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Simulating the Effects of Alternative Forest Management Strategies on Landscape Structure

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Quantitative, spatial tools are needed to assess the long-term spatial consequences of alternative management strategies for land use planning and resource management. We constructed a timber harvest allocation model (HARVEST) that provides a visual and quantitative means to predict the spatial pattern of forest openings produced by alternative harvest strategies. HARVEST was used to investigate the effect on landscape structure of alternate management plans formulated for the Hoosier National Forest (HNF) in southern Indiana, U.S.A. The 1985 Forest Plan for the HNF specified primarily clearcutting across most of the forest, and the 1991 Amended Forest Plan specified primarily group selection (removal of small groups of trees), limited to a much smaller portion of the forest. We assessed the relative importance of variation in the extent and intensity of timber harvest on landscape spatial pattern. We simulated 150 years for each alternative and calculated several measures of forest spatial pattern. The total area of forest interior and the mean size of forest interior blocks declined more under the 1985 Plan than under the 1991 Plan, primarily because of the greater area dedicated to timber production in the 1985 Plan. Despite the 65% decrease in timber production in the 1991 Plan, that Plan produced almost as much forest edge as the 1985 Plan due to heavy reliance on small harvests with large perimeter-to-area ratios. Both Plans resulted in an even distribution of age classes up to the age equal to rotation length, a dramatic decline in mid-age classes, and a large area of mature forest. The restriction of harvest activity to more limited areas in the 1991 Plan appeared to have a greater effect on forest spatial pattern than did the differences in harvest intensity of the two Plans. HARVEST provides a tool to link planning alternatives with potential changes in landscape structure, commodity production, and other resource values that are spatially dependent.

Keywords: forest management planning, landscape ecology, simulation models, habitat fragmentation, forest interior, forest edge, clearcutting, age-class distribution, biological diversity, spatial pattern, scale.

1. Introduction

Provisions of the National Forest Management Act of 1976 (NFMA) require the U.S. Department of Agriculture Forest Service to complete a plan for each National Forest

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that constitutes a comprehensive statement of management direction. The contents of a Forest Plan include forest-wide, multiple-use goals and objectives, standards and guidelines for fulfilling these goals and objectives, projections of timber harvest quantities, and procedures for monitoring management impacts. The Forest Plan is a guiding document, covering a 10-year period, that provides the broad framework for more site-specific analysis and project implementation. NFMA requires the preparation of an Environmental Impact Statement as part of the planning process, including the delineation and evaluation of multiple management alternatives (USDA Forest Service, 1985a).

Because there are ecological consequences of creating different landscape patterns in space and time, quantitative, spatial tools are needed to assess the long-term spatial consequences of alternative management strategies (Franklin and Forman, 1987; Hemstrom and Cissel, 1991; Li *et al.*, 1992; Thompson, 1993). To this end, we have constructed a timber harvest allocation model (HARVEST) that provides a visual and quantitative means to predict the spatial pattern of forest openings produced under alternative harvest strategies (Gustafson and Crow, 1994). The model allows simulation of differences in the size of timber harvest units, the total area harvested, rotation lengths, and the spatial distribution of harvested areas. In this paper, we present a case study in which we used HARVEST to predict the effects of published management alternatives for the Hoosier National Forest (HNF) on the spatial pattern of forest openings, and we assessed the relative importance of variation in harvest intensity and management area configuration.

In 1985, the HNF in southern Indiana released its Forest Plan. Even-age management, primarily clearcutting, was emphasized in this Plan, and reaction of some segments of the public was swift and clear: clearcutting on 85% of the land base was not an acceptable option. As a result, the Forest Plan was amended in 1991, changing the management emphasis from even to uneven-age management and reducing the timber base to about 40% of the forest. The Amended Plan proposed that timber harvest and vegetation management be applied "within the context of perpetuating and enhancing biological diversity at different spatial scales and of differing desired conditions in different management units" (USDA Forest Service, 1991). A primary silvicultural tool for implementing this new management direction was group selection (i.e. the harvesting of small forest patches no more than 0·4 ha in size). Furthermore, in the amended Plan, emphasis was placed on creating interior forest conditions and reducing the amount of forest edge.

However, these goals are not always easy to achieve because of existing conditions. The current composition and structure of a landscape reflect the physical environment, past land uses, and the interaction between the two (Crow, 1991; Baker, 1992). Past forest treatments often create age structures that are fragmented and distributed in small patches (Ripple *et al.*, 1991; Mladenoff *et al.*, 1993). Federal ownership, especially in the eastern U.S., is often fragmented and interspersed with commonly up to 50% private ownership, creating management problems for both ownerships and restricting some management options. Furthermore, the effectiveness of the change in management strategy in achieving the desired future condition is difficult to predict without spatial information and without the ability to project change in spatial patterns with time.

In our study, we used HARVEST to simulate management alternatives for the HNF, using stand maps compiled by the HNF for initial conditions. We used the standards and guidelines provided in the 1985 Hoosier Forest Plan (primarily clearcutting) and the 1991 Amended Plan (primarily group selection) as rule-bases for the model. Our objectives were to (1) characterize the differences in landscape structure over time that result from the implementation of these fundamentally different management strategies, and (2) determine the relative effects of differences in harvest intensity and the spatial extent of harvested areas.

2. Methods

2.1. HARVEST

HARVEST was constructed to allow the input of specific rules to allocate forest stands for even-age harvest (clearcuts and shelterwood) and group selection, using parameters commonly found in National Forest Plan standards and guidelines. The model produces landscape patterns that have spatial attributes resulting from the initial landscape conditions and the proposed management activities. The model is simplistic in that it does not attempt to optimize timber production or quality, nor does it predict the specific locations of future harvest activity, as it ignores many considerations such as visual objectives and road access. Instead, the model mimics stochastically the allocation of stands for harvest by Forest planners within the constraints of the broad management strategies. Modelling this process allows experimentation to link variation in management parameters with the resulting landscape patterns. In our study, we considered only harvests that produce openings within the forest. Harvest by single-tree selection was not modelled because such methods usually maintain an essentially closed canopy.

