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Linking linear programming and spatial simulation models to predict landscape effects of forest management alternatives

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Abstract

Forest management planners require analytical tools to assess the effects of alternative strategies on the sometimes disparate benefits from forests such as timber production and wildlife habitat. We assessed the spatial patterns of alternative management strategies by linking two models that were developed for different purposes. We used a linear programming model (Spectrum) to optimize timber harvest schedules, then a simulation model (HARVEST) to project those schedules in a spatially explicit way and produce maps from which the spatial pattern of habitat could be calculated. We demonstrated the power of this approach by evaluating alternative plans developed for a national forest plan revision in Wisconsin, USA. The amount of forest interior habitat was inversely related to the amount of timber cut, and increased under the alternatives compared to the current plan. The amount of edge habitat was positively related to the amount of timber cut, and increased under all alternatives. The amount of mature northern hardwood interior and edge habitat increased for all alternatives, but mature pine habitat area varied. Mature age classes of all forest types increased, and young classes decreased under all alternatives. The average size of patches (defined by age class) generally decreased. These results are consistent with the design goals of each of the alternatives, but reveal that the spatial differences among the alternatives are modest. These complementary models are valuable for quantifying and comparing the spatial effects of alternative management strategies.

Keywords: Forest management planning; Landscape pattern; Models; Decision support

1. Introduction

Landscape ecology is the study of the reciprocal link between landscape spatial pattern and ecological function (Turner, 1989). Forest ecosystems are a mosaic of patches (stands) of varying tree species, vertical structures, and age classes. The spatial pattern of this mosaic helps determine the functioning of the ecological communities found there. Many species that live in forests require multiple habitat conditions to meet their life history requirements, and they are affected by the landscape context of the habitats in which they live (Mazerolle and Villard, 1999). For example, forest birds may experience higher levels of nest predation if their nests are near edge habitats (Rudnicky and Hunter, 1993; Suarez et al., 1997; King et al., 1998). Although the amount of forest in various age classes across a landscape is an important factor in providing the habitat needed to support a diversity of species, the fragmentation of this habitat into smaller patches also has potential consequences for the viability of populations of many plants and animals (Saunders et al., 1991; Trzcinski et al., 1999).

Diverse habitat conditions are maintained through time by the interaction of disturbance (natural or harvest-based) and forest growth. Forest edge habitats, the amount and distribution of forest interior, and the amount, location, and patch sizes of various seral (successional) stages across the landscape are particularly sensitive to the spatial configuration of harvest activity (Gustafson and Crow, 1999; Gustafson and Rasmussen, 2002). Forest managers have come to recognize this important link, and seek to make strategic management decisions based on spatial

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information. National forest planners must consider the interactions between timber management objectives and forest landscape pattern. They are particularly interested in the consequences of timber management alternatives on the amount and distribution of forest interior and edge habitat, and the patch size distribution of habitat. Many species appear to require large blocks of relatively undisturbed forest to provide the interior habitat conditions (free from impacts associated with edges) in which they live (Hoover et al., 1995; Boulinier et al., 2001). Conversely, other species prefer edge habitats, or use the open habitats created by natural or harvest disturbance to meet their life history requirements (Whitcomb et al., 1981).

Managers of industrial and public land bases are also increasingly examining the effects of management strategies on the multiple benefits derived from forested ecosystems. For example, the Sustainable Forest Initiative of the American Forest & Paper Association requires member corporations to follow specific forestry principles to conserve soil, air and water resources, wildlife and fish habitat, and forest aesthetics (American Forest & Paper Association, 2000).

The National Forest Management Act (1976) requires that US national forests periodically update forest management plans to provide for multiple uses and ecological values. As of late 2001, 12 US national forest plan revisions had been completed, 39 were underway, and 76 needed revision (USDA Forest Service, 2001). The plan revision process requires managers to consider the impacts of a number of management alternatives on biodiversity, timber supply, recreational opportunities, local economies, water quality, and other forest values (Morrison and Marcot, 1995). Models are used to provide important information on many of the projected impacts. The first round of plans, completed mostly in the late 1980s, relied on aspatial linear programming models to assess timber sustainability and species habitat requirements. Since then, many models have been developed to deal with spatial issues such as the patchiness of the forest mosaic, the creation of edge and interior habitat, and harvest adjacency constraints.

Some modeling approaches use optimization to identify timber harvest and wildlife habitat targets (Bevers and Hof, 1999; Turner et al., 2002), while others simulate change produced by management activities (Gustafson, 1996). Optimization and simulation have inherent strengths and weaknesses. For example, most linear optimization models can select from many harvesting options, but only coarsely address spatial details (e.g., area but not adjacency). Simulation models may incorporate many spatial details, but they are not suited for finding optimal solutions to meet specific objectives (e.g., non-declining timber production). A number of heuristic models have also been proposed to address spatial and temporal wildlife habitat and harvest scheduling problems (Bettinger et al., 2002; Mullen and Butler, 2000).

A variety of models are available to managers, planners and researchers (Bettinger and Chung, 2004). Perera et al. (2003) used a Boreal Forest Landscape Dynamics Simulator to explore landscape changes associated with potential for old-growth development. Wimberly (2002) used a different simulation modeling approach, a landscape age-class demographics simulator, to assess fire disturbance effects in old-growth dominated ecosystems in the Oregon Coast Range. Pennanen and Kuuluvainen (2002) adapted LANDIS (He and Mladenoff, 1999; Gustafson et al., 2000) to examine forest composition, the relative occurrence of tree species, and the pattern of the tree age distribution from historic to current times.

These broad-scale approaches are required to understand the role of disturbance in a regional context, but forest managers and planners are also interested in forest-level analyses. Johnson et al. (1998) provided a combination of management (prescribed fire and timber harvest) and natural processes to model landscape change for a national forest. Traditionally, models such as Spectrum and Woodstock (Remsoft Inc., 1996; Maclean et al., 1999) are used to develop forest-level, aspatial harvest schedules. These can be used in conjunction with other software such as HARVEST (Gustafson and Rasmussen, 2002) or Stanley (Remsoft Inc., 2000) to provide spatial simulations of the harvest schedules.

In this study, we assessed the spatial pattern implications of alternative management strategies by linking two models that were developed for different purposes (Leefers et al., 2003). We demonstrate the power of this approach by evaluating alternatives developed for a forest plan revision on the Chequamegon-Nicolet National Forest (CNNF) in northern Wisconsin. The objectives of our study were to (1) demonstrate the linkage of a timber production optimization model (Spectrum v2.6, USDA Forest Service, 1999) and a spatially explicit timber harvest simulator (HARVEST v6.0, Gustafson and Rasmussen, 2002) for a real-world forest management planning problem, (2) predict the long-term effects of specific alternative management plans on forest fragmentation and other landscape characteristics, (3) discuss the ecological implications of the alternatives, and (4) discuss the utility of this approach for strategic forest management planning. We describe a specific case study, but the approach can be applied to examine the spatial implications of any timber harvest optimization model having limited abilities to consider the spatial arrangement of harvests.

2. Methods

2.1. Description of case study area

The CNNF covers over 600,000 ha, and is located in the transition zone between the broadleaf forests to the south and the boreal forests to the north (Fig. 1). It was formerly two separate national forests with two separate forest plans, but has been managed as a single administrative unit since 1993. The ownership pattern of the CNNF is a mosaic of large blocks of public forestland and small blocks of privately owned land within the CNNF proclamation boundaries. Much of the private and other public (county- and state-owned) land in the region is also forested, and these contiguous pieces enhance the interior habitat available on the national forest lands. The CNNF is one of the largest sources of interior forest habitat in the region, which makes it an important source of wildlife habitat. For example, the Nicolet National Forest is on the American Bird Conservancy's list of 100 globally important bird areas (American Bird Conservancy, 2002).

