsin, Madison, WI 53706, United States

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Abstract

Incorporating an ecosystem management perspective into forest planning requires consideration of the impacts of timber management on a suite of landscape characteristics at broad spatial and long temporal scales. We used the LANDIS forest landscape simulation model to predict forest composition and landscape pattern under seven alternative forest management plans drafted for the Chequamegon-Nicolet National Forest in Wisconsin. We analyzed 20 response variables representing changes in landscape characteristics that relate to eight timber and wildlife management objectives. A MANOVA showed significant variation in the response variables among the alternative management plans. For most (16 out of 20) response variables, plans ranked either directly or inversely to the extent of even-aged management. The amount of hemlock on the landscape had a surprising positive relationship with even-aged management because hemlock is never cut, even in a clear cut. Our results also show that multiple management objectives can create conflicts related to the amount and arrangement of management activities. For example, American marten and ruffed grouse habitat are maintained by mutually exclusive activities. Our approach demonstrates a way to evaluate alternative management plans and assess if they are likely to meet their stated, multiple objectives.
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1. Introduction

Management of forests for a stable supply of products and amenities while insuring the maintenance of healthy ecosystems requires consideration of long time periods and broad spatial areas (Shifley et al., 2000; Boutin and Herbert, 2002). In the past 50 years there has been a shift in the goals of forest management to produce more non-timber benefits such as wildlife habitat (Bettinger and Chung, 2004). Ecosystem-based approaches to managing dynamic forest landscapes emphasize the maintenance of ecological processes as the key to sustaining economic and non-economic benefits. Sustaining ecological processes necessitates planning at multiple spatial and temporal scales (Crow, 2002), and accounting for complex interactions among natural and management processes (Mladenoff and Pastor, 1993; Kurz et al., 2000).

Applications of ecosystem science to forest management are often limited by significant informational gaps regarding the cumulative impacts and interactions of management actions on ecosystem processes (Mladenoff and Pastor, 1993; Mladenoff, 2004). Forest managers possess a wide variety of tools for assessing the results of timber management, but the majority of these are aspatial (Turner et al., 2002; Bettinger and Chung, 2004). The growing importance of resource goals that rely upon the appropriate juxtaposition of management activities (e.g. wildlife habitat, stream buffers) emphasizes the need to explicitly consider the spatial implications of forest management actions at appropriate temporal and spatial resolutions.

* Corresponding author at: Department of Forestry and Natural Resources Purdue University, 1195 Marsetller Street, West Lafayette, IN 47906, United States. Tel.: +1 765 496 9495; fax: +1 765 496 2422.
E-mail address: pzollner@purdue.edu (P.A. Zollner).

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Spatially explicit simulations of forest succession and disturbance (including timber harvesting) provide a crucial tool for understanding the interactions between ecosystem processes and management activities (Crow, 2002; Boutin and Herbert, 2002). The long lifespan of trees and slow transition of some forest communities necessitates simulations that span many decades to centuries. Landscape simulators have been used to assess patterns of disturbance by wildfire (Gustafson et al., 2004; Sturtevant et al., 2004a), susceptibility of a landscape to outbreaks of forest pests (Sturtevant et al., 2004b), volume of coarse woody debris on the forest floor (Shifley et al., 2000), distribution of old growth patches across landscape (Klenner et al., 2000; Perera et al., 2003), and the distribution of woody biomass across landscapes (Scheller and Mladenoff, 2004). The spatially explicit output of these simulations allows for quantification of the landscape characteristics that respond to forest management over time and that are indicators of key ecosystem processes. These landscape characteristics include forest composition, age class distributions, patch size distributions, forest fragmentation and wildlife habitat (Marzluff et al., 2002; Akcakaya et al., 2003; Radeloff et al., 2006). Thus, forest landscape simulation models such as those reviewed by Scheller and Mladenoff (2007) offer great utility for forest planning and management.

Important differences in landscape characteristics and ecosystem function have been found with the Lake States region of North America by comparing remnant old growth landscapes with managed forests. Modern landscapes contain structurally simpler forests with fewer tree species and smaller patches (Mladenoff et al., 1993). This change resulted from extensive clear cutting and burning 75–150 years ago followed by a dramatic shift toward subsistence agriculture and timber harvesting. The resulting changes in structural diversity, age class distributions, and disturbance intervals have altered ecological processes within this region to a state that rarely existed naturally (Mladenoff and Pastor, 1993). These changes have a profound impact on wildlife habitat configuration, connectivity, and ecological processes such as disturbance (Crow et al., 1999). Modern landscapes are also depauperate of older age classes of several tree species that were once historically important in this region and are now rare as dominant species in large patches (Schulte et al., 2002), including hemlock (*Tsuga canadensis*), red pine (*Pinus resinosa*), and white pine (*Pinus strobus*).

The Chequamegon-Nicolet National Forest (CNNF) in northern Wisconsin used knowledge of the links between landscape pattern and ecosystem function to design management "alternatives" (Table 1) as part of its forest plan revision process (CNNF, 2004a). The range of alternatives considered represents the efforts of the CNNF to manage landscape pattern rather than to allow pattern to emerge from a series of independent aspatial decisions. The alternatives share some objectives such as; increasing the size of patches to maintain forest interior conditions, increasing the occurrence of mid to late successional forest types, and decreasing the interspersion of early successional habitat within blocks of late successional habitat (Crow et al., 2006). However, a diverse array of ecosystem conditions are also explicit management objectives, including habitat for specific wildlife species.

Table 1
Description of the alternative forest plans simulated using LANDIS. The alternatives were developed for the Chequamegon-Nicolet National Forest Plan revision process, except the 'no-harvest' baseline alternative (A), which was developed for comparative purposes for this study. For each alternative the last column lists the percent of the study area where even aged harvesting practices were implemented during each decade of the simulation

Alternative	Management objective	% Even aged
A	No harvest (baseline alternative)	0.00
B	Decrease aspen and increase hardwoods	4.34
C	Emphasize ecosystem restoration	4.70
D	Increase hardwoods and restore ecosystems	4.86
E	Decrease aspen increase pine and hardwoods	5.05
F	Emphasize saw timber (pine and hardwoods)	5.46
G	Maintain aspen increase pine and hardwoods	5.93
H	Emphasize early-successional habitat (aspen)	6.60

We used a landscape level forest succession and disturbance model (LANDIS) to simulate forest dynamics under the alternative forest plans developed by the CNNF (Table 1). We examined whether these plans differed in their impacts on ecologically important landscape characteristics (Table 2). Because even-aged management produces the greatest disruption in the continuity of forests (Lord and Norton, 1990), we hypothesized that the relative impacts of the alternatives on landscape pattern (Table 2) will be directly related to the amount of even-aged management prescribed within each alternative. We consider how the alternatives affect (1) the extent to which the resulting landscapes are dominated by a single forest type, (2) the frequency of occurrence of early and late successional forest types across the study area, (3) the total area and patch characteristics (patch size and complexity of shape) of three tree species (eastern hemlock, red pine, and white pine), and (4) the potential of the resulting landscapes to provide habitat for American marten (*Martes americana*), ruffed grouse (*Bonasa umbellus*) and Kirtland's warbler (*Dendrocia kirtlandii*).

In this study, we assess the efficacy of these alternative plans at meeting the CNNF's ecosystem function objectives by monitoring the amount and spatial pattern of habitat for three wildlife species with very different habitat requirements. The American marten is a small carnivorous mammal that is a state threatened species and is strongly associated with large blocks of mature northern hardwoods habitat in Wisconsin (Gilbert et al., 1997; Wright, 1999). The ruffed grouse is a popular game bird (Fearer and Stauffer, 2003) that is strongly associated with areas where there is an even mixture of age classes of early successional aspen (Rickers et al., 1995). The Kirtland's warbler is a federally threatened migratory song bird that occurs rarely in Wisconsin (Probst et al., 2003) and is strongly associated with early successional jack pine (*Pinus banksiana*) on xeric land types (Probst, 1986). The land allocated to habitat for any of these species can eliminate habitat for the others, illustrating the difficulty of managing forest landscapes for multiple objectives.