HARVEST was constructed to run within ERDAS v.7·5 (Erdas, Inc., Atlanta, GA, U.S.A.) Geographic Information System (GIS) software using ERDAS Toolkit (FORTRAN) routines for input and output. ERDAS is a grid-cell GIS that allows flexible display and manipulation of digital maps. Timber harvest allocations were made by the model using a digital stand map, where grid-cell values reflect the age (in years) of each timber stand. The model allows control of the size distribution of harvests, the total area of forests to be harvested, the rotation length (by specifying the minimum age on the input stand map where harvests may be allocated), and the width of buffers left between adjacent harvests and between harvests and non-forest habitats. HARVEST selects stands randomly for harvest, checking first to ensure that the stand is old enough to meet rotation length requirements. The assumption that past harvest allocations have been spatially random was tested, and that test is described below. Group selection is implemented on the HNF such that one-sixth of a stand is cut on each entry, and entries occur every 20–30 years (USDA Forest Service, 1991; T. Thake, pers. comm.). The model randomly selects stands for group selection from those stands with an age greater than the prescribed rotation length, and tracks the stands managed by group selection, ensuring re-entry at 30 year intervals and preventing other treatments in those stands. Within group-selected stands, openings are placed randomly, with at least 30 m (1 pixel) between openings.

2.2. STUDY AREAS

Simulations were conducted at two spatial scales. Input data at 30 m resolution allowed simulation of openings within stands and enabled detailed, stand-level analysis to be made of the ecological pattern produced by the management alternatives. Data with 100 m resolution allowed analysis of how the management alternatives would produce landscape patterns across an entire National Forest. Areas to be studied at 30 m resolution were selected in three of the four administrative units of the HNF [Pleasant Run study area (PRUN, 34 053 ha), Lost River (LRIV, 38 822 ha), and Tell City (TELL, 49 515 ha)]. Stand age maps of National Forest land within the three study areas were digitized from paper-based and mylar planning maps and gridded to 30 m cells, and ages were calculated as of 1988. The two management Plans included maps delineating management area (MA) boundaries. Each MA has a specific management objective, the MA boundaries encompass tracts to be managed to meet that objective, and several disjunct polygons of a particular MA may be designated within an administrative unit. The objectives of each MA and the decimal designations (e.g. 3·1) are used consistently among all National Forests. MA boundaries were manually transferred from the Forest Plan maps (approximate scale, 1:127 000) to 1:100 000 scale U.S. Geological Survey (USGS) maps and digitized. Land use on non-Forest Service land was derived from Landsat Thematic Mapper (TM) imagery collected in 1988, as described in Gustafson and Crow (1994). The Lost River study area encompassed most of Martin State Forest (MSF), and limited group selection (21·6 ha/decade) was simulated on MSF land.

Simulations were conducted using maps with 100 m resolution on a rectangular study area (1 058 046 ha) that included the entire HNF Purchase Area. Ownership boundaries were digitized from 1:24 000 scale paper maps produced by USGS for the Forest Service. Because it was not feasible to digitize stand maps for the entire Forest, we generated a forest cover map by resampling USGS-Land Use Data Acquisition (LUDA) data (200-m cells) to produce a map with 100 m resolution which allowed allocation of harvests as small as 1 ha. We assumed that the LUDA data represented forest cover at the start of the simulations (1988), even though they were derived from aerial photography acquired in 1978. We assumed that stand ages were distributed randomly across the Forest (see test of this assumption below), and we began the simulations with a homogeneous stand age map (i.e. all stands = 90 years).

Because the mean size of group selection openings under both Plans was less than the cell size (1 ha), we attempted to mimic the pattern produced by group selection by allocating 9 pixels (3 × 3) to represent each group selection stand. Nine pixels (9 ha) reflects the average size of HNF stands. Because the prescription calls for one-sixth of a stand to be harvested on each entry (9 pixels/6 = 1·5 pixels) and fractions of pixels could not be allocated, the model allocated either 1 or 2 pixels on each entry. Each pixel allocated represented a group of groups (i.e. pixel dominated by group openings). This algorithm thus modelled the location of group selected stands and produced small openings at 30-year intervals in those stands, but some of the fine-grain spatial detail of group selection was lost at this scale. Management on the MSF was not simulated at this scale.

We examined the assumption of random distribution of stand ages by conducting a nearest neighbor analysis (Davis, 1986) on ten subareas of the (30 m) stand age maps in all three study areas, randomly selected from areas where there were few gaps in the stand maps (i.e. little privately-owned land). We conducted two analyses: (1) to determine the distribution of stands allocated by HNF planners, we analyzed stands between 1–10 years on five of the subareas; and (2) to determine the distribution of stands reaching rotation age in the most recent decade, we analyzed stands between 80–89 years on the remaining five subareas. To eliminate edge effects, nearest neighbors outside the subareas were included in the analysis. This analysis required point data, so we identified the centroid of each stand, and used FRAGSTATS 1.0 (McGarigal and Marks, 1993) to calculate the mean nearest neighbor distance ($\bar{d}$) of these centroids. The expected mean distance between nearest neighbors is:

$$\bar{\delta}=\frac{1}{2}\sqrt{\frac{A}{N}} \tag{1}$$

with standard error:

$$S_{\bar{\delta}}=\sqrt{\frac{0.06831A}{N^2}} \tag{2}$$

where A is the area of the subset and N is the number of stand centroids. The ratio:

$$R=\bar{d}\,/\,\bar{\delta} \tag{3}$$

is the nearest neighbor statistic and ranges from 0·0 for a distribution where all points are in the same location to 1·0 for a random distribution, to a maximum of 2·15 for a regular hexagonal pattern. We constructed a two-tailed z-test for each subset to test the null hypothesis that the stands are distributed randomly (H_o: $R=1{\cdot}0$):

$$z=(\bar{d}-\bar{\delta})/S_{\bar{\delta}}, \tag{4}$$

rejecting the null with a confidence coefficient $(1-a)$ of 0·95 when $|z|>1{\cdot}96$. The results of this simple analysis (Table 1) suggest that a random allocation of treatments is consistent with historical allocations, and that random allocations for the 100 m simulations should approximate those that would be produced if actual stand age maps were available.