The predominant forest type on the CNNF is northern hardwood, but other types occur, including: (in roughly descending order of abundance) deciduous–conifer forest, aspen monoculture, mixed white pine/red pine forest (including plantations), conifer swamps, jack pine barrens, and bogs (Albert, 1995; Finley, 1976). Most of these forest types receive some form of harvesting, but the intensity varies widely among types.

2.2. Modeling management alternatives

Eight alternatives were developed for the CNNF plan revision to encompass a range of timber production, ecosystem restoration, recreation and other social and economic goals. Because some of the alternatives produced very similar landscape patterns, we present four of the preliminary alternatives (as of July 2002) that highlight the variation in timber production and ecosystem restoration of the full set of alternatives (Table 1). Alternative A follows a 'current plan' direction, where management continues according to the original plans adopted in 1986. Alternative B increases the area managed for early successional habitat. Alternative C is designed for intermediate levels of timber production and ecosystem restoration, with a focus on increased economic output. Alternative D focuses on ecosystem restoration goals through different levels of reduction in early successional (mainly aspen) habitat and/or increase in 'alternative management areas' (such as old-growth) (Chequamegon-Nicolet National Forest, 2002a).

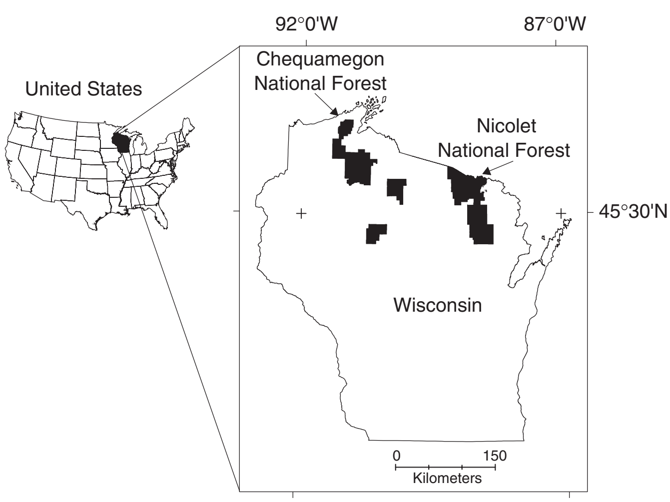

Fig. 1. Map of the study area. The CNNF is comprised of four discontiguous land bases, each shown in black.

The management paradigm assumed for our study is based on the new (draft) standards and guidelines used by the CNNF (Chequamegon-Nicolet National Forest, 2002b). The broad goals of management alternatives are achieved by providing a mix of specific forest conditions distributed in varying amounts across the landscape. These specific conditions are achieved by applying explicit management guidelines and strategies within spatial subsets of the CNNF called Management Areas (MAs, Table 2). The MAs may be discontinuous, allowing the forest conditions they produce to be explicitly distributed across the landscape. Each MA is further subdivided into stands, which are contiguous spatial units that are relatively homogeneous with respect to age class and composition (forest type). The alternatives developed by CNNF planners differ only in the spatial distribution and extent of the various MAs (i.e., the management guidelines and strategies are constant for each MA—only the boundaries of the MAs differ among alternatives). The MAs are further subdivided by corridors designed to protect the scenic views seen from major roads and to protect riparian areas. These corridors restrict cutting (no clearcutting or seed–tree cuts) in sensitive areas. Because HARVEST is designed to model such even-aged treatments, we did not allow harvesting within the corridor areas (up to 450 m wide). Alternative A did not have any protected corridors, and the other alternatives had identical corridor restrictions.

Table 1
Description of the emphasis for four CNNF management alternatives

Alternative	Management emphasis	ASQ rank
A	'Current plan'—continue to implement the current management plan	1
B	'Aspen emphasis'—increase early successional habitat and maintain levels of pine and hardwood habitat	2
C	'Sawtimber production'—large increase in pine and hardwood habitat and maintain levels of aspen	3
D	'Ecosystem restoration'—decrease early successional habitat and increase late successional habitat	4

The goals are to be achieved over time through the spatial allocation of MAs (Table 2) across the CNNF. ASQ (allowable sale quantity) ranks the alternatives from highest (1) to lowest (4) volume of timber production.

Table 2
HARVEST parameters used for each MA

MA	Description	Maximum harvest size (ha)	Mean harvest size (ha)	Std. dev. harvest size (ha)	Dispersion method	Green-up interval (yr)
1A	Early successional: Aspen	16	10	6	'Oldest first'	10
1B	Early successional: Mixed aspen-conifer	16	10	6	'Oldest first'	10
1C	Early successional: Aspen-hardwood	16	10	6	'Oldest first'	10
2A	Uneven-aged[a] Northern hardwoods	16	10	6	'Oldest first'	20
2B	Uneven-aged[a] Northern hardwoods: interior	16	10	6	'Oldest first'	20
2C	Uneven-aged[a] Northern hardwoods: early successional	16	10	6	'Oldest first'	20
3A	Even-aged Northern hardwoods	16	10	6	'Oldest first'	20
3B	Even-aged hardwood: oak-pine	16	10	6	'Oldest first'	20
3C	Even-aged hardwood: oak-aspen	16	10	6	'Oldest first'	20
4A	Conifer: Red-White-Jack pine	16	10	6	'Oldest first'	20
4B	Conifer: natural pine-oak	16	10	6	'Oldest first'	20
4C	Conifer: surrogate pine barrens	100	60	40	'Oldest first'	10
5, 6, 8	Wilderness, semi-primitive non-motorized, and alternative management areas	N/A	N/A	N/A	N/A	N/A

The 'total area cut' parameter came from the Spectrum schedules. See Table 3 for 'minimum harvest age' parameters.
[a]The dominant prescription for this MA is uneven-aged, but the parameters given are for even-aged harvest activities that were scheduled by Spectrum.

2.3. Harvest schedule optimization

The CNNF planning team used the Spectrum model to develop harvest schedules for each alternative. Spectrum is a fairly flexible resource-scheduling model that evolved from FORPLAN to provide extensive vegetation manipulation options (e.g., clearcutting, shelterwood sequences, etc.) within a constrained optimization framework (USDA Forest Service, 1999). The user selects a quantitative criterion (objective function) such as maximizing economic returns or minimizing forest type conversion, and Spectrum returns a schedule of timber harvest activity across a large land base that provides the optimal solution. It is an aspatial model that schedules the acreage to be cut by forest type and MA in each decade, so the location of each harvest is not specified.

Within Spectrum, resource attributes (levels) are used to define analysis units. The levels are often land layers (e.g., vegetation type, site index, etc.). The CNNF used five land layers in their Spectrum models: ranger district, management area, forest type, forest age class and timber suitability. Ranger district is a large administrative subdivision of the forest and management area was described previously. Forest type and age class provide important characteristics that often define wildlife habitat. Forest type is a classification based primarily on the dominant tree species within stands, but includes other factors such as soil and site potential. The CNNF used 10-year age cohorts, and 10 forest types: aspen (*Populus* spp.), balsam fir (*Aibes balsamea*), hemlock (*Tsuga canadensis*), jack pine (*Pinus banksiana*), northern hardwood (primarily *Acer* spp. *Fraxinus* spp.), oak (*Quercus* spp.), paper birch (*Betula papyrifera*), red pine (*Pinus resinosa*), white pine (*Pinus strobus*) and upland spruce (*Picea* spp.) . Forest types and age cohorts are combined with timber inventory and yield data to define the timber suitability of stands. Timber suitability indicates whether stands are available for silvicultural treatment or not, based on regulations related to site productivity or access (USDA Forest Service, 1982).