Table 2
Response variables used to describe the influence of management alternatives on forest succession variables of interest

Question addressed	Variable used
Quantify diversity of cover types	Relative landscape dominance
Quantity of early successional deciduous	Area containing aspen 0–40 years old
Quantity of late successional deciduous	Area containing northern hardwoods >60 years old
Quantity of tree species of management concern	% Change in total area containing hemlock >120 years old
	% Change in total area containing red pine >120 years old
	% Change in total area containing white pine >120 years old
Quantify landscape characteristics of selected cover types	Average patch area of northern hardwoods >60 years old
	Fractal dimension of northern hardwoods patches >60 years old
	Average patch area of hemlock >120 years old
	Fractal dimension of hemlock patches >120 years old
	Average patch area of red pine >120 years old
	Fractal dimension of red pine patches >120 years old
	Average patch area of white pine >120 years old
	Fractal dimension of white pine patches >120 years old
Influence on American marten (a state threatened species)	Area containing potential marten habitat
	Average patch area of potential marten habitat
Influence on Kirtland's warbler (a federally endangered species)	Area containing potential Kirtland's warbler habitat
	Average patch area of potential Kirtland's warbler habitat
Influence on ruffed grouse (an important game species)	Area containing potentially suitable ruffed grouse habitat
	Average patch area of potentially suitable ruffed grouse habitat

2. Methods

2.1. Study area

We studied management alternatives on two Ranger Districts (RD) of the Chequamegon-Nicolet National Forest (CNNF), located in northern Wisconsin, USA (Fig. 1). Our simulations included only the upland forests (218,000 ha) on national forest lands within the Washburn and Great Divide RDs (approximately 20% of the total area of the CNNF). The Washburn and Great Divide RDs are representative of the land-type composition of the entire CNNF. Quaternary geology and mesoclimatic gradients are the primary determinants of environmental variation in the region. The northern portion of the Washburn RD is within the Bayfield Sand Plains Subsection (Keys et al., 1995), and is characterized by well-drained outwash sand deposits and jack pine and red pine forests. Several natural barrens (land type 5, Fig. 1) are found here, and fire has historically been a dominant

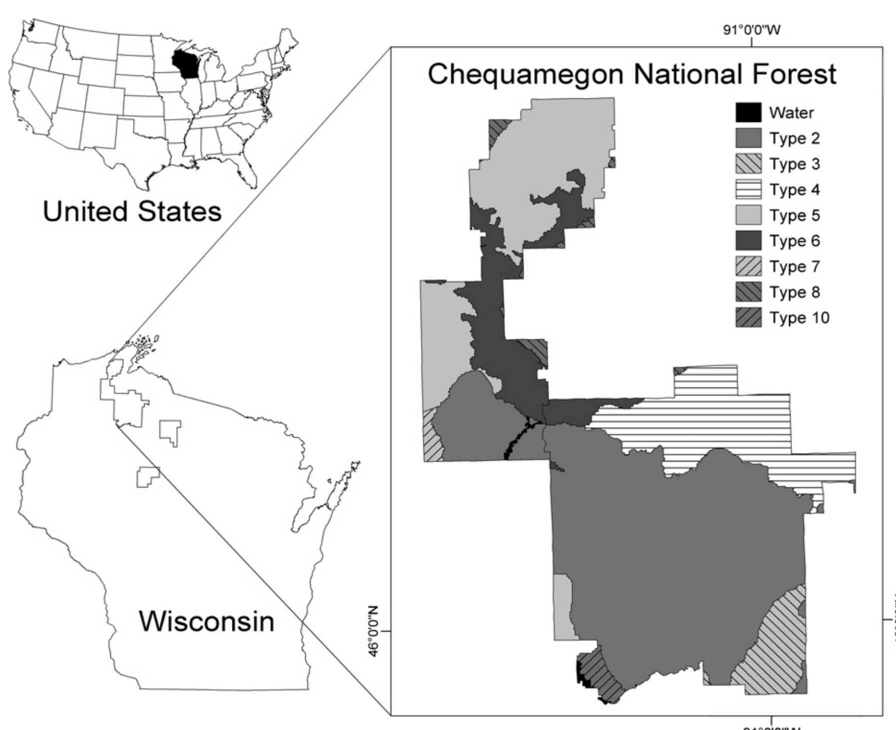

Fig. 1. Land type boundaries within the study area. See Gustafson et al. (2004) for descriptions of land type characteristics. The inset depicts the location of the study area in the Chequamegon-Nicolet National Forest in Wisconsin, USA.

driver of ecosystem processes. The southern portion of the Washburn RD and the Great Divide RD are located mostly within the Winegar Moraine and Central Wisconsin Loess Plain Subsections, characterized by glacial till and mixed deciduous and hemlock forests that are dominated by sugar maple (Schulte et al., 2002). Fire was historically less common in these subsections. Fires are routinely suppressed in the region, but wind disturbance is regular (Canham and Loucks, 1984).

2.2. Simulation scenarios

We simulated 250 years of landscape change in response to seven draft alternatives developed by the Plan Revision Team of the CNNF as of early 2001 (Table 1). We choose to truncate our simulations at 250 years because the objective of this study was to assess the relative outcomes of projections based upon each planning alternative and simulations of a 250 years duration were sufficient in pilot studies to clearly delineate the relative rankings of alternative plans for all response variables (unpublished data). Presumably this stability in the relative rankings of alternatives for our response variables relates to the age for maturity of the tree species we modeled. The alternative forest plans differ in the amount and spatial arrangement of the various Management Areas (MAs) (Fig. 2). MA objectives are achieved through the application of generic harvest prescriptions (Table 3). The amount, timing and type of harvest