2.3. EXPERIMENTAL DESIGN

We simulated 5 specific management alternatives on each study area: (1) the 1985 Forest Plan (USDA Forest Service, 1985b), (2) the 1991 Forest Plan Amendment (USDA Forest Service 1991), (3) the management area (MA) boundaries of the 1985 Plan with the harvest intensity of the 1991 Amended Plan (85 Intensity–91 Map), (4) the MA boundaries of the 1991 Plan Amendment with the harvest intensity of the 1985 Plan (91 Map–85 Intensity), and (5) no harvest (i.e. no openings produced or maintained on National Forest land). The 91 Map–85 Intensity scenario used the parameters of MA 3·1, which is the most intense of the 1985 Plan harvest scenarios (Table 2), to provide the greatest contrast with the 1991 Plan harvest intensity (MA 2·8). We simulated 150 years of management under each alternative and produced three replicates of each simulation. The variability of the spatial pattern of the simulations was very low, and three replicates were deemed adequate to ensure robust results. Because the harvesting rules differed among MAs under the 1985 Plan, each MA was simulated separately, and the maps output by the model were combined to produce a complete stand age map for each decade. Wildlife openings were maintained throughout the simulations except in the "no-harvest" scenario where conversion to forest was simulated and closed canopy forest was achieved in two decades.

To avoid confounding our investigation of the effects of alternative management strategies on public lands, we did not simulate harvest activities on privately-owned inholdings. The existing pattern of forest openings on private land was derived from the TM imagery, and these conditions were maintained throughout the simulations.

TABLE 1. Nearest neighbor analysis of stand spatial distribution, testing the hypothesis that stands were randomly distributed on ten subsets of the three study areas

Study area	Stands 1–10 years						Stands 80–89 years					
	A (ha)[a]	N[b]	$\bar{d}$ (m)[c]	$\bar{\delta}$ (m)[d]	R[e]	z	A (ha)[a]	N[b]	$\bar{d}$ (m)[c]	$\bar{\delta}$ (m)[d]	R[e]	z
PRUN	5276·16	33	415·75	632·22	0·66	−3·76*	2827·44	18	714·19	626·66	1·14	1·13
PRUN	3129·84	21	683·55	610·41	1·12	1·05	5177·52	25	634·60	719·55	0·88	−1·13
LRIV	3460·86	21	572·31	641·88	0·89	−0·95	2244·51	15	605·60	611·62	0·99	−0·07
TELL	3423·24	20	563·35	654·14	0·86	−1·19	3170·34	15	473·27	726·90	0·65	−2·58*
TELL	3214·80	18	671·77	668·21	1·00	0·04	1734·84	9	528·13	694·19	0·76	−1·37

[a] Area of stand age map subset.
[b] Number of stands in the subset.
[c] Observed mean nearest neighbor distance.
[d] Expected mean nearest neighbor distance of a random distribution of points on a map of area A.
[e] Nearest neighbor statistic. $R<1{\cdot}0$, clumped; $R=1{\cdot}0$, random; $R>1{\cdot}0$, overdispersed. See text.
* Reject the null hypothesis that stands were distributed randomly.

TABLE 2. Harvest intensities as derived from the 1985 Hoosier National Forest Plan and the 1991 Forest Plan Amendment

Model parameter	1985 MA[1]					1991 MA[2]
	2·1	3·1	3·2	6·1	Total	2·8
Mean clearcut opening size (ha)	—	7·0	4·9	4·0	—	2·8
Mean group opening size (ha)	0·4	—	—	—	—	0·2
Maximum opening size (ha)	0·7	10·8	7·2	5·4	—	4·0
Total harvested/decade[3] (ha)	96·0	2360·6	2890·0	363·0	5709·6	2504·8
Harvest rate/decade[4] (%)	5·4	11·5	7·8	7·5	9·5	10·1
Timber yield/decade[3] (Mbf)	180	4928	6006	767	11 881	4360
Rotation length (years)	80	80	120	120	—	80
Buffer width[5] (m)	30	30	30	30	—	30

[1] 1985 Forest Plan Management Areas. The decimal designation of MAs is that used by the Forest Service.
[2] 1991 Forest Plan Amendment Management Areas.
[3] Represents harvest activity by Management Area across the entire Forest.
[4] Represents percent of forest *within the Management Area* that is harvested each decade.
[5] The width of buffers left between harvest allocations and other harvests, streams, and openings.

2.4. SPATIAL ANALYSIS

To assess the pattern of forest openings produced by the management alternatives, we assumed that forest pixels ≤20 years old functioned as openings, and all other forest pixels were considered closed-canopy forest. Because the management alternatives remained constant throughout the 150-year simulations, the relative difference in the equilibrium pattern among alternatives would hold even if openings were defined differently. Using a GIS proximity function, we produced maps of forest interior habitat [forest pixels >210 m from an opening (DellaSalla and Rabe, 1987; Andren and Angelstam, 1988)] and calculated the area of forest interior, the mean size of contiguous blocks of forest interior and linear forest edge at each decade for each alternative. At 100 m resolution, forest interior was defined as forest pixels >300 m from an opening.