The CNNF employed a two-step optimization process. First, an objective function that minimized forest type conversion was used because this was a forest-wide management goal. The effect of this step is to remove most of the type conversion pathways from consideration, thereby focusing management on the maintenance of current forest types. The resulting area converted was then translated into a less than or equal-to constraint. The second step uses a new objective function that "maximized net economic returns." For both steps, a standard "Model I" linear programming formulation was used (Johnson and Scheurman, 1977). The model covered a 20-decade planning horizon, with standard, non-declining timber flow constraints and many other vegetation-related constraints. Our simulations are confined to the first 10 decades. Because national forests are also required to maintain wildlife species viability (USDA Forest Service, 1982), there is a need to predict the effects of the alternatives on wildlife habitat. Although some habitat needs may be incorporated directly into Spectrum (Bevers and Hof, 1999), structuring the

Spectrum inputs and outputs so that they could link with HARVEST added a spatially explicit analysis component.

2.4. Spatial timber harvest simulation

HARVEST was designed as a strategic research and planning tool, allowing assessment of the spatial pattern consequences of broad timber management strategies (Gustafson and Rasmussen, 2002). The model is well suited to evaluate alternative strategies, providing comparable predictions about how the alternatives affect the age class distribution of the forest or MA, the spatial distribution of forest interior and edge habitats, and the patch structure of the resulting forest landscape. HARVEST has been shown to mimic patterns produced by timber management activity (Gustafson and Crow, 1999).

One of the most compelling features of HARVEST is its limited input data requirements and ease of use. Requirements for data input include four raster layers for stand age, forest type, MA, and stand ID. The stand age map has grid-cell values that reflect the age (in years) of the forest type in that cell. The forest type map contains cells whose values represent a specific forest type or other land cover type. The MA map contains cells whose values represent the MA in which that cell falls. The stand ID map contains unique ID numbers for each stand, and these values are used for bookkeeping purposes by HARVEST. Simulation parameters for HARVEST are specified for each forest type/MA combination (defined in Spectrum as Analysis Units), and include size distribution of harvest openings, spatial dispersion method for placing openings within an MA, minimum stand age for harvest, total area to be harvested, and information about adjacency constraints (Tables 2 and 3). Riparian buffers were specified in the MA map, rather than as a HARVEST parameter. HARVEST produces a new age map incorporating simulated harvest activity at each time step, where harvested cells are reset to age 1, and unharvested cells increase in age according to the length of the time step (in this case, 10 years). Forest type is assumed to remain static in HARVEST, which is consistent with the CNNF goal to minimize type conversion. See Gustafson and Rasmussen (2001, 2002) for a complete description of HARVEST v6.0.

We produced HARVEST input maps from existing CNNF GIS (vector) data layers by converting them to 30-m grid cell (raster) maps. Stand age was calculated from the stand year of origin, and uneven-aged hardwood stands that had no year of origin recorded were given an age of 65 years, based on an estimate of the average age for these stands (Phil Freeman, CNNF, personal communication). The forest type maps showed the actively harvested types (Table 3), inactive (not harvested) forest types, and the non-forested types that were used to conduct interior forest analyses. Harvesting was not simulated on privately owned land within the CNNF Proclamation Boundary because such activity is not considered in the CNNF planning process.

Table 3
Forest type categories appearing in the forest type maps

Forest type	Proportion of the study area	Minimum harvest age (yr)	Fragmenting Status
Aspen	0.163	40	Forest
Balsam fir	0.015	40	Forest
Hemlock	0.004	N/A	Forest
Jack pine	0.015	40	Forest
Lowland conifer	0.091	N/A	Forest
Lowland hardwood	0.021	N/A	Forest
Lowland open	0.064	N/A	Open
Northern hardwood	0.221	90	Forest
Oak	0.022	70	Forest
Paper birch	0.015	40	Forest
Red pine	0.053	80	Forest
Upland open	0.013	N/A	Open
Upland spruce	0.017	70	Forest
White pine	0.012	100	Forest
Private	0.251	N/A	From TM
Water	N/A	N/A	Open
Roads/urban	0.022	N/A	Open

Forest types with no minimum harvest age were not harvested in our study. Fragmenting status indicates if the type was considered forest or open for defining forest interior habitat. Types on private land were derived from a classified Thematic Mapper (TM) image (Wisconsin Department of Natural Resources, 1999) and held constant for the purpose of defining interior habitat.

2.5. Linking Spectrum to HARVEST

The timing (decade) and general location (ranger district and management area) for various treatments were generated in Spectrum, then converted into the input parameters needed by HARVEST. We automated this conversion by developing a utility program (Spec2Harv) that reads in the Spectrum output files, and prompts the analyst as needed to resolve ambiguities about rotation intervals and provide additional HARVEST-specific parameters (Gustafson et al., 2003). Spec2Harv produces a HARVEST script file that can be run in a batch-processing mode, which simulates all the harvests specified for multiple time periods without user intervention. Documentation and download of Spec2Harv is available at http://www.ncrs.fs.fed.us/4153/Spec2Harv.asp.

2.6. Description of simulations

We ran two replicates for 10 decades of each alternative on each of the four land bases of the CNNF (Fig. 1). The CNNF Standards and Guidelines (Chequamegon-Nicolet National Forest, 2002b) were used to set the HARVEST parameters (Table 2). For example, adjacency constraints were enforced in all MAs, prohibiting harvest activity directly adjacent to any stands that have recently been cut. 'Recently' is defined by a 'green up interval' (see Table 2). The amount of forest to be cut in each forest type/

Management Area combination in each time step came from the Spectrum model. We assumed that uneven-aged prescriptions (e.g., selection cutting) did not change stand age, so uneven-aged prescriptions generated by Spectrum were not simulated by HARVEST. Moreover, the small, crown-sized openings associated with selective cutting were assumed not to fragment forest interior. Stands that would in reality be cut selectively to create an uneven age structure were simply increased in age at each time step within HARVEST, and in the analyses were considered to be part of the age class as determined by that age.

2.7. Landscape pattern analysis

The CNNF Planning Team identified several landscape pattern objectives, including (1) maintaining interior forest conditions, (2) restoring large patches across the landscape, (3) increasing mid- to-late-successional forest habitat, and (4) decreasing the interspersion of early successional habitat (edge) within large concentrated blocks of late-successional habitat (Chequamegon-Nicolet National Forest, 2002a). We used HARVEST to calculate the area of forest edge and interior habitat from the age and forest type maps. Because forest interior is spatially dependent on adjacent conditions, we included forests on private land in this analysis by using a 1992 Landsat Thematic Mapper (TM) classification map (WISCLAND, Wisconsin Department of Natural Resources, 1999) to fill in the privately owned gaps in our forest type map. We assumed that forested cells on private land had closed canopies throughout the 10-decade simulation. We calculated the amount of interior habitat based on the assumption that edge effects penetrate 90 m into the forest (Temple and Cary, 1988), and we assumed that harvested areas persist as openings for 20 years before canopy closure (Fig. 2).