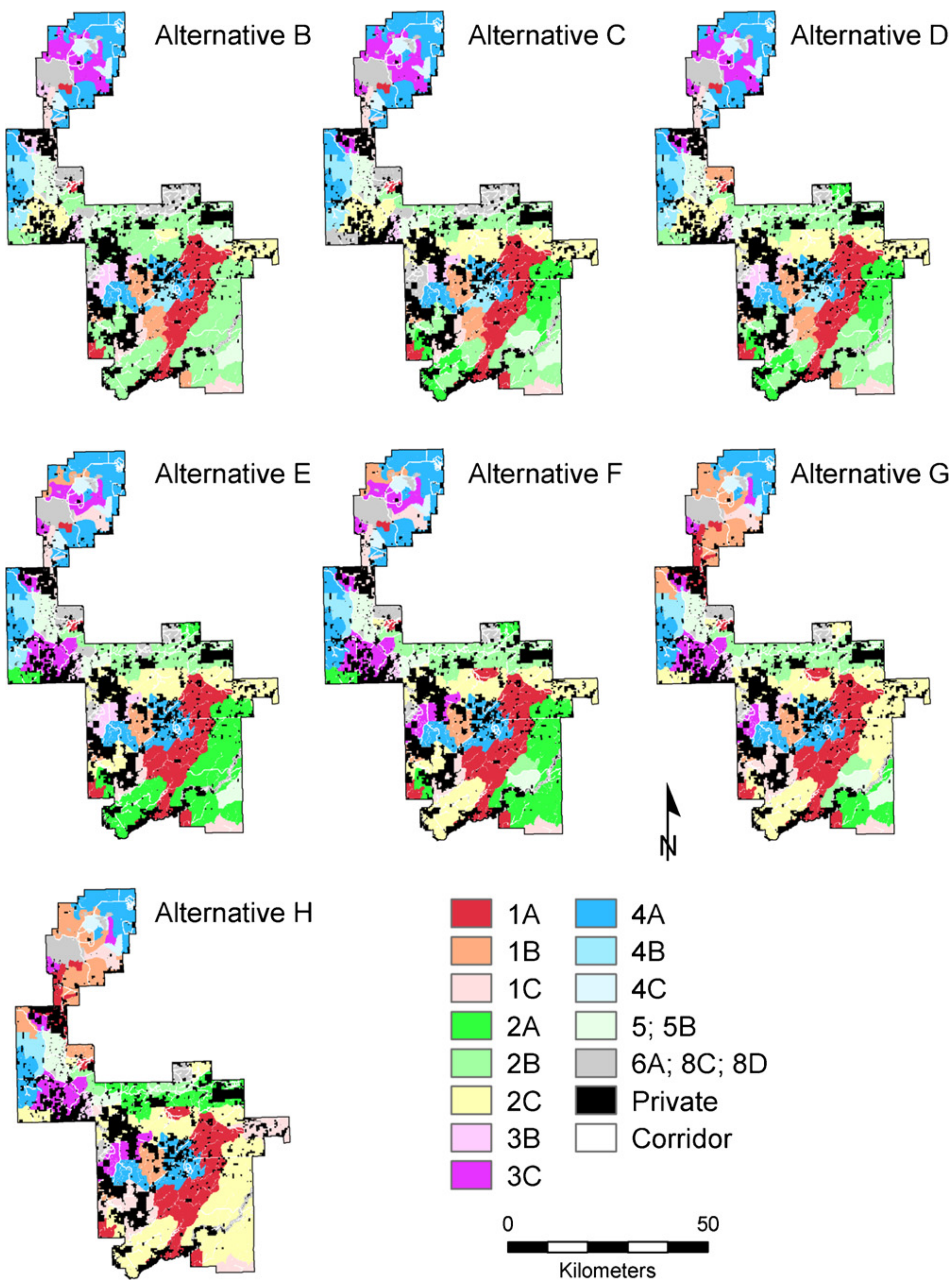

Fig. 2. Management area boundaries for each alternative that incorporated forest harvesting. See Table 3 for a description of what proportion of the study area received each prescription for each alternative. See Table 4 for a description of the simulated harvests within the boundaries of each prescription.

Table 3
Management Area (MA) objectives and the percentage of each MA that was treated in each decade by various silvicultural treatments (prescriptions) as calculated by CNNF staff from the Spectrum linear programming model. MA boundaries for each alternative are shown in Fig. 2. MA designations were developed by the CNNF Planning team

MA	Management objective	Selective tree harvest	Clear cut no regeneration	Clear cut plant jack pine	Clear cut plant red pine	Clear cut plant spruce	Clear cut mechanical site prep for paper birch	Shelterwood underplant white pine	Shelterwood underplant red oak	Shelterwood mechanical site prep for balasam fir	Prescribed fire
1A	Early successional aspen	6.21	10.88	0.08	0.19	0.12	0.11	0.12	0.10	0.34	0.00
1B	Early successional aspen-conifer	2.13	8.77	0.63	0.77	0.09	0.40	0.16	0.14	0.29	0.00
1C	Early successional aspen-hardwood	6.40	9.21	0.05	0.41	0.21	0.06	0.12	0.32	0.28	0.00
2A	Uneven-aged northern hardwoods	5.45	1.21	0.16	0.09	0.05	0.05	0.19	0.30	0.05	0.00
2B	Uneven-aged northern hardwoods interior	23.12	0.96	0.05	0.03	0.00	0.05	0.28	0.21	0.04	0.00
2C	Uneven-aged northern hardwoods early successional	16.33	5.79	0.15	0.19	0.07	0.06	0.18	0.72	0.08	0.00
3B	Even aged hardwoods: oak-pine	11.47	1.34	0.20	0.05	0.01	0.05	0.16	3.37	0.07	1.50
3C	Even aged hardwoods: oak-aspen	4.30	6.24	0.45	0.47	0.00	0.47	0.05	2.10	0.05	0.75
4A	Conifer: red-white-jack pine	0.26	4.73	1.75	2.34	0.02	0.22	0.19	1.33	0.02	0.50
4B	Conifer: natural pine-oak	0.03	0.90	0.50	0.57	0.00	0.11	0.90	2.39	0.02	1.00
4C	Surrogate barrens jack pine-aspen	0.00	4.30	3.83	1.70	0.00	0.06	0.09	0.96	0.01	0.80
5	Wilderness	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6A	Semi-primitive non-motorized	3.00	0.00	0.00	0.00	0.00	0.00	1.5	1.5	0.00	0.00
8C	Moquah barrens and riley lake	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00
8D	Wild scenic and recreational rivers	5.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
8E	Research natural areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
8F	Small natural areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
8G	Old growth areas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Cor	Corridor	6.80	0.00	0.00	0.00	0.06	0.00	0.69	0.27	0.00	0.00

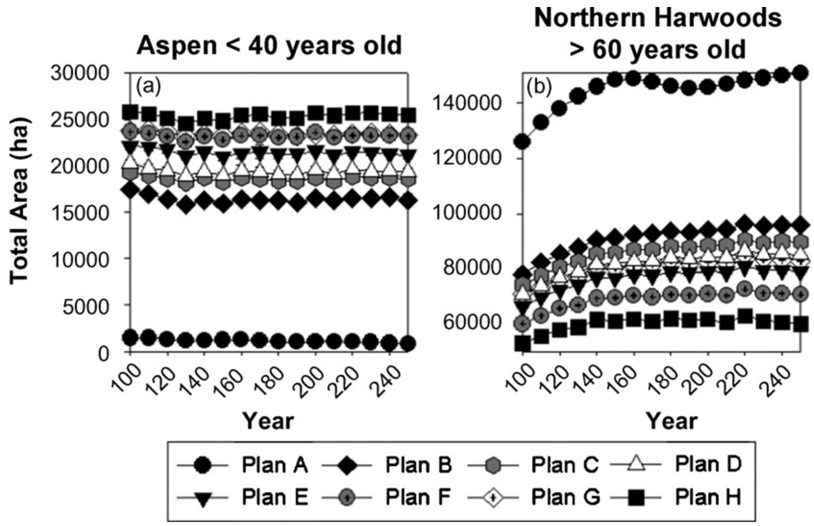

Fig. 3. Total area containing (a) aspen <40 years old and (b) northern hardwoods >60 years old during the last 150 years of the simulation for all nine simulated alternatives. Error bars represent two standard deviations for five replicate simulations, where error bars are not apparent, they are hidden by the symbols. The total amount of aspen area in alternative A is the result of natural disturbances because no harvesting took place.

treatment for each MA was generated by CNNF personnel using the linear programming model Spectrum. Harvesting prescriptions are the same for each MA designation regardless of alternative, so it is only the MA maps that differ among the alternatives (see Fig. 3). The different amounts (Table 4) and arrangements of MAs in the alternatives provided a range of forest conditions that varied according to the objectives of each alternative (Table 1). For comparative purposes we also simulated a 'no-harvest' alternative (Plan A) that was not proposed by the CNNF. We assigned labels to the plans according to amount of even-aged management, from the lowest (A) to highest (H). The simulations held all potentially confounding factors constant so that the differences in response among alternatives can be attributed to the alternatives.

2.3. LANDIS model

We used LANDIS v3.7 to simulate the seven CNNF alternatives. LANDIS was designed to simulate the ecological processes of succession, fire, wind, and timber management across large (10^4–10^7 ha) landscapes and long time scales (50–1000 years). LANDIS simulates succession using the vital attributes of tree species, and natural and anthropogenic disturbances using key spatial and process attributes (Mladenoff, 2004). The design and behavior of the model and model testing are described in detail elsewhere (He et al., 1999; He and Mladenoff, 1999a,b). LANDIS is well suited to predicting relative differences between scenarios and assessing landscape trajectories over long time periods.