Each index of spatial pattern was plotted as a function of time. To establish the pre-simulation trend, we successively recoded the 1988 stand age maps by decrementing the age value (A) at time t for each pixel j by 10 to produce the stand age map of the previous decade (i.e. $A_{j(t-10)} = A_{j(t)} - 10$). This was done four times to establish the pattern of forest openings since 1948. Stands that reached an age of zero (i.e. harvested) during this process were assumed to have been mature forest (>80 years) before that time.

Also tabulated throughout the simulations were the stand age-class distributions on HNF land. To illustrate long-term age-class distribution trends clearly, we simulated the 1985 and 1991 Plan scenarios for an additional 60 years (a total of 210 years) on the Tell City study area.

To evaluate the relative effects of harvest intensity and the zonation of harvest activity, a repeated measures ANOVA was used to test for treatment effects reflecting harvest intensities (INTENSITY), management area boundaries (MAP) and time (DECADE). The time periods were included in the analysis to account for potential autocorrelation among spatial pattern measures across successive decades.

3. Results

The replications of the simulations produced little variability. Harvest levels in all MAs were high enough that most stands >rotation age were allocated each decade. Variability would be likely to be higher if harvest rates in timber production management areas were lower, allowing stochasticity in harvest placement to have more of an effect on the resulting pattern of openings. Even the 1991 Plan had a high intensity of harvest in MA 2·8, because the use of groups of small openings required the allocation of many stands to achieve the specified timber production. Although harvest intensity was high within MA 2·8, much less of the land base was dedicated to timber production. Alternatives with lower harvest intensities within MAs would result in greater spatial pattern variability. The variability in our results was too low to show clearly with error bars on histograms and line graphs, so error bars are not shown. The standard deviation from the mean of interior area produced by three replicates never exceeded 0·03 ha in any combination of treatments, and the standard deviation from mean linear edge never exceeded 0·008 km.

3.1. SPATIAL PATTERN OF FOREST OPENINGS

Scenarios that used the 1985 Plan MA boundaries (1985 Plan, 85 Map–91 Intensity) showed a decline in the total area of forest interior habitat (forest >210 m from an edge) on all study sites, and the decline was greater than for those scenarios that used the 1991 Plan boundaries (1991 Plan, 91 Map–85 Intensity, Figure 1). This was due primarily to a greater proportion of the total area dedicated to timber production under the 1985 Plan (see Table 2). The total area of forest interior habitat decreased under scenarios that used the 1991 Plan boundaries, except on the TELL site (Figure 1). This site was different because timber harvest activity had been greater than on the other sites in recent decades and because it included the greatest proportion of area in management areas where timber harvest was excluded. The relationship among management scenarios was similar when simulated at 100 m resolution over the entire HNF area (Figure 2) and suggests that the PRUN and LRIV sites are more representative of the Forest as a whole than the TELL site in terms of forest interior characteristics. The decline in forest interior at the start of the 100 m simulations was steeper than in the 30 m resolution simulations because the simulations produced a pattern of openings with a finer grain than the original 200 m resolution map.

The mean size of forest interior blocks (not plotted) changed through time in a pattern very similar to that of total area of forest interior (Figure 1) although variability was somewhat greater. Even though the total area of forest interior habitat remained fairly constant after the 2020 (Figure 1), forest interior habitat on these landscapes occurred as a shifting mosaic through time. The location and size of blocks of forest interior habitat were dynamic as harvest activity removed some blocks and re-growth replaced others (Figure 3).

All scenarios except "no-harvest" showed an increase in the amount of linear forest edge (Figure 4). The amount of edge produced by the 1991 Plan was nearly as high as that produced by the 1985 Plan due to a heavy reliance on group selection in the 1991 Plan, a practice that produces great amounts of edge relative to the area harvested (Gustafson and Crow, 1994). Note the very large increase in forest edge of the 85 Map–91 Intensity scenario as a result of implementing group selection over a greater proportion of the Forest. Forest edge over the entire HNF area (100 m resolution) increased much more under the scenarios using the 1985 Plan management boundaries than scenarios using the 1991 Plan boundaries (Figure 5). This result is different from the results of the simulation at 30 m resolution (Figure 4), because the model was not

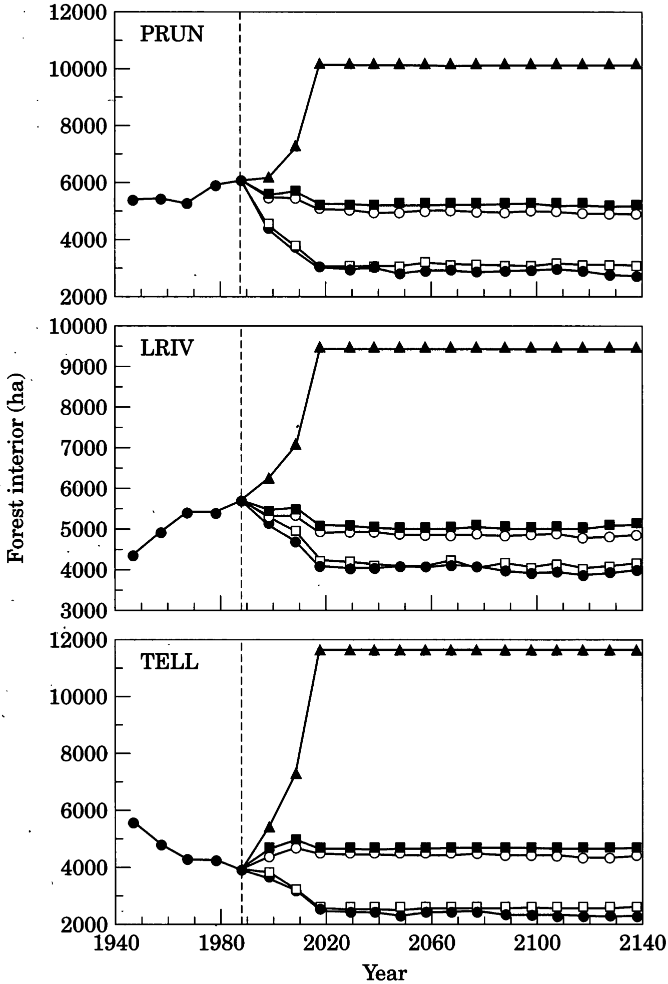

Figure 1. Changes in the amount of forest interior habitat (forest >210 m from an edge) over time resulting from simulation of management strategies at 30 m resolution. Simulations began at year 1988. PRUN, LRIV, and TELL are study areas. ▲ = no harvest; ■ = 91 Plan; ● = 85 Plan; ○ = 91 Map–85 Intensity; □ = 85 Map–91 Intensity.