We analyzed the amount of interior (forest >90 m from harvested openings <20 years old) for three different categories of habitat (i.e., all forest types, northern hardwoods, and mature pine) that were deemed important for wildlife species of concern on the CNNF (Chequamegon-Nicolet National Forest, 2002a). Forest interior defined using all forest types combined (excluding all lowland and upland open habitats, water, and roads) was assumed to be important for generalist forest interior species such as the gray wolf (*Canis lupus*). Edge habitat was assumed to be important for edge-dependent species such as Nashville warbler (*Vermivora ruficapilla*). Forest interior defined using mature northern hardwood (northern hardwood and aspen cells >80 years old) was assumed to be important for deciduous interior species such as northern goshawk (*Accipiter gentilis*). Forest interior defined using mature pine (red and white pine >70 years old) was assumed to be important for conifer-dependent interior species such as American marten (*Martes americana*). We plotted the change in these measures of forest interior and edge habitat over time for each alternative. We also used HARVEST to calculate age class distribution and

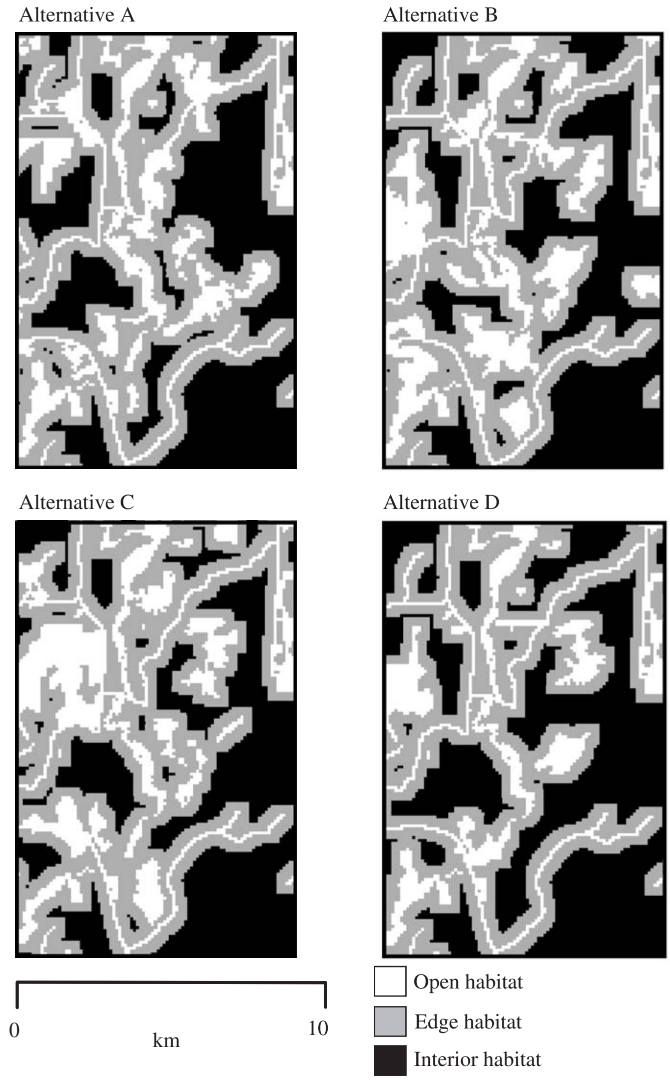

Fig. 2. An example of a map of edge and interior habitat taken from the northern part of the Nicolet National Forest after 100 years of simulation of each alternative. Open habitat includes both non-forested and recently harvested (<20 years) areas. Edge habitat was defined as forest within 90 m of open habitat. The linear features are roads and rivers.

patch sizes for three age classes; regeneration (1–20 years old), young (21–69 years old), and mature (>70 years old). Patches were defined as contiguous areas of the same age class. We plotted the change in age class distribution and patch size over time for each alternative to show how the supply of habitats varied temporally.

3. Results

The Spectrum solution could not always be allocated spatially because of adjacency constraints and green up periods, harvest size, and other HARVEST-based rules. We found that between 93% and 96% of the Spectrum solutions forest-wide could be allocated for the four alternatives. Others have noted similar or greater reductions in volume or area harvested when spatial restrictions are considered (Barrett et al., 1998, Walters and Cox, 2001).

The results for habitat calculations are presented as averages of the two replicates and, where applicable, one standard deviation is shown. All-forest interior habitat is important for generalist interior species, and Alternatives B, C and D consistently produced more than Alternative A (Fig. 3a), and the amount of interior was inversely related to the amount of timber cut (see Table 2 for ASQ rankings). The amount of interior habitat is least variable under Alternative D, but varies <10% of the mean for all alternatives. Alternative A remains relatively close to the present condition. Alternatives B, C and D exhibit a rapid initial increase in the area of interior, due to corridors and blocks of wilderness areas that are not harvested. Forest edge habitat is important for edge-dependent species, and Alternative A consistently produced more forest edge habitat than Alternatives B, C and D (Fig. 3b), and the amount of edge was positively related to the amount of timber cut (see Table 2 for ASQ rankings). The abundance of edge habitat is the most stable under Alternative D, but all alternatives exhibit a positive temporal trend. The fact that Alternative A shows an increase in edge habitat over time is most likely the result of the recently implemented maximum harvest size of 16 ha, smaller than previous practice on the CNNF, and the highest level of timber harvesting of the alternatives studied. All of the alternatives except A appear to increase the amount of both interior and edge habitat. This result can be attributed to the design of the alternatives, since a random distribution of harvest activity causes interior and edge to vary inversely (Gustafson and Crow, 1994).

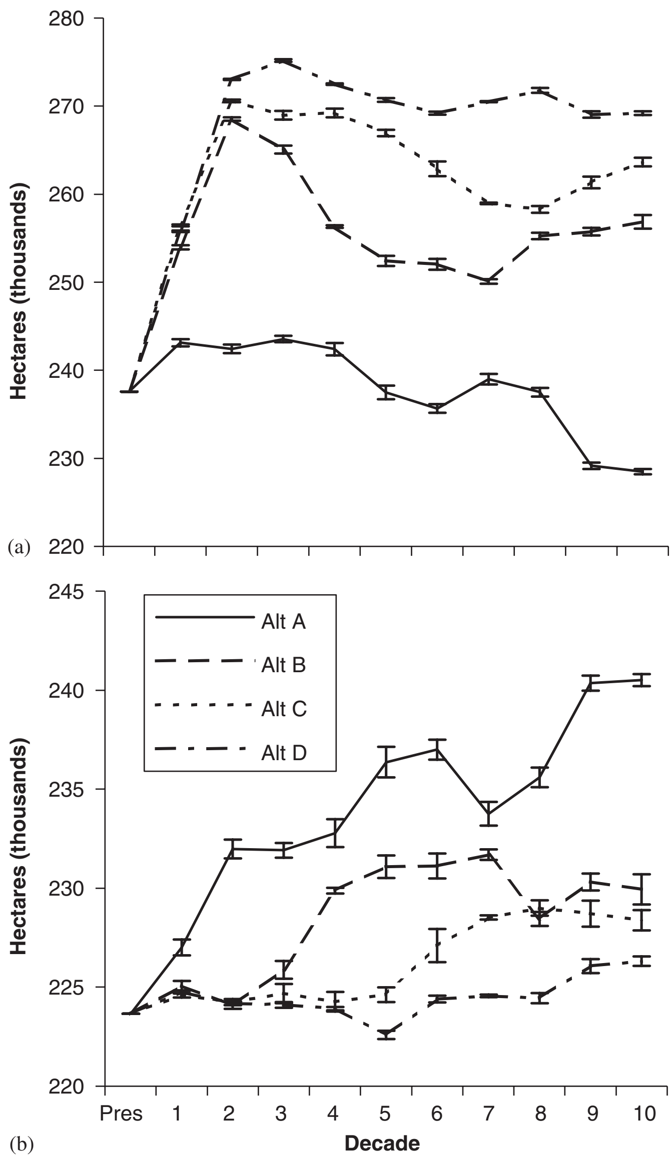

Fig. 3. Area of (a) all-forest interior habitat (important for the gray wolf) and (b) all-forest edge habitat (important for the Nashville warbler) through simulated time, by alternative. The interface between edge and interior habitat was 90 m from a harvested opening (<20 years old) or a fragmenting land cover type (Table 3). Error bars show one standard deviation.

Mature northern hardwood interior is important for species such as goshawk, and it shows a 7-fold increase in the first two decades for all alternatives (Fig. 4a), followed by either a steady increase until decade 8 (Alternatives B, C and D), or a slight decline (Alternative A). The rank order of the alternatives is the same as for total forest interior. The large increase in mature hardwood interior in the first two decades was caused by a large number of stands in the 50–70 year age range (including the uneven-age stands) at the start of the simulation, which quickly moved into the mature age class. Northern hardwood experienced very little even-aged harvesting, resulting in predominantly mature stands. The differences among alternatives (Fig. 4a) were caused by varying levels of shelterwood harvesting. A very similar pattern was seen for mature northern hardwood edge habitat (Fig. 4b).