Table 4
Percent of the study area designated to each Management Area under each alternative

MA	Alternative							
	A	B	C	D	E	F	G	H
1A	0	9.63	10.11	9.63	11.75	12.32	13.58	13.58
1B	0	3.86	3.38	4.72	2.72	3.06	8.85	9.71
1C	0	3.51	3.51	3.51	4.62	4.62	4.71	6.9
2A	0	0.01	7.36	7.86	18.14	13.38	3.88	4.88
2B	0	29.01	14.96	18.43	6.01	7.79	8.46	1.92
2C	0	4.66	10.5	10.67	9.26	12.86	19.23	25.03
3B	0	2.84	1.24	2.09	2.09	0.38	1.24	0.38
3C	0	4.23	4.98	4.98	5.48	7.19	4.62	5.49
4A	0	13.37	13.37	13.37	14.54	15.19	11.59	11.59
4B	0	4.01	4.01	4.01	2.84	1.86	1.86	1.86
4C	0	1.76	1.76	1.76	1.76	1.76	1.26	1.26
5	100	1.65	1.65	1.65	1.65	1.65	1.65	1.65
6A	0	3.78	3.68	2.52	2.52	2.34	3.46	0.96
8C	0	2.64	2.64	2.64	2.64	2.64	2.64	2.64
8D	0	0.63	0.58	0.63	0.63	0.58	0.58	0.63
8E	0	0.19	0.36	0.19	0.19	0.19	0.19	0.19
8F	0	0.79	0.8	0.49	0.76	0.49	0.49	0.49
8G	0	2.95	4.63	0.38	1.93	1.23	1.23	0.38
Corridor	0	10.47	10.47	10.47	10.47	10.47	10.47	10.47

LANDIS operates on a raster map where each cell contains information on the presence or absence (not abundance or size) of tree species by their 10-year age-cohorts (i.e. a list of species by age classes). The model also requires a land type map (Fig. 1), which delineates spatial zones that are relatively homogeneous with respect to environmental factors such as climate, soils, and natural disturbance. Land types affect the probability of seedling establishment, fuel accumulation, and fire behavior. Within each simulation time step, succession results from the interaction of tree species' life history parameters (age of reproduction, age of senescence, dispersal distance, shade tolerance, fire tolerance, probability of seedling establishment in different land types, and resprouting capabilities) and disturbance (if any). In this way it is fundamentally different from other forest management simulation models that track the transition between predetermined states (i.e. successional classes or cover types). Succession is therefore an emergent property of the life history of each tree species and the dynamic spatial pattern of cells containing different age cohorts of different species.

LANDIS can simulate a wide variety of forest management activities, including multiple types of timber harvest, mechanical site preparation, prescribed burning, and replanting. The user specifies the details about how management activities remove and/or add age-cohorts of each species on harvested cells. Harvest activity is controlled by a unique set of parameters (Table 3) for each Management Area (MA) that define the amount and type of timber harvesting in each time step. The MA map defines the areas from which stands (homogeneous units of vegetation defined by the CNNF) are selected for harvesting, and in this study the MA map was different for each alternative. Within the MAs, the order in which stands are selected for harvest is based on user specified algorithms that reflect specific management goals. In our application we used the economically based ranking algorithm to mimic actual management practices, with no spatial restrictions (adjacency, buffers, or dispersal parameters). Succession on harvested cells is based on dispersal from neighboring cells and the residual tree species age classes within the cell following harvest or natural disturbance. The timber harvest module of LANDIS is described in detail by Gustafson et al. (2000). We selected model parameters to mimic the reality of management decisions as closely as possible. The long lifespan of some tree species in northern Wisconsin made it necessary to run simulations for more than a century in order to reveal significant differences between management plans.

We simulated wind and fire disturbance regimes, using historical size and frequency parameters for each land type. Disturbances are spatially implemented on the landscape using a stochastic algorithm to approximate the empirically observed disturbance return interval across the land type over a long-temporal scale (e.g., >100 years) (He and Mladenoff, 1999b). LANDIS sequentially simulates windthrow, fire, harvesting, and forest succession at each 10-year time step.

The spatial configuration of tree species presence and seral stages that make up LANDIS output is well suited for mapping potential wildlife habitat (Akcakaya et al., 2003; Larson et al., 2004). However, it is important that habitat be assessed at the scale at which the wildlife species interacts with the landscape (D'Eon et al., 2002) and in locations that provide the best opportunities to establish viable home ranges (Liu et al., 1995). Thus, we used moving window analyses in a GIS to assess habitat conditions at scales appropriate to each wildlife species we modeled (Larson et al., 2003).

2.4. Simulation inputs

Input maps for LANDIS were derived from existing spatial databases, and were gridded to a 60 m (0.36 ha) cell size. The eight land types used in the simulation (Fig. 1) were the same as those used by Gustafson et al. (2004), and were derived from an ecosystem classification system developed by Host et al. (1996) based upon soils and monthly average temperature and precipitation data. The probabilities of species establishment on cells within each land type were derived by He et al. (1999) using the LINKAGES model (an ecosystem process model that synthesizes the response of tree species to soil and climatic characteristics of a site; Pastor and Post, 1986). Windthrow return intervals (approximately 1200 years) were derived from a regional historical and empirical study (Canham and Loucks, 1984; Schulte and Mladenoff, 2005). Our fire disturbance values were not based on the historical fire regime (He et al., 1999), but rather on the modern era of fire suppression with mean fire return intervals ranging from 100 to 700 years depending upon land type (Cardille et al., 2001; Gustafson et al., 2004). Initial forest composition maps (species and age-cohort data) were similar to those used by Gustafson et al. (2004) and were created by assigning values (He et al., 1999) to all the pixels in each stand based on the CNNF GIS database and the composition and age distributions of tree species from the U.S. Forest Service Forest Inventory and Analysis (FIA) database (Hansen, 1992). The life history characteristics of the 23 tree species that we used in our simulations were based on values determined by Mladenoff and He (1999).

Silviculturists familiar with management practices on the CNNF assisted in designing 10 LANDIS harvest prescriptions to emulate the range of forest management practices used on the study area. For MAs (Table 3) that incorporated considerable vegetative management (1A, 1B, 1C, 2A, 2B, 2C, 3B, 3C, 4A, 4B, and 4C) we used a linear programming model (Spectrum) to generate harvest schedules (percentages of the 10 prescriptions per decade for each MA). We used the 1986 Land Management Plan and the 1999 draft Management Area Prescriptions and Standards and Guidelines (CNNF, 2004b) to design harvest schedules for the less intensively managed MAs (5, 6A, 8C, 8D, 8E, 8F, 8G, and corridors, Table 3). The proportional area of each MA treated by each prescription during each decade of the simulation was constant for all alternatives; it was only the allocation of MAs across the study area that differed (Fig. 2).

The frequency and intensity of natural disturbance was similar for each alternative. Each simulation was replicated five times (to create some variation in the patterns of succession observed) with different random number seeds that control the natural disturbance modules. The seeds varied across replicates, but the same set of five random numbers was used for each alternative. Fire probability coefficients for each land type were adjusted according to the techniques described by He and Mladenoff (1999b) to ensure that the amount of fire was similar across replicates, and to account for the interaction between management and fire disturbances (Sturtevant et al., 2004a). These coefficients produced similar patterns of disturbance within each replicate random number seed across all harvesting alternatives but allowed local forest composition (a function of local management prescription that varies with alternative plans) to dictate the extent of the area impacted by each disturbance event. Thus, some of the differences in our response variables may be attributable to indirect interactions of management alternative with the disturbance regime and not solely direct effects of the forest harvesting pattern. However, the objective of this study was not to partition out these direct and indirect effects but instead to understand their cumulative influence upon the relative rank order of these planning alternatives for each of our 20 response variables.

2.5. Response variables

All response variables (Table 2) were calculated by post processing LANDIS output files in ArcInfo (ESRI Redlands, CA) and analyzing the spatial characteristics of the resulting maps using APACK (DeZonia and Mladenoff, 2002). Relative dominance (a measure of departure from maximal diversity (Turner, 1990)) was calculated from a map where cells were assigned to one of eight forest types (aspen, northern hardwood, red and white pine, oak, jack pine, yellow birch and hemlock, spruce and balsam fir). Early successional deciduous forest was defined as cells containing either big tooth aspen (*Populus grandidentata*) or quaking aspen (*Populus tremuloides*) ≤ 40 years of age. Cells containing sugar maple, white ash (*Fraxinus americana*), basswood (*Tilia americana*), or red oak (*Quercus rubra* L.) > 60 years were classified as late successional northern hardwoods. Late successional eastern hemlock, red pine, and white pine types were similarly classified by identifying cells with cohorts >120 years. Response variables were calculated from the total area, average patch size, and patch fractal dimension (a measure of the complexity of patch shape, (Sugihara and May, 1990)) for each type.