able to adequately simulate at 100 m resolution the fine-scale pattern of openings associated with group selection.

3.2. STATISTICAL ANALYSIS

The restriction of harvest activity to a more limited area in the 1991 Plan appeared to have a greater effect on the measures of forest spatial pattern than did the differences in harvest intensity of the two Plans. Although all of the main effects were highly significant in the ANOVA models, examination of the sums of squares showed that the zonation of harvest activity (MAP) explained 67–98% of the variance of forest interior, while differences in harvest intensity (INTENSITY) explained only <1–2% and DECADE explained 2–25%, depending on the site (Tables 3 and 4). Figures 1, 2, 4

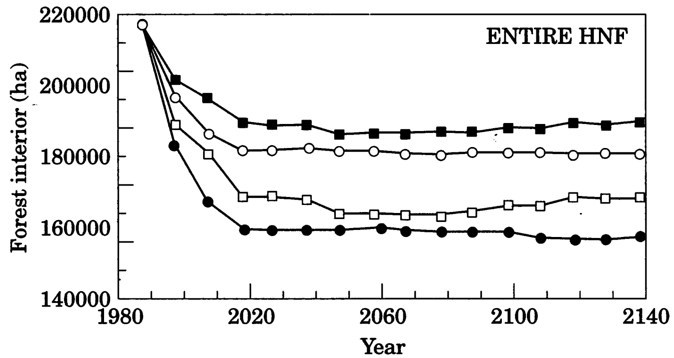

Figure 2. Changes in the amount of forest interior habitat (forest >300 m from an edge) over time resulting from simulation of management strategies across the entire HNF at 100 m resolution. Simulations began assuming a homogeneous 90 year-old forest. Symbols as for Figure 1.

and 5 show that the curves representing a common Plan map are clustered. The main effects are less important in explaining the length of forest edge, but the zonation of harvest activity (MAP) explained 43–64% of the variance, while harvest intensity explained only 1–27% and DECADE explained 13–29%. The curves in Figures 4 and 5 are not clustered as much by Plan map, but the use of group selection in the 1991 Plan consistently increased the amount of forest edge.

3.3. STAND AGE CLASS DISTRIBUTIONS

Simulation of the 1985 Plan resulted in an even distribution of young age classes (Figure 6) related to the rotation lengths specified in the Plan. Approximately two-thirds of the timber base was to be managed with a rotation length of 80 years, and the remainder was to be managed with a rotation length of 120 years (Table 2). In the MAs managed for timber, most stands were harvested at rotation age which, over time, caused a dramatic drop in the abundance of mid-age classes. A significant number of very old stands resulted in areas where timber harvesting was restricted. It should be noted here that we maintained a static management strategy throughout our simulations, while National Forest managers are required by law to review their management plans every 10 years. Our results show that static management would in fact produce striking consequences for age class distribution. The 1991 Plan showed a great reduction in even-aged stands, and a preponderance of uneven-aged and old-growth stands (Figure 7). Recall that our simulations did not consider single-tree selection, and a few of these older stands may in fact have undergone multiple single-tree selection treatments. However, most of these stands are in areas set aside from any timber harvest, and these would be true old-growth stands.

4. Discussion

HARVEST is a versatile model to simulate timber harvest management alternatives, when combined with the user interface of the ERDAS GIS system. Using HARVEST, we simulated two published management alternatives for the HNF and three variants to assess how those plans might be expected to impact forest interior habitat and forest