The relative abundance of mature red and white pine interior habitat varied through time (Fig. 5a). Alternative A consistently had the lowest abundance, while Alternative D was consistently highest. The total area (800–4800 ha) was relatively small compared to mature northern hardwood (up to 88,000 ha). There was a rapid increase in the first two decades resulting from the transition of the 50–70 year age classes into the mature stage. By the sixth decade much of the pine forest reached the minimum harvest age (see Table 3), and the subsequent harvest activity resulted in a steady decline in interior area (Fig. 5a). The area of mature red and white pine edge habitat also varied through time, with an initial increase and a decline after decade 6, although the decline was not as pronounced as for interior habitat (Fig. 5b).

The age-class distributions over time show an increase in the mature age class (Fig. 6a), and a decrease in the young and regeneration stages (Fig. 6b and c) compared to present conditions under all alternatives. Alternative A produced the least area of mature forest and the most regeneration and young age class habitat, and the relative amount of age class habitats was again related to the ASQ rank of alternatives (Table 2). The abundance of age class

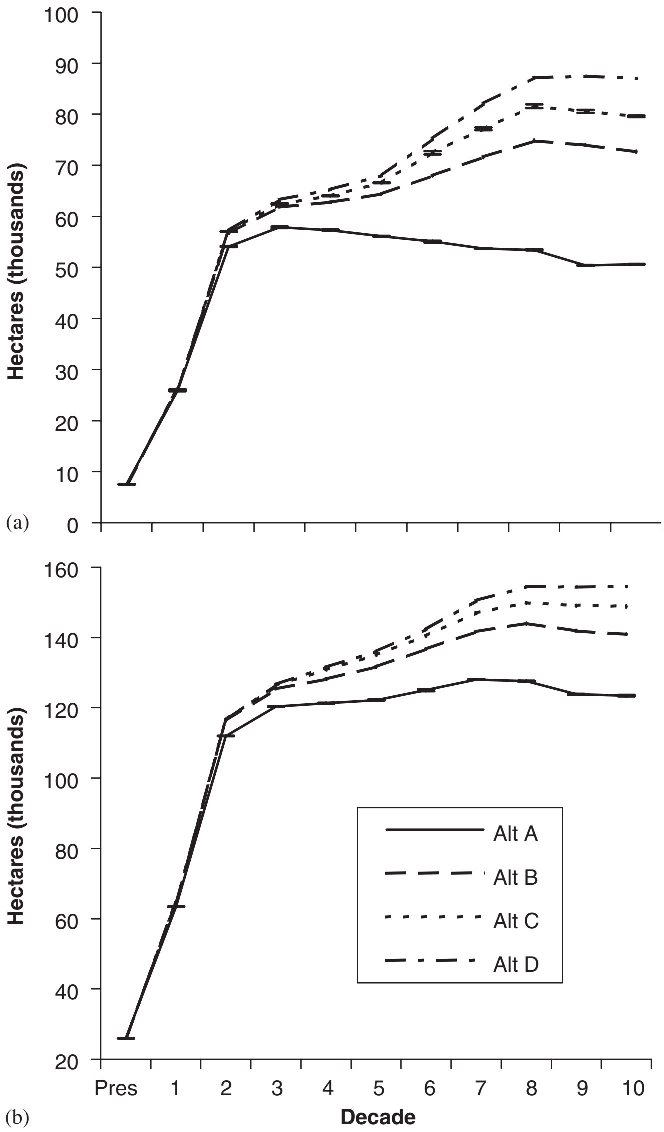

Fig. 4. Area of mature northern hardwood (a) interior (important for the northern goshawk) and (b) edge habitat through simulated time, by alternative. The definition of interior was any forested cell more than 90 m from a harvested opening (<20 years old) or a fragmenting land cover type (Table 3). Error bars show one standard deviation.

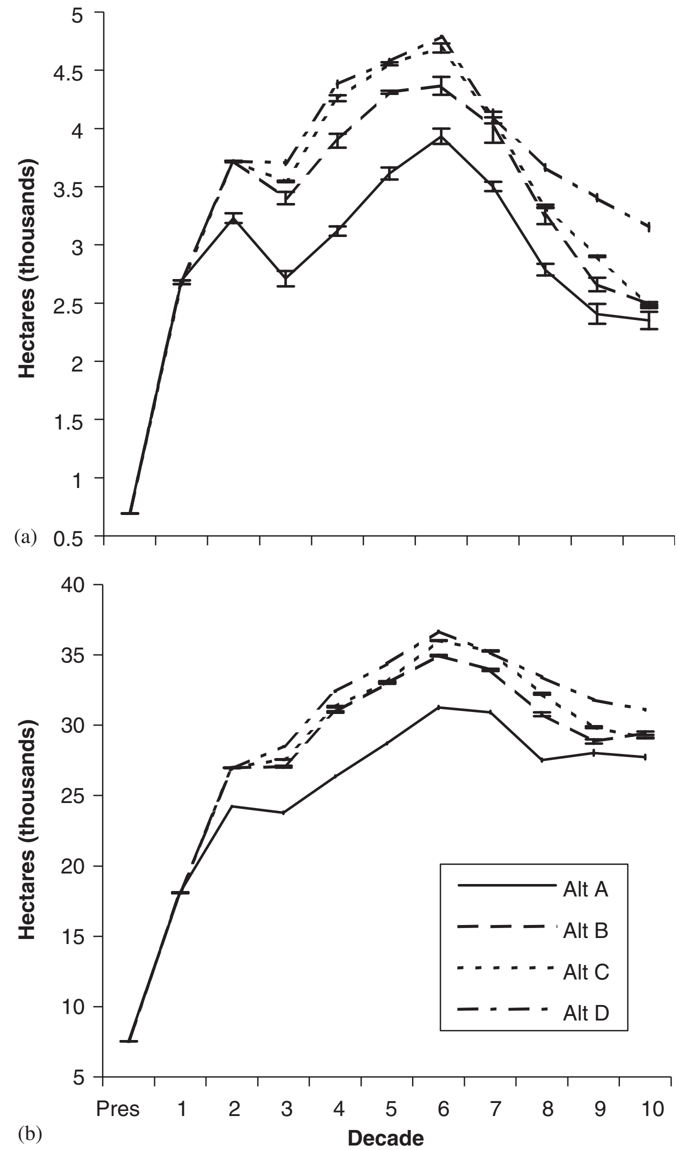

Fig. 5. Area of mature pine (a) interior (important for American marten) and (b) edge habitat through simulated time, by alternative. The definition of edge was any forested cell within 90 m of a harvested opening (<20 years old) or a fragmenting land cover type (Table 3). Error bars show one standard deviation.

habitats was relatively stable after decade 2 for mature and regeneration stages, but the amount of young forest declined until decade 7.

The average size of patches (defined by age class) generally decreased under all alternatives (Fig. 7). Patches of mature forest increased from the present condition for the first two decades, and then gradually decreased in size thereafter. Mature forest patch size was positively related to the ASQ rank of alternatives (Table 2). Mean regeneration patch size (Fig. 7b) was smaller than the predominant mean size simulated by HARVEST (10 ha) by decade 2, reflecting the fact that some harvests do not reach their target size because of limitations imposed by stand boundaries. The mean size of young patches (Fig. 7c) approached 10 ha by decade 6. For regeneration and young classes, Alternative A generally had the largest patches, while Alternative C had the smallest, although the differences were small. The relative size of patches in the three age classes is partly determined by the number of cohorts in each class; a greater number (and area) of cohorts are more likely to coalesce into larger patches.