We also used LANDIS output to predict habitat for three wildlife species. American marten favor the most structurally complex forest types available, which typically are the oldest ones (Bissonette et al., 1997; Chapin et al., 1998; Forsey and Baggs, 2001). Martens in northern Wisconsin occur most frequently in areas that contain large blocks of contiguous late successional northern hardwood forests (Dumyahn et al., 2008; Gilbert et al., 1997; Wright, 1999). Landscape level models for marten in Wisconsin indicate that home ranges are most likely to be established in areas where at least 58% of the surrounding 341 ha (average home range size for marten in the study area (Dumyahn et al., 2008)) contains suitable cover (Zollner et al., in preparation). The American marten habitat definition included mature northern hardwood forest types >60 years old. We classified cells as suitable marten habitat if a 3.41 km^2 circular window around the cell contained >58% northern hardwoods >60 years of age.

Kirtland's warblers are strongly associated with young (5–23 years old) stands of jack pine (Probst and Weinrich, 1993) and adjacent openings (Houseman and Anderson, 2002) on land types suitable for growing jack pine (Kashian and Barnes, 2000; Kashian et al., 2003). Our model assumed that cells on land type 5 (xeric, fire-prone lands (Sturtevant et al., 2004a) Fig. 1) containing jack pine between 0 and 20 years of age, and adjacent non-forest cells, were suitable for Kirtland's warbler. Kirtland's warblers are also known to prefer large patches of habitat (>200 ha in size; (Zou et al., 1992; Probst et al., 2003)), but do use patches as small as 40 ha (Probst et al., 2003) or even smaller when such patches are found in landscapes dominated by suitable conditions (J. Probst and D. DonnerWright, Pers. Comm. USDA NCRS, October 2004). We therefore classified cells as potential Kirtland's warbler habitat if they were part of contiguous patches of suitable habitat >40 ha in size or if the patches were smaller than 40 ha in size but more than 50% of the area within a 200 ha area contained suitable habitat.

The most important characteristic of ruffed grouse habitat is the interspersion of seral stages of forest types that provide different aspects of its life history needs (Fearer and Stauffer, 2003). In northern Wisconsin, habitat quality is a function of the presence of four different seral stages of aspen within a home range (Rickers et al., 1995). We adapted the habitat suitability index (HSI) model of Rickers et al. (1995) to classify the LANDIS simulation output as ruffed grouse habitat. An HSI value is assigned based on the proportion of four age classes of aspen (brood cover, spring/fall cover, nesting cover, and winter food) in a 7×7 (17.7 ha) window around the cell (Larson et al., 2003). We classified cells containing either big-tooth or quaking aspen of age 0–10 as brood cover, 10–20 as spring/fall cover, 20–40 as nesting cover, and over 40 as providing winter food. The HSI score increases linearly with the proportion of each age class in the window, but no more than 25% of a given age class can contribute to the score. The proportions of each age class in the window are summed to provide an HSI value for the cell that reaches a maximum (1.0) when the window surrounding the cell has an even distribution of the four age classes. We reclassified the HSI map by assigning cells with HSI values ≥ 0.5 as ruffed grouse habitat and all other cells as non-habitat.

2.6. Analysis of model outputs

Statistical analyses were conducted on the results of the year 250 because the rankings of plans remained constant beyond year 100 for all statistically significant response variables (see results, Fig. 3). We analyzed all of the response variables in a multivariate analysis of variance (MANOVA) to test the global hypothesis that the alternative forest plans did not influence the average value of each response variable. The MANOVA was computed using PROC GLM in SAS (1988). Shapiro–Wilk's W values were calculated for each combination of response variable and planning alternative to test for deviations from normality in univariate space by each of these response variables. We used the Pillai's Trace statistic to test our hypotheses because it is the least sensitive of the four multivariate tests provided by SAS to the heterogeneity of variance assumption of MANOVA (Zar, 1999). The 'no harvest' alternative (Plan A) was not included in the MANOVA because this alternative was developed for heuristic comparisons only. Response variables were decomposed into separate ANOVAs to examine each response variable's sensitivity to the alternative forest plans. The no harvest alternative (Plan A) was incorporated into these comparisons to elucidate the magnitude and direction of the effects of management on the response variables. Ryan–Einot–Gabriel–Welsch multiple range tests were used to examine the relative ranks of the alternative forest plans for each response variable.

3. Results

The large variation in response variables seen in early time steps can be attributed to initial conditions (see Section 4), and is consistent with many other similar simulation studies (Xu et al., 2004). The relative ranking of alternative forest plans was constant from year 100 through year 250 (Fig. 3) except for response variables associated with Kirtland's warbler habitat (see below). The MANOVA revealed a significant effect of alternative on the succession related response variables (excluding the no harvest plan A, Table 5). Shapiro–Wilk's W values were greater than 0.78 (with corresponding probability of rejecting the null hypothesis of normally distributed data of between 0.1966 and 0.7485) for all variables except landscape dominance. Shapiro–Wilk's W for landscape dominance was on average 0.62 with a corresponding probability of rejecting the null hypothesis of normality of 0.0033. We made 140 comparisons of Shaprio–Wilk's W, and the Bonferroni corrected critical value suggests that this deviation from normality for landscape dominance is only a minor concern, and we elected to include this variable in the subsequent MANOVA analyses. F statistics revealed that all component ANOVAs except for those related to Kirtland's warblers were highly significant ($P < 0.0001$) with a very high proportion of the variance (average $R^2 = 0.9$) in the simulated data explained by forest plan alternative (Table 5).

Table 5
MANOVA and individual ANOVA results for the 20 response variables quantifying forest succession as a function of the seven alternative forest plans simulated (not including the 'no harvest' alternative). Evaluations were performed on data from year 250 of the simulation

Effect	Management alternative
MANOVA global test of hypotheses	
d.f. (n,d)	120, 84
Pillai's trace	5.46
F	7.07
Prob > F	<0.0001

Source of variation	d.f.	Type III SS	F	Prob > F
Individual ANOVA tests of hypotheses				
Relative dominance of cover type map—model $R^2 = 0.7529$				
Management alternative	6	0.00001829	14.22	<0.0001
Error	28	0.000006		
Total	34	0.00002429		
Area containing aspen age 0–40—model $R^2 = 0.9939$				
Management alternative	6	278335257	767.68	<0.0001
Error	28	1691977		
Total	34	280027234		
Area containing northern hardwoods older than 60 years—model $R^2 = 0.9987$				
Management alternative	6	4359945480	3496.85	<0.0001
Error	28	5818502		
Total	34	4365763981		
Area containing hemlock older than 120 years—model $R^2 = 0.8698$				
Management alternative	6	0.16299406	31.16	<0.0001
Error	28	0.02440762		
Total	34	0.18740168		
Area containing red pine older than 120 years—model $R^2 = 0.9816$				
Management alternative	6	20.02957	249.31	<0.0001
Error	28	0.37492		
Total	34	20.40448		
Area containing white pine older than 120 years—model $R^2 = 0.9939$				
Management alternative	6	25.205	757.9	<0.0001
Error	28	0.155		
Total	34	25.36		

Table 5 (*Continued*)