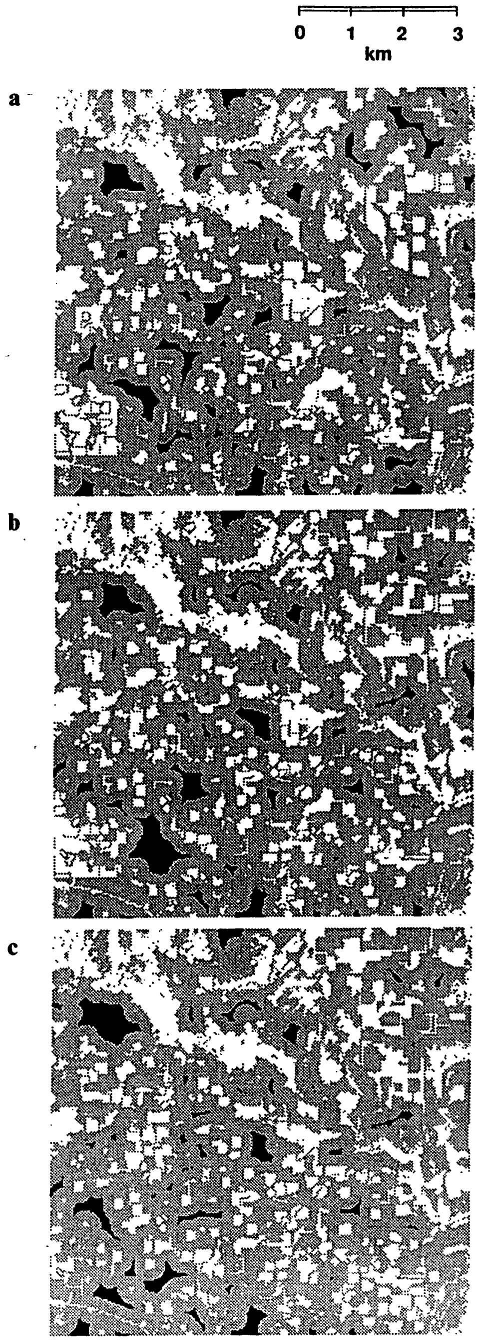

Figure 3. Maps of forest interior habitat (forest >210 m from an edge) during decades 13, 14, and 15 (a, b, and c, respectively) of simulation of the 1985 Plan on the TELL study area, demonstrating the shifting mosaic nature of interior habitat through time. □ = non-forest; ▩ = edge; ■ = interior.

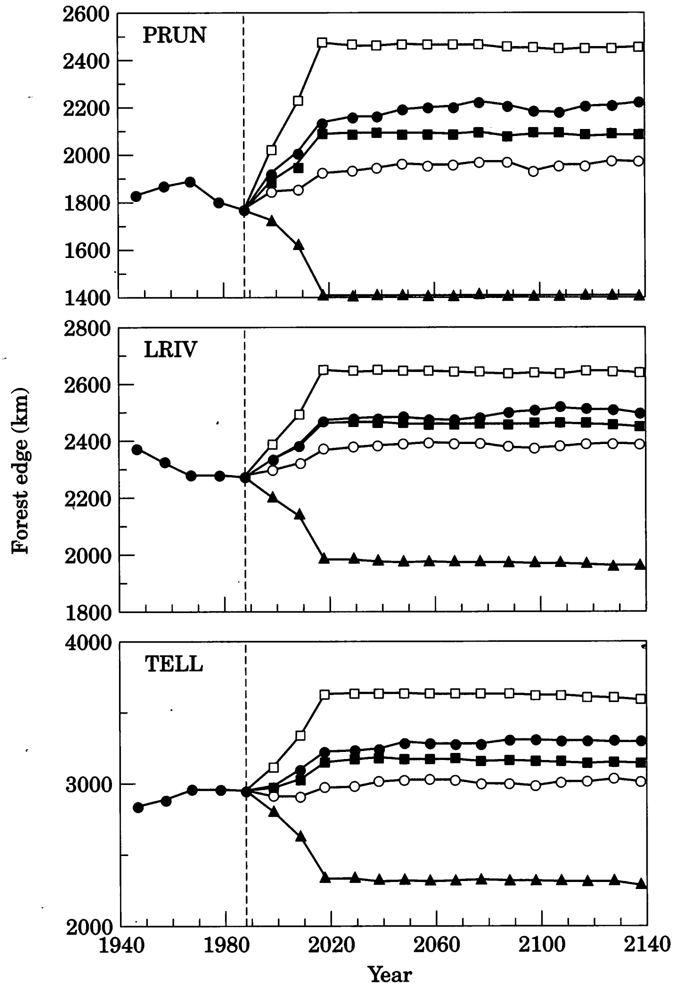

Figure 4. Changes in the amount of linear forest edge over time resulting from simulation of management strategies at 30 m resolution. Simulations began at year 1988. PRUN, LRIV, and TELL are study areas. Symbols as for Figure 1.

edge over time, and to evaluate the relative effects of timber harvest intensity and zonation of timber harvest on forest spatial pattern.

Projections of landscape structure and commodity outputs using the 1985 Plan and the 1991 amended Plan as the rule-bases for the model suggest that the nearly 60% reduction in timber production under the 1991 Plan would not improve the spatial components of habitat for interior-forest species as much as might be expected. Only small reductions in forest edge and relatively small increases in forest interior occurred during the 150-year simulation, due to the change in management approach of the 1991 Plan. Widely distributed small harvest units, with their large perimeter-to-area ratios, result in large amounts of forest edge even when it is assumed that edges are ephemeral. Using the HARVEST model, Gustafson and Crow (1994) found that the amount of forest edge increased dramatically and amount of forest interior decreased dramatically when the size of the cutting edge unit was reduced to 10 ha or less. This

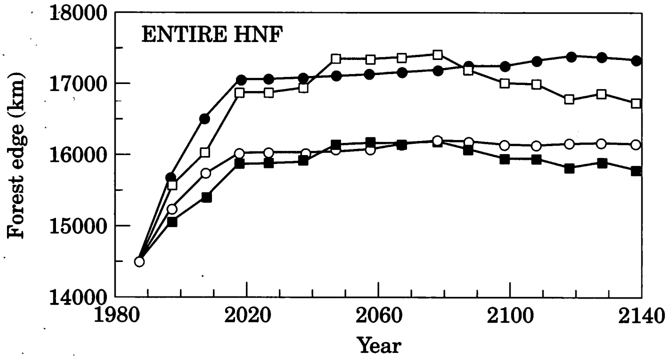

Figure 5. Changes in the amount of linear forest edge over time resulting from simulation of management strategies across the entire HNF at 100 m resolution. Symbols as for Figure 1.

TABLE 3. Analysis of variance comparing the effect of harvest intensity (INTENSITY), the zonation of harvest activity by management area boundaries (MAP), and the time period simulated (DECADE) on the area of forest interior and linear forest edge maintained on the landscape. Analysis included three replicates of simulations conducted on the entire HNF at 100 m resolution for 15 decades

		Forest interior (ha)				Forest edge (km)			
Source	df	SS	*F*	Prob>*F*	R^2	SS	*F*	Prob>*F*	R^2
MAP	1	1·269E+10	99 999·9	0·0001	—	4·740E+09	2033·4	0·001	—
INTENSITY	1	7·404E+07	723·5	0·001	—	1·044E+08	44·8	0·0001	—
DECADE	14	2·254E+08	157·3	0·0001	—	2·131E+09	65·3	0·0001	—
Error	163	1·668E+07	—	—	—	3·800E+08	—	—	—
Total	179	1·300E+10	—	—	0·99	7·356E+09	—	—	0·95

trend held even with significant reductions in total harvested area and clustering of cutting units.