4. Discussion

Our results illustrate the value of a spatial analysis of alternative harvest strategies. First, the spatial feasibility of harvest schedules can be verified. Second, the abundance of habitats that are defined spatially (e.g., interior and edge) can be quantified over time. Such information can be used to assess the temporal variability in the supply of habitat,

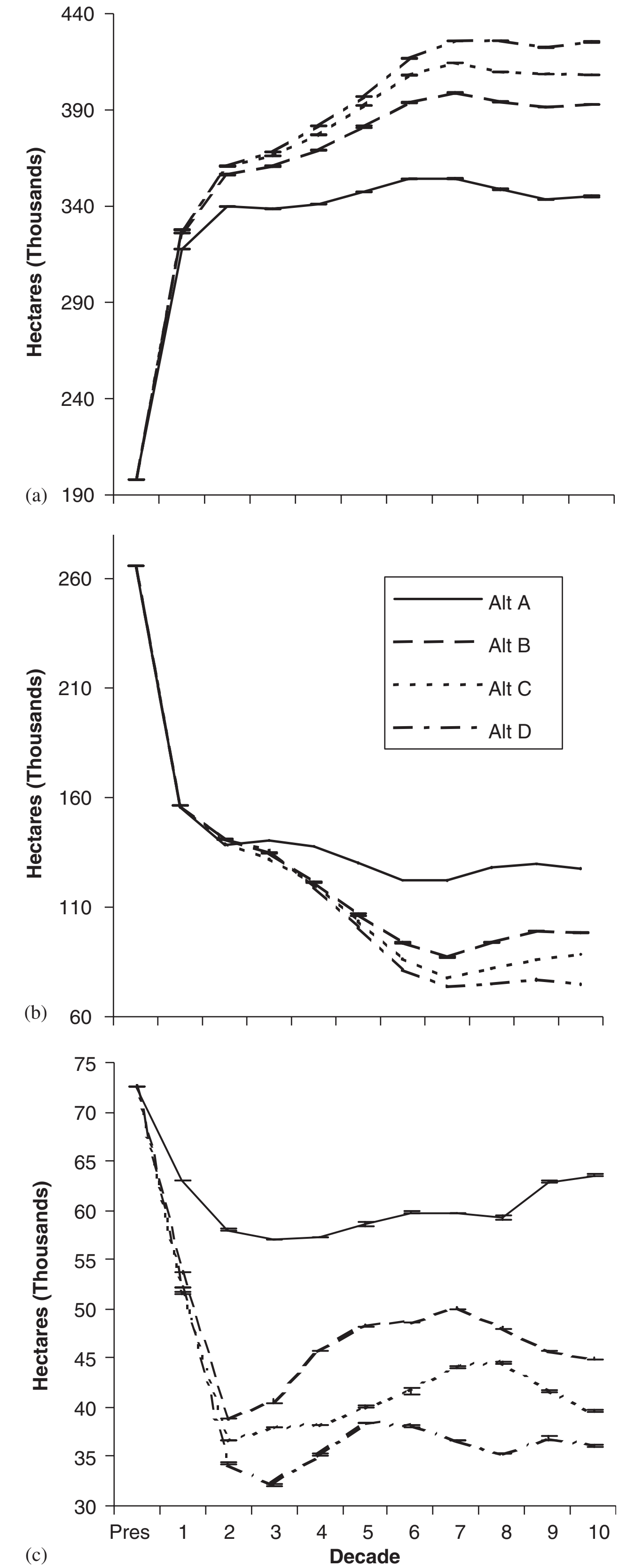

Fig. 6. Age class distribution through simulated time, by alternative. Age classes were defined as: (a) mature (>70 years old), (b) young (21–69 years old), and (c) regeneration (1–20 years old). Error bars show one standard deviation.

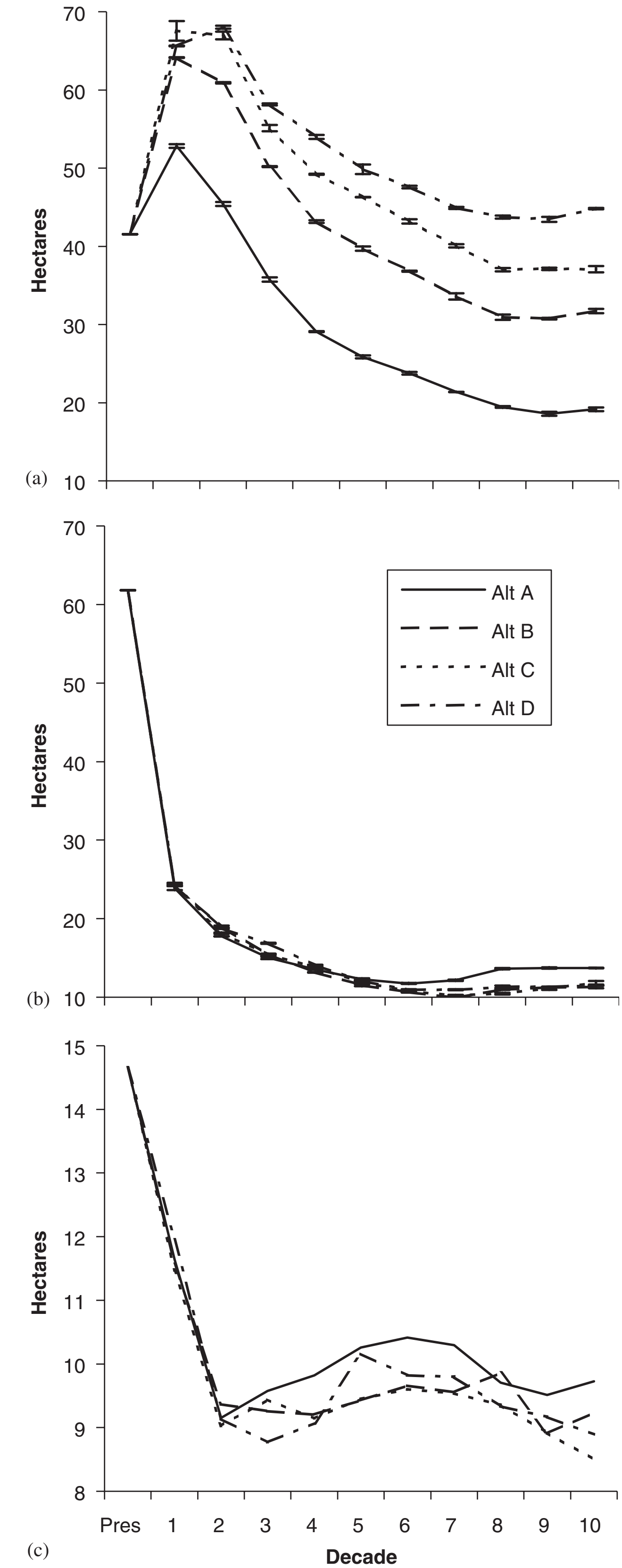

Fig. 7. Mean patch size through simulated time, by alternative. Patches were defined as contiguous areas of the same age class: (a) mature (>70 years old), (b) young (21–69 years old), and (c) regeneration (1–20 years old). Error bars show one standard deviation.

and to determine if the amount and distribution of habitat meets management objectives over the life of the management plan. For example, if a management goal on the CNNF were to increase habitat for interior species, such as wolves, while maintaining current levels of edge habitat, then Alternative A would be less desirable than the other alternatives (Fig. 3). Spatial information can also be used to help predict the viability of species that depend on spatially defined habitat. For example, Fig. 5a suggests that species dependent on interior conifer forests, such as American marten and pine warbler (*Dendroica pinus*), will see a $>300\%$ increase in habitat under all alternatives. But after decade 6 there will be a marked contraction in available habitat, which may result in population declines. The supply of habitat for species that rely on mature forests increases compared to present conditions, and remains fairly stable, for all alternatives. However, the supply of young forest habitats declines, and is especially limited under Alternatives C and D. This may have negative implications for disturbance-dependent species such as ruffed grouse (*Bonasa umbellus*).