Source of variation	d.f.	Type III SS	F	Prob > F
Average patch area of northern hardwoods older than 60 years—model $R^2 = 0.9947$				
Management alternative	6	121.24	872.71	<0.0001
Error	28	0.65		
Total	34	121.89		
Fractal dimension of northern hardwoods older than 60 years—model $R^2 = 0.8554$				
Management alternative	6	0.00095	27.6	<0.0001
Error	28	0.00016		
Total	34	0.00112		
Average patch area of hemlock older than 120 years—model $R^2 = 0.8365$				
Management alternative	6	0.2289	23.87	<0.0001
Error	28	0.0448		
Total	34	0.2737		
Fractal dimension of hemlock older than 120 years—model $R^2 = 0.665$				
Management alternative	6	0.00006	9.26	<0.0001
Error	28	0.00003		
Total	34	0.00009		
Average patch area of red pine older than 120 years—model $R^2 = 0.9933$				
Management alternative	6	2.027	689.5	<0.0001
Error	28	0.014		
Total	34	2.041		
Fractal dimension of red pine older than 120 years—model $R^2 = 0.9828$				
Management alternative	6	0.00222	267.24	<0.0001
Error	28	0.00004		
Total	34	0.00226		
Average patch area of white pine older than 120 years—model $R^2 = 0.9961$				
Management alternative	6	8.0053	1176.26	<0.0001
Error	28	0.0318		
Total	34	8.037		
Fractal dimension of white pine older than 120 years—model $R^2 = 0.9889$				
Management alternative	6	0.0033	418.5	<0.0001
Error	28	0.00004		
Total	34	0.00331		
Area containing potential pine marten habitat—model $R^2 = 0.9982$				
Management alternative	6	1421628553	2648.23	<0.0001
Error	28	2505166		
Total	34	1424133719		
Average patch area of potential pine marten habitat—model $R^2 = 0.9083$				
Management alternative	6	61.44	46.24	<0.0001
Error	28	6.2		
Total	34	67.64		
Area containing potential Kirtland's warbler habitat—model $R^2 = 0.1513$				
Management alternative	6	81184.37	0.83	0.5554
Error	28	455364.42		
Total	34	536548.49		
Average patch area of potential Kirtland's warbler habitat—model $R^2 = 0.0268$				
Management alternative	6	0.1259	0.13	0.9917
Error	28	4.5688		
Total	34	4.6947		
Area containing potential ruffed grouse habitat—model $R^2 = 0.9656$				
Management alternative	6	79443300	130.92	<0.0001
Error	28	2831794		
Total	34	82275094		
Average patch area of potential ruffed grouse habitat—model $R^2 = 0.4258$				
Management alternative	6	1.80299	3.46	0.011
Error	28	2.43056		
Total	34	4.42335		

The no harvest alternative (Plan A) created the most landscape dominance, followed by the aspen emphasis alternative (Plan H, Table 6a). None of the remaining plans differed significantly in the degree of landscape dominance (Table 6a). For 16 of the 19 other response variables (Table 6b–t), the alternative forest plans ranked either directly or inversely along a gradient of even-aged management (Table 1). In almost every case, the no harvest alternative (Plan A) and the aspen emphasis alternative (Plan H) were ranked at opposite ends of the order (Table 6). The two exceptions were variables associated with habitat for Kirtland's warblers (which were not significant according to ANOVA tests, Table 5).

Table 6
Results of Ryan–Einot–Gabriel–Welsch (REGW) multiple range tests comparing the seven planning alternatives on the listed response variables at an alpha level of 0.05 for year 250 of the simulation

ANOVA test
(a) Relative dominance of cover type map
A > H > G & B & C & F & E & D
(b) Area containing aspen age 0–40
H > G > F > E & D > C > B > A
(c) Area containing northern hardwoods older than 60 years
A > B > C > E > D > F > G > H
(d) Area containing hemlock older than 120 years
H > G & F & E & C & D & B > A
(e) Area containing red pine older than 120 years
A > B > C > E & D > F > H > G
(f) Area containing white pine older than 120 years
A > B > C > D > E > F > G > H
(g) Average patch area of northern hardwoods older than 60 years
A > B > C > D & E > F > G > H
(h) Fractal dimension of northern hardwoods older than 60 years
H > G & C > C & F & D & E > F & D & E & B & A
(i) Average patch area of hemlock older than 120 years
H > G & F & C & B & E & C & D > A
(j) Fractal dimension of hemlock older than 120 years
H > F & B & E & G & D & C > A
(k) Average patch area of red pine older than 120 years
A > B > C > D & E > F > G & H
(l) Fractal dimension of red pine older than 120 years
A > B > C > D & E > F > H & G
(m) Average patch area of white pine older than 120 years
A > B > C & D > D & E > F > G > H
(n) Fractal dimension of white pine older than 120 years
A > B > C & D > D & E > F > G > H
(o) Area containing potential pine marten habitat
A > B > C > E > D & F > G > H
(p) Average patch area of potential pine marten habitat
A > B & C & E > F & G & D > H
(q) Area containing potential Kirtland's warbler habitat
F & C & G & E & H & B & D > A
(r) Average patch area of potential Kirtland's warbler habitat
C & D & H & F & G & B & E > A
(s) Area containing potential ruffed grouse habitat
H > G > F > D & E > C > B > A
(t) Average patch area of potential ruffed grouse habitat
D & B & C & E & F > B & C & E & F & G & H > A

">" Indicates that the level of the factor on the left was significantly greater than the level of the factor on the right at an alpha level of 0.05 in the REGW multiple range test. "&" Indicates that the levels of the factor were not significantly from each other at an alpha level of 0.05 in the REGW multiple range test.

The total area and landscape characteristics of red and white pine were inversely related to the amount of even-aged management (Table 6e and f). The total area of red pine decreased slightly through time for all alternatives (Fig. 4b). The total area of white pine increased slightly for the alternatives with the lowest levels of even-aged management (Plans B and C) but decreased for all other plans (Fig. 4c). Average patch size and complexity of patch shape for these pine species followed a similar rank order with respect to the amount of even-aged management in the alternatives (Table 6k–n). Conversely, the model predicted that plans with more even-aged management (Plan H) will provide the most hemlock in the largest patches with the most complex shapes (Table 6d, i and j). Total area (Fig. 3) and patch size (Table 6g) of northern hardwood >60 years old was also inversely related to the amount of even-aged management. However, the complexity of the shape of northern hardwood patches was greatest under the aspen emphasis alternative (Plan H) and the ecosystem restoration alternative (Plan C, Table 6h).

The total area and average patch size of marten habitat (Table 6o and p) were related to the gradient of even-aged management, where plans having less even-aged management provided the most marten habitat in the largest patches (Fig. 5). The hardwood restoration (Plan D) and increase pine (Plan E) alternatives were juxtaposed in their rankings (Table 6o and p), but these two plans differ in the amount of even-aged management by less than 0.2%. The influence of management alternative on the response variables associated with Kirtland's warbler habitat (total area and average patch size) was statistically insignificant (Table 5). The only significant difference was between the no harvest alternative (Plan A), which provided no Kirtland's warbler habitat, and all of the rest of the alternative forest plans, which on average provided between 600 and 1200 ha of Kirtland's habitat (Fig. 6 and Table 6q and r). There was more variation in the amount of Kirtland's warbler habitat than for any other response variable (Fig. 6).

The amount of ruffed grouse habitat was directly related to the amount of even-aged management (Table 6s). The aspen emphasis strategy (Plan H) provided the most grouse habitat in the largest patches while the no harvest alternative (Plan A) and the decrease aspen while increasing hardwoods alternative (Plan B) provided the least (Fig. 7). The average patch size of grouse habitat was smallest for the no harvest alternative (Plan A; Table 6t) but the remaining plans were not significantly different.

4. Discussion

Ecosystem based approaches to forest planning emphasize the creation of landscape conditions that support specific ecological processes (e.g. desired mix of early and late successional forest types, maintenance of a range of seral stages, and habitat for specified wildlife species). We used LANDIS to predict forest dynamics and landscape conditions in response to seven alternative forest management plans on the CNNF. Consistent with our hypothesis, our results showed that