Consolidation of management activities appears to have a more important effect on spatial pattern than changes in intensity of harvest. Forest interior is especially sensitive to the management area boundaries (identified as MAP in Tables 3 and 4). This trend is confirmed by Figures 1 and 2, where projections of forest interior area are clustered by common management area boundaries (MAP). Much of the gain in forest interior related to the 1991 Plan resulted from withdrawing lands from timber production. Very little interior forest remained or was created in production areas where harvesting occurred under either plan. The similarity in forest interior over time between the 1991 Plan and the 91 Map–85 Intensity scenario indicates that high intensity timber production can be sustained and yet maintain levels of forest interior similar to that of a lower intensity, group-selection strategy if timber production is concentrated in only a part of the landscape. Comparing the effects of harvest intensity and zonation of harvest intensity activity by management area boundaries also showed zonation to be more important than harvest intensity in terms of linear forest edge maintained on the landscape, but not to the same extent as forest interior. The increase in edge

TABLE 4. Analysis of variance comparing the effects of harvest intensity (INTENSITY), the zonation of harvest activity by management area boundaries (MAP), and the time period simulated (DECADE) on the area of forest interior and linear forest edge maintained on the landscape. Analysis included three replicates of simulations conducted on the three study areas within the HNF at 30 m resolution for 15 decades

		Forest interior (ha)				Forest edge (km)			
Source	df	SS	F	Prob>F	R^2	SS	F	Prob>F	R^2
(a) LRIV		29 956 027	1918·3	0·0001	—	850 529·6	957·8	0·0001	—
MAP	1								
INTENSITY	1	876 897	56·2	0·0001	—	531 448·5	598·5	0·0001	—
DECADE	14	11 002 428	50·4	0·0001	—	438 687·8	35·3	0·0001	—
Error	163	2 543 696	—	—	—	144 739·9	—	—	—
Total	179	44 359 048	—	—	0·94	1 965 405·7	—	—	0·93
(b) PRUN		180 600 901	7702·8	0·0001	—	3 583 623·9	1365·3	0·0001	—
MAP	1								
INTENSITY	1	2 118 528	90·4	0·0001	—	1 614 153·9	615·0	0·0001	—
DECADE	14	14 621 016	44·5	0·0001	—	1 137 397·8	31·0	0·0001	—
Error	163	3 821 701	—	—	—	427 852·5	—	—	—
Total	179	201 162 145	—	—	0·98	6 763 028·2	—	—	0·94
(c) TELL		176 380 778	4441·0	0·0001	—	5 200 194·8	1242·6	0·0001	—
MAP	1								
INTENSITY	1	1 363 464	34·3	0·0001	—	2 467 538·3	589·6	0·0001	—
DECADE	14	6 840 519	12·3	0·0001	—	1 254 361·2	21·4	0·0001	—
Error	163	6 473 799	—	—	—	683 132·8	—	—	—
Total	179	191 105 560	—	—	0·97	9 604 227·1	—	—	0·93

produced by group selection under the 1991 Plan appears to have offset the reduced area where harvesting occurred.

If minimizing forest fragmentation across the entire forest is a goal, these results suggest that the most effective approach to reaching this goal is to establish areas of undisturbed forest with continuous canopy adjacent to forests with relatively high harvest intensity, rather than simply reducing cutting intensity across the entire forest. The 85 Map–91 Intensity scenario illustrates the effect on the area of forest interior of a reduction in cutting intensity across a large area, and it differs little from the high-intensity 1985 Plan scenario (Figures 1 and 2). For the Lake States region, Solheim *et al.* (1987) advocate establishing large, contiguous blocks of undisturbed forest (i.e. no harvest) to minimize edge effects and to protect sensitive species. Our results do not address the question of how large such blocks should be, but do suggest that protecting blocks from harvesting is the most effective means for increasing forest interior and decreasing forest edge even when more intensive harvesting results on lands outside the protected area. Indeed, various management strategies on different parts of the land base are required to meet the needs of species with disparate life histories and habitat requirements (Freemark and Merriam, 1986; Hansen *et al.*, 1993). HARVEST could be used to evaluate alternative management area boundaries and harvest strategies over long time periods to optimize the allocation and temporal rotation of multiple uses on public lands.