Age class often determines vertical forest structure, plant and animal diversity, and the complexity of the ecological community. Organisms perceive habitat at certain scales (O'Neill et al., 1988), making patch size a relevant metric of habitat structure. Many species are associated with habitat defined by age class (e.g., white-tailed deer, ovenbird (*Seiurus aurocapillus*)), and quantitative predictions of age class patch size under alternative plans are an important component of population viability analyses conducted as part of Forest Plan revisions. Species viability assessments are often conducted by panels of experts who consider how each alternative affects the amount, composition and spatial configuration of habitat of all species of concern on a national forest. Our approach provides information on the spatial characteristics of habitat that is not available from Spectrum modeling alone.

Our results allow a comparison of the current management strategy with the proposed alternatives, and some indication of the stability of the landscape patterns produced by the alternatives. The CNNF alternatives represent a gradient of management emphases, constrained by the mandates of the Multiple Use Sustained Yield Act (1960) and the National Forest Management Act (1976). Furthermore, the Standard and Guidelines (Chequamegon-Nicolet National Forest, 2002b) represent fixed management prescriptions, and they were identical for all alternatives. Spatial analysis results mirror the emphases or goals for the alternatives (Table 1). The "current plan" direction, Alternative A, creates the most intensively managed landscape with higher amounts of edge, less interior and mature forest, and more young forest. With the exception of Alternative A, Alternative B provides the highest level of harvesting and the most early successional habitat. Alternative C provides an intermediate level of harvesting and the second highest amounts of interior and mature forest. Finally, Alternative D, which emphasizes ecosystem restoration, has the highest amount of mature and interior forest.

The difference among alternatives in terms of regenerating and young forest average patch size is negligible, but for mature forest the difference is notable. Mean patch size seems to approach the mean harvest size implemented in HARVEST (10 ha, Table 2). The effect of a 1982 regulation limiting harvest block sizes to a maximum of 16 ha in most forest types (USDA Forest Service, 1982) is evident in the present patch size of the regenerating forest (Fig. 7c). The alternatives displayed in our figures separate more neatly from each other than do all eight alternatives combined. When all alternatives are plotted, the graph lines sometimes cross each other, although Alternative A (the current plan) tends to be separate from the others. Even though the differences are relatively subtle, our results demonstrate that key metrics of spatial pattern can be used to discern some of the trade-offs inherent in the alternatives.

The simplifying assumptions that were made to make HARVEST easy to parameterize and use also impose some limitations. HARVEST v6.0 does not allow for forest type conversions, and although the Spectrum models were designed to minimize them, some conversions were scheduled. This undoubtedly had some effect on the ability of HARVEST to meet some of the cutting targets, and likely resulted in some cutting of forest types that Spectrum viewed as converted to another type. However, this problem was not considered serious because conversions were minimal, and the area involved was not expected to become significant until after 10 decades. HARVEST targets age cohorts above a minimum age rather than the explicit cohorts targeted by Spectrum, but this allows flexibility in spatially achieving the Spectrum solution. Timber suitability class is also not explicitly considered by HARVEST. However, most unsuitable stands were excluded by MA designation, no-cut buffers around riparian areas, or an initial stand age of zero (which can never be cut).

Another limitation is the inability of HARVEST to make multiple cuts in the same stand in the same decade. Even with the imposition of adjacency constraints, large stands are sometimes cut in multiple harvest blocks with buffers of uncut forest left between blocks. The effect of this limitation is that the simulated harvests under alternatives with high harvest levels may be more dispersed than are real harvest units, which would tend to reduce interior habitat (Gustafson and Crow, 1994). This limitation may be overcome by subdividing large stands into smaller stands prior to HARVEST analyses.

HARVEST also does not simulate natural disturbance. Windthrow and fire are the primary natural disturbances in this landscape, but such disturbance events are typically small (<0.2 ha) and rarely stand-replacing. We did conduct a similar study of the CNNF alternatives using the more complex succession and disturbance model LANDIS, but found that the effects of natural disturbance were minor in the first 10 decades (Zollner et al., submitted). The approach described here has the advantages of a better link to the commonly used Spectrum model, and HARVEST is much easier to implement than LANDIS.

Many forest managers must apply spatial constraints to management actions. These constraints are generally believed to restrict where actions can occur, and they may also limit the amount of activity that is feasible. HARVEST simulations can identify spatially infeasible schedules, allowing them to be modified to ensure consistency between aspatial harvest scheduling solutions and their spatial distribution across the landscape. However, because there are several differences between how Spectrum develops timber cutting schedules and how HARVEST allocates them spatially (e.g., type conversions, cutting targeted to specific age cohorts), exact consistency is not possible. Our finding that only 93–96% of the Spectrum solutions forest-wide could be allocated for the four alternatives is a measure of the confidence we have that the Spectrum solutions are spatially feasible. Analysts should set a cut-off confidence level (e.g., 90%), below which a new, more constrained Spectrum model may be needed to increase the likelihood of spatial feasibility.

HARVEST is also useful for evaluating proposed management standards and guidelines that have a spatial component, such as the effect of a 30 vs. 60 m buffer along streams or roads, or the definition of forest conditions considered to fragment the forest (e.g., Leefers et al., 2005). The ability to simulate multiple replicates allows users to calculate confidence intervals around the estimates of the spatial attributes expected under simulated alternatives. It is also quite feasible to use HARVEST to simulate the management activity that occurs on adjacent lands held by other owners, to assess the cumulative spatial effects of forest management activities on the entire landscape.

5. Conclusions

Our study demonstrates the utility of combining the commonly used Spectrum model and HARVEST to produce information that neither model can produce alone. Spectrum produces management schedules that vary actions through time to optimize a specific management objective. The link with HARVEST makes it possible to evaluate resource attributes (such as habitat) that are spatially dependent. This allows managers to quantify these resource effects for objective comparisons and to generate confidence intervals around the estimates. The spatial outputs, which include maps of habitat distribution, are also a valuable tool to help managers and the public visualize the effects of the alternatives. These maps also can be imported into a GIS for spatial analysis beyond the capabilities built into HARVEST. Together, these models expand the scope of quantitative effects analysis, and lead to better-informed management decisions. In fact, the results of this study were used by the CNNF as part of an analysis of the effects of the alternatives on specific wildlife species.

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References

Albert, D.A., 1995. Regional landscape ecosystems of Michigan, Minnesota, and Wisconsin: a working map and classification. General Technical Report NC-178, USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN, 250pp.

American Bird Conservancy, 2002. First 100 globally important bird areas designated by American Bird Conservancy [online]. Available from http://www.abcbirds.org/iba/first100IBAs.pdf (Last accessed July 7, 2005).

American Forest & Paper Association, 2000. 2001 Edition: Sustainable Forestry Initiative Standard. American Forest and Paper Association, Washington, DC 5pp.

Barrett, T.M., Gilless, J.K., Davis, L.S., 1998. Economic and fragmentation effects of clearcut restrictions. Forest Science 44, 569–577.

Bettinger, P., Chung, W., 2004. The key literature of, and trends in, forest-level management planning in North America, 1950–2001. The International Forestry Review 6, 40–50.

Bettinger, P., Graetz, D., Boston, K., Sessions, J., Chung, W., 2002. Eight heuristic planning techniques applied to three increasingly difficult wildlife planning problems. Silva Fennica 36, 561–584.

Bevers, M., Hof, J., 1999. Spatially optimizing wildlife habitat edge effects in forest management linear and mixed-integer programs. Forest Science 45, 249–258.

Boulinier, T., Nichols, J.D., Hines, J.E., Sauer, J.R., Flather, C.H., Pollock, K.H., 2001. Forest fragmentation and bird community dynamics: inference at regional scales. Ecology 82, 1159–1169.

Chequamegon-Nicolet National Forest, 2002a. Draft environmental impact statement. USDA Forest Service, Chequamegon-Nicolet National Forest, R9-CN-DEIS-0403.