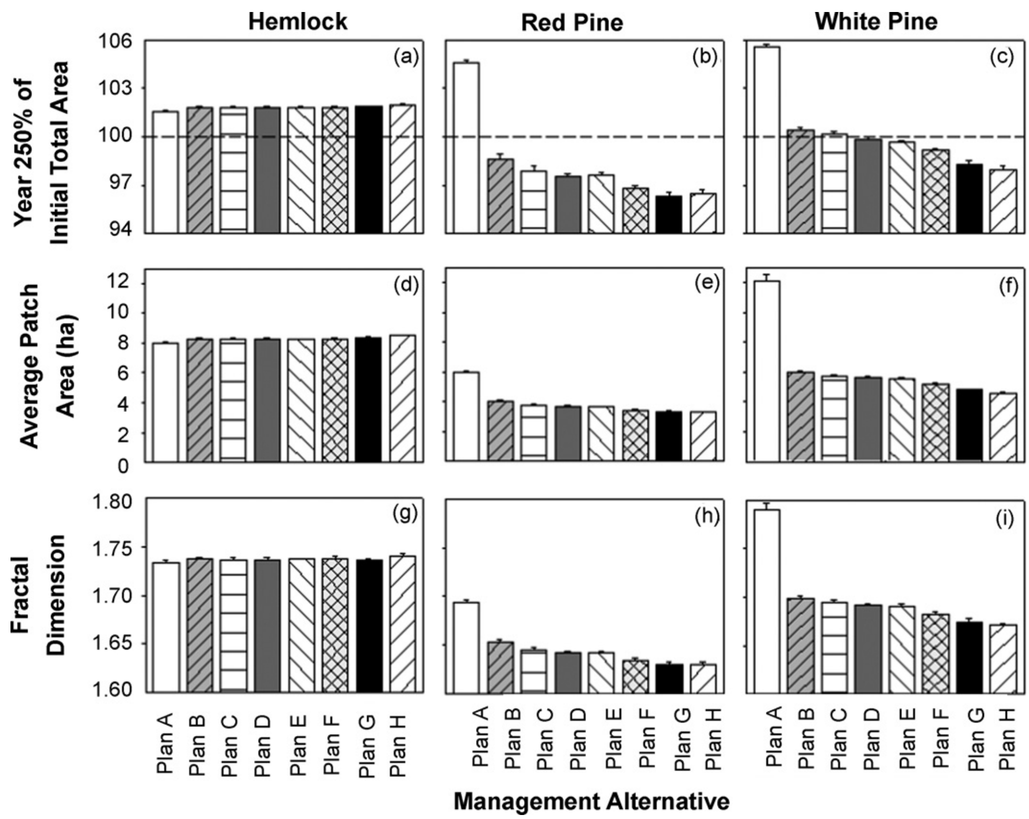

Fig. 4. Response during year 250 of three tree species of management concern (hemlock >120 years old {a, d, g}, red pine >120 years old {b, e, h}, and white pine >120 years old {c, f, i}) to the eight simulated management alternatives. Error bars represent two standard deviations between the five replicate simulations, and indicate the variation caused by natural disturbances. The dashed line on panels a, b, and c indicated no change in simulated totals from initial condition to year 250.

these plans vary greatly in their effects on a suite of response variables. Furthermore, most ecosystem process response variables (16 out of 20) were directly or inversely related to the amount of even-aged management associated with those plans (Table 6).

Our results highlight that ecological systems are complex and individual components may respond to management activities in opposite ways. For example, habitat for marten and ruffed grouse ranked in opposite directions to the extent of even-aged harvesting proposed in each alternative. Marten are sensitive to clear cuts and the fragmented landscape patterns resulting from them (Chapin et al., 1998; Forsey and Baggs, 2001). The alternatives that employed less even-aged management provided more habitat for marten (Soutiere, 1979; Steventon et al., 1998). Conversely, increased even-aged management produced more mixed aspen and thus more grouse habitat (Rickers et al., 1995; Fearer and Stauffer, 2003).

Increasing mature red pine, white pine and hemlock was emphasized in the design of these alternative forest plans because of the historical and ecological importance of these species in this region (Schulte et al., 2002). Our simulation results predict that the amount of mature red and white pine occurring in future landscapes is inversely related to the amount of even-aged management incorporated (Table 6). Interestingly, the amount of hemlock is directly related to this factor (see below). Our simulations also predict that overall abundance of mature pine species should decline slightly in response to most of the management alternatives (Fig. 4), despite the design goals of the alternatives to increase pine. This prediction is consistent with other modeling work that suggests that the development of mature pine in CNNF landscapes may not be achieved by the alternatives (Gustafson et al., 2006). These results together suggest future difficulties for attempts to return older pines to their historic condition in this region and imply that the amount of even-aged management within the landscape should receive attention as a factor affecting the development of mature pines.

Large patches of hemlock were prevalent in pre-settlement landscapes (Mladenoff et al., 1993), and we similarly expected that the no harvest alternative (Plan A) would produce the most hemlock. However, our results showed that the amount of mature hemlock is directly proportional to the amount of even-aged management. Because stands containing hemlock were avoided by the stand ranking algorithms and because none of our simulated prescriptions harvested hemlock from any cells (Table 3), the increased intensity of even-aged management associated with the aspen emphasis alternative (Plan H) created more stands where everything except hemlock was harvested. Because all prescriptions leave hemlock as a residual species, there are more opportunities for hemlock recruitment (Mladenoff and Stearns, 1993).

Pre-settlement landscapes in Wisconsin contained larger patches of more complex shapes (Mladenoff and Pastor, 1993), conditions that can be mimicked with uneven-aged management

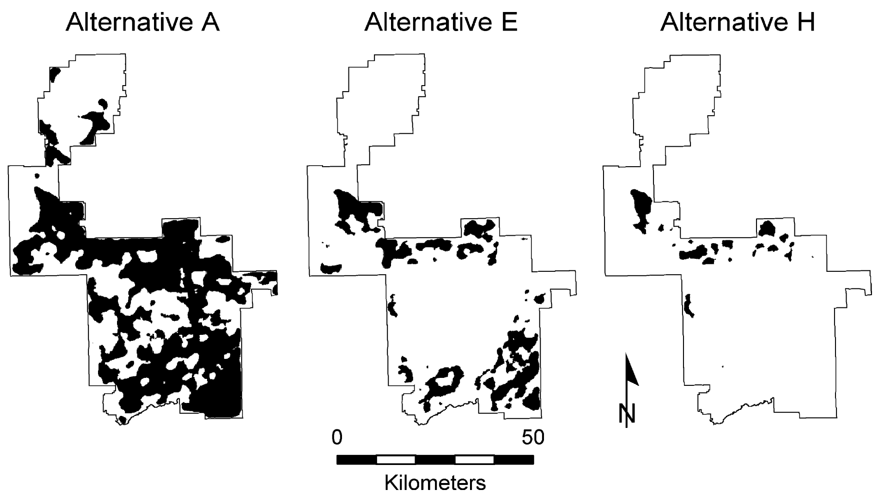

Fig. 5. Spatial arrangement of suitable American marten habitat at simulation year 250 for one replicate of three management alternatives (A, E, H). Scenarios shown represent the range of conditions found in our results.

(Crow et al., 2002). Our simulation results demonstrate that the alternatives rank inversely to the amount of even-aged management for patch size of mature northern hardwoods, red pine, and white pine, while the patch size for hemlock rank positively with the amount of even-aged management. Empirical observations in Wisconsin demonstrate that fragmented landscapes (which incorporate harvesting) contain patches of simpler shape than those on a nearby old growth landscape (Mladenoff et al., 1993). Patch shape of red and white pine sort inversely to the amount of even-aged management while patch shape for mature northern hardwoods and hemlock sorts directly to the amount of even-aged management. These different patch shape relationships for different species are difficult to interpret. For example, the two pine species were replanted by the simulation following selected harvest prescriptions (Table 3) while hemlock and the species that contributed to northern hardwoods were not planted following harvest. Note that all simulated alternatives used the same stand map and that stands were completely harvested in each prescription. Thus, the potential complexity of patch shape in our results may be constrained by the stand map in ways that unbounded harvests were not.

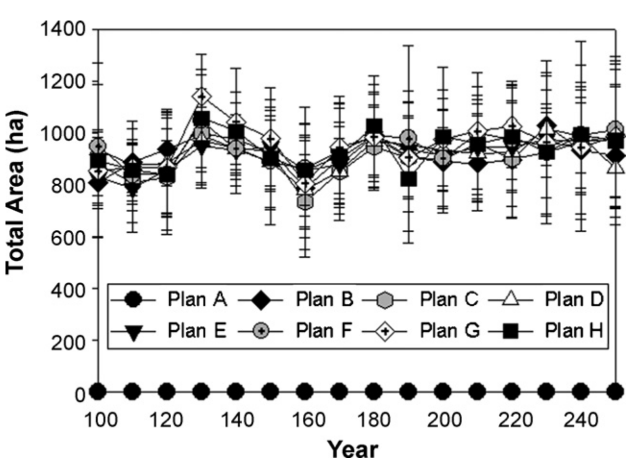

Fig. 6. Total area containing suitable Kirtland's warbler habitat during the last 150 years of the simulation for all eight simulated alternatives. There was no significant difference between any of the plans for Kirtland's warbler habitat. Error bars represent two standard deviations for five replicate simulations.