Chequamegon-Nicolet National Forest, 2002b. Proposed land and resource management plan. USDA Forest Service, Chequamegon-Nicolet National Forest, R9-CN-FP-0403.

Finley, R.W., 1976. Vegetation of Wisconsin in the 1830's (map). Cartographic Laboratory, University of Wisconsin-Madison.

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

Gustafson, E.J., Crow, T.R., 1994. Modeling the effects of forest harvesting on landscape structure and the spatial distribution of cowbird brood parasitism. Landscape Ecology 9, 237–248.

Gustafson, E.J., Crow, T.R., 1999. HARVEST: linking timber harvest strategies to landscape patterns. In: Mladenoff, D.J., Baker, W.L. (Eds.), Spatial Modeling of Forest Landscapes: Approaches and Applications. Cambridge University Press, Cambridge, UK, pp. 309–332.

Gustafson, E.J., Rasmussen, L.V., 2001. HARVEST for Windows: Users guide [online]. Available from http://www.ncrs.fs.fed.us/4153/harvest/v60/Harv60_User.asp (Last accessed July 7, 2005).

Gustafson, E.J., Rasmussen, L.V., 2002. Assessing the spatial implications of interactions among strategic forest management options using a Windows-based harvest simulator. Computers and Electronics in Agriculture 33, 179–196.

Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., He, H.S., 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. Canadian Journal of Forest Research 30, 32–43.

Gustafson, E.J., Rasmussen, L.V., Leefers, L.A., 2003. Spec2Harv: User's guide [online]. Available from http://www.ncrs.fs.fed.us/4153/userguide.asp (Last accessed July 7, 2005).

He, H.S., Mladenoff, D.J., 1999. Spatially explicit and stochastic simulation of forest landscape fire disturbance and succession. Ecology 80, 81–99.

Hoover, J.P., Brittingham, M.C., Goodrich, L.J., 1995. Effects of forest patch size on nesting success of wood thrushes. Auk 112, 146–155.

Johnson, K.N., Scheurman, H.L., 1977. Techniques for prescribing optimal timber harvest under different objectives: discussion and synthesis. Forest Science Monograph 18.

Johnson, K.N., Sessions, J., Franklin, J., Gabriel, J., 1998. Integrating wildfire into strategic planning for Sierra Nevada forests. Journal of Forestry 96 (1), 42–49.

King, D.I., Degraaf, R.M., Griffin, CR., 1998. Edge-related nest predation in clearcut and groupcut stands. Conservation Biology 12, 1412–1415.

Leefers, L.A., Gustafson, E.J., Freeman, P., 2003. Linking temporal optimization and spatial simulation models for forest planning. In: Arthaud, G.J., Barrett, T.M. (Eds.), Systems Analysis in Forest Resources. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 165–173.

Leefers, L.A., Roberts, L.J., Gustafson, E.J., 2005. Spatial sensitivity analysis: an application of HARVEST to a Spectrum alternative. In: Bevers, M., Barrett, T.M., (Eds.), Systems Analysis in Forest Resources: Proceedings of the 2003 Symposium. Gen. Tech. Rep. PNW–GTR–656. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. p. 366.

MacLean, D.A., Etheridge, P., Pelham, J., Emrich, W., 1999. Fundy Model Forest: partners in sustainable forest management. The Forestry Chronicle 75, 219–227.

Mazerolle, M.J., Villard, M.A., 1999. Patch characteristics and landscape context as predictors of species presence and abundance: a review. Ecoscience 6, 117–124.

Morrison, M.L., Marcot, B.G., 1995. An evaluation of resource inventory and monitoring program used in national forest planning. Environmental Management 19, 147–156.

Mullen, D.S., Butler, R.M., 2000. The design of a genetic algorithm based spatially constrained timber harvest scheduling model. In: Vasievich, J.M., Fried, J.S., Leefers, L.A. (Eds.), Proceedings of the Seventh Symposium on Systems Analysis in Forest Resources. General Technical Report NC-205, US Department of Agriculture, Forest Service, North Central Experiment Station, St. Paul, MN, pp. 57–65.

O'Neill, R.V., Milne, B.T., Turner, M.G., Gardner, R.H., 1988. Resource utilization scales and landscape pattern. Landscape Ecology 2, 63–69.

Pennanen, J., Kuuluvainen, T., 2002. A spatial simulation approach to natural forest landscape dynamics in boreal Fennoscandia. Forest Ecology and Management 164, 157–175.

Perera, A.H., Baldwin, D.J.B., Yemshanov, D.G., Schnekenburger, F., Weaver, K., Boychuk, D., 2003. Predicting the potential for old-growth forests by spatial simulation of landscape ageing patterns. The Forestry Chronicle 79, 621–631.

Remsoft Inc., 1996. Woodstock Forest Modelling System Users Guide, Version 1.1. Fredericton, NB, Canada.

Remsoft Inc., 2000. Stanley Functional Overview, Version 4.5. Fredericton, NB, Canada.

Rudnicky, T.C., Hunter, M.L., 1993. Avian nest predation in clearcuts, forests, and edges in a forest-dominated landscape. Journal of Wildlife Management 57, 358–364.

Saunders, D.A., Hobbs, R.J., Margules, C.R., 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5, 18–32.

Suarez, A.V., Pfennig, K.S., Robinson, S.K., 1997. Nesting success of a disturbance-dependent songbird on different kinds of edges. Conservation Biology 11, 928–935.

Temple, S.A., Cary, J.R., 1988. Modeling dynamics of habitat-interior bird populations in fragmented landscapes. Conservation Biology 2, 340–347.

Trzcinski, M.K., Fahrig, L., Merriam, G., 1999. Independent effects of forest cover and fragmentation on the distribution of forest breeding birds. Ecological Applications 9, 586–593.

Turner, B.J., Chikumbo, O., Davey, S.M., 2002. Optimisation modelling of sustainable forest management at the regional level: an Australian example. Ecological Modelling 153, 157–179.

Turner, M.G., 1989. Landscape ecology: the effect of pattern on process. Annual Review of Ecology and Systematics 20, 171–197.

USDA Forest Service, 1982. National Forest System and resource management planning. 36 CFR 219, subpart A. Federal Register (September 30) 47(190), 43026-43052.

USDA Forest Service, 1999. Spectrum Overview. Inventory and Monitoring Institute, Fort Collins, CO.Available from http://www.fs.fed.us/institute/planning_center/files/Spectrum26_Overview.pdf (Last accessed July 19, 2005).

USDA Forest Service, 2001. Land and resource management plan revision schedule. Federal Register (November 30) 66(231), 59775-59777.

Walters, K.R., Cox, E.S., 2001. An empirical evaluation of spatial restrictions in industrial harvest scheduling: the SFI planning problem. Southern Journal of Applied Forestry 25, 60–68.

Whitcomb, R.F., Robbins, C.S., Lynch, J.F., Whitcomb, B.L., Klimkiewicz, M.K., Bystrak, D., 1981. Effects of forest fragmentation on avifauna of the eastern deciduous forest. In: Burgess, R.L., Sharpe, D.M. (Eds.), Forest Island Dynamics in Man Dominated Landscapes. Springer, New York, pp. 125–206.

Wimberly, M.C., 2002. Spatial simulation of historical landscape patterns in coastal forests of the Pacific Northwest. Canadian Journal of Forest Research 32, 1316–1328.

Wisconsin Department of Natural Resources, 1999. WISCLAND land cover map (online). Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data, Madison, Wisconsin. Available from http://www.dnr.state.wi.us/maps/gis/datalandcover.html. [Updated 3 July 2002].

Zollner, P.A., Roberts, L.J., Gustafson, E.J., He, H.S., Radeloff, V.C., in review. Modeling the influence of forest management alternatives on patterns of ecological succession in Northern Wisconsin, USA. Forest Science, submitted.