Four response variables did not rank directly or inversely with respect to the amount of even-aged management in the alternative plans. Two of these were measurements of habitat for Kirtland's warblers (Table 5). The apparent reason for this result was that potential Kirtland's warbler habitat was restricted to a single land type where management prescriptions did not differ between the alternatives (Fig. 2). The third variable was the average patch size of habitat for ruffed grouse, which was weakly related to even-aged management. The size of patches of ruffed grouse habitat may have been less sensitive to planning alternatives because the definition of grouse habitat included the local presence of multiple seral stages of aspen. The simulated prescriptions did not explicitly create these conditions. The fourth variable was forest type dominance. The plans with very little even-aged management (Plan A) and with the most even-aged management (Plan H) produced landscapes that were dominated by a single, but different forest type class. This difference is not detected by the index.

Our results suggest that even subtle differences in the amount of even-aged management (Table 1) can be a primary driver of landscape pattern and forest succession, and that many ecosystem process variables respond directly (either positively or negatively) to this form of management. Thus, the amount of even-aged management implemented in a landscape can be a key factor determining the ecological functioning of a forested landscape. However, there is no simple guideline for determining the amount of even-aged management compatible with healthy ecosystems, because some desired ecosystem processes respond positively to even-aged management and others negatively. Examples include marten habitat versus grouse habitat, total area of mature red and white pine versus area of mature hemlock, and average patch size of mature red and white pine versus average patch size of hemlock. Forest managers must ultimately prioritize among multiple objectives. However, tools such as LANDIS allow managers to quantitatively predict how well the specific amount and distribution of

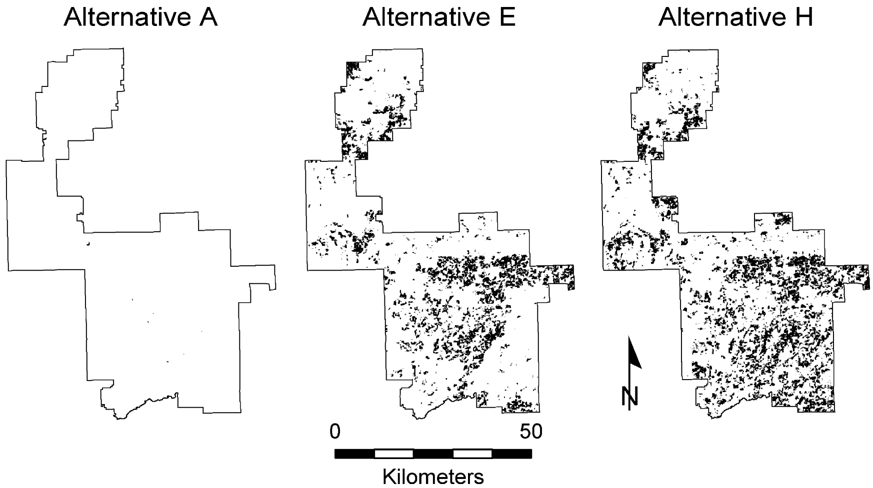

Fig. 7. Spatial arrangement of suitable ruffed grouse habitat at simulation year 250 for one replicate of three management alternatives (A, E, H). Scenarios shown represent the range of conditions found in our results. Alternative H provided the most grouse habitat because it created more early-successional aspen than the other plans.

proposed management activities will achieve the desired mix of objectives.

Applications of the principles of ecosystem science to forest management are often limited by significant informational gaps regarding the cumulative impacts in both time and space of management actions on ecosystem processes (Mladenoff and Pastor, 1993; Mladenoff, 2004). This is problematic as forest planners strive to consider spatial issues in order to address resource goals that are primarily determined by the juxtaposition of management activities in space and time (Bettinger and Chung, 2004). Spatially explicit simulations of forest succession and natural and anthropogenic disturbance provide a potential solution by comparing alternative forest management strategies to understand the interactions between ecosystem processes and management activities (Boutin and Herbert, 2002). Furthermore, landscape models such as LANDIS can facilitate heuristic exploration in planning. The quantitative comparisons from such exercises can inspire innovative solutions to resource conflicts (Klenner et al., 2000). For example, the ability to quantify trade-offs between timber production and wildlife habitat in a spatially explicit predictive framework provides useful information to make decisions and sometimes reveals unanticipated outcomes (Arthaud and Rose, 1996; Kliskey et al., 1999; Marzluff et al., 2002). Our simulations allowed the CNNF to quantify projected effects on specific wildlife habitat characteristics for evaluation by a panel of experts (CNNF, 2004b). CNNF planners were able to assess whether the alternatives addressed concerns about landscape pattern and associated ecosystem functions. Because LANDIS models succession and natural disturbance, it provided the CNNF with ecosystem response projections that other complementary tools (e.g., HARVEST, (Gustafson et al., 2006)) did not.

There are several important caveats to our results and to the approach we used. First, we simulated the implementation of the alternatives for 250 years. We realize that management strategies will undoubtedly change over that time span given that national forest management plans are updated every 10–20 years, and other exogenous factors such as global change and invasive species will affect forest dynamics. We have not shown the results of our simulations from time steps less than 100 years due to the large amount of non-equilibrium variation. Our results should be interpreted as projections of the relative outcome of alternative management scenarios given a relatively constant environment. LANDIS projects the long-term ecological trajectory expected under a specific management and disturbance regime rather than absolute predictions of future conditions (Shifley et al., 2000). Therefore, these results are useful for comparing alternatives to each other, but provide little insight into tactical management strategies or economic and timber volume objectives. Second, the alternatives that we simulated were designed to meet objectives across the entire CNNF, but we simulated the response on only two ranger districts. Although we chose these two districts because they are representative of the entire national forest, it is unreasonable to expect that the objectives should be fully met on just two districts. Third, constraints represented by the initial forest conditions (e.g. stand boundaries) represent a legacy that may limit the ability of any planning alternative to reach objectives such as patch sizes for desired cover types (Mehta et al., 2004; Radeloff et al., 2006). Fourth, our wildlife habitat response variables rely upon landscape level spatial patterns of forest types and seral stages to define habitat (Roloff and Haufler, 1997; Cooper and Walters, 2002). However, these habitat variables certainly do not capture all of the components of habitat for the species we studied (Kliskey et al., 1999; Larson et al., 2004). Furthermore, our projections quantify only potentially suitable habitat, but do not address population viability. If we had incorporated wildlife population models into our study (Akcakaya et al., 2003), the plans may have ranked differently. Finally, LANDIS is not designed to track timber-harvest volumes or economic output directly, however economic constraints (such as non-declining timber volume outputs) were included in the Spectrum schedules developed by the CNNF (Table 3). Our results show that there are few, if any, spatial conflicts in the alternative forest plans, but we could not assess whether the timber outputs of these plans will satisfy the CNNF's economic objectives.

5. Conclusion

Management of forests for a stable supply of products and amenities requires planning over long time scales and broad spatial areas to insure the maintenance of healthy ecosystems (Shifley et al., 2000; Boutin and Herbert, 2002). Using ecosystem-based management principles provides distinct advantages to fulfilling multiple-use and conservation goals over traditional timber and economic-based forest planning. However, it makes the job of land managers more complex by introducing management targets that can be directly opposed to each other. Forest landscape modelers can help managers balance these goals in space and time, and provide comparative data that can help to choose the most appropriate alternative management scenario. Our simulations predict that alternative forest management plans that vary their timber harvest prescriptions in time and space will produce significantly different landscape patterns. Furthermore, variation in ecosystem process response variables related to landscape pattern is associated with the amount of even-aged management in the alternatives. Some ecosystem characteristics were positively related to even-aged management while others were negatively related. Our approach provides a general method to evaluate the long-term landscape consequences of proposed management alternatives that accounts for forest succession, natural disturbance and forest management activities.

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