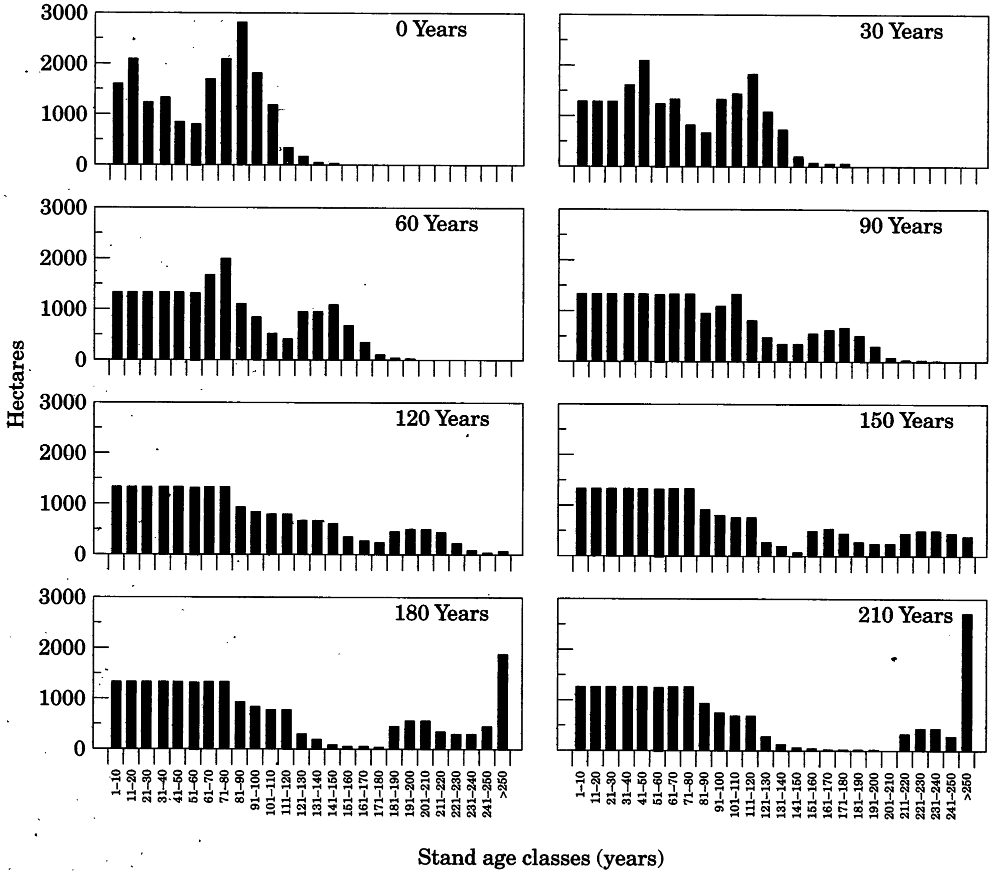

Figure 6. Changes in stand age class distribution during simulation of 210 years of implementation of the 1985 Plan on the Tell City Unit of the Hoosier National Forest. The distributions on the other study areas were similar, and are not shown.

The three study areas provided different initial conditions related to past management history. The study areas differed in stand age-class distribution and in the temporal trends in amounts of forest edge and forest interior before the 1988 baseline year. In spite of these differences, the resulting measures of forest spatial pattern produced over time by the simulations were similar for all three areas. Small error terms were associated with estimates of total edge and total forest interior among the three replicates run for each study area. Low variability in these parameters does not suggest static conditions. The simulated landscapes were indeed dynamic, with shifting mosaics, as seen in Figure 3.

Variance also serves as a source of error propagation that may be serious if the variance is large, and multiple time steps are run (Gardner *et al.*, 1990). The low variability associated with our simulations produced robust results with relatively few ($N=3$) replicates. Scale is also an important determinant of predictability (Costanza and Maxwell, 1994). Possible effects of resolution on predictability can be analyzed by comparing the simulations for the three study areas (30 m resolution) with those conducted at 100 m resolution for the entire Hoosier National Forest. For all three

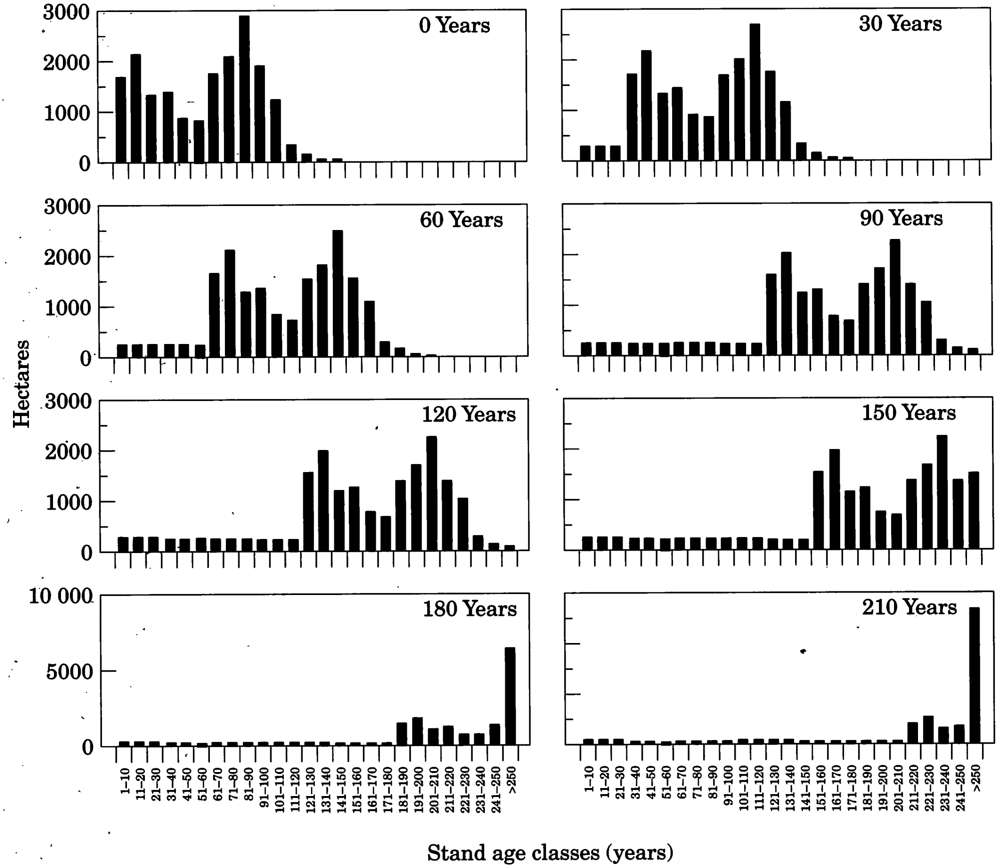

Figure 7. Changes in stand age class distribution during simulation of 210 years of implementation of the 1991 Plan on the Tell City study area of the HNF. Note the change in scaling of the y-axis for years 180 and 210. The distributions on the other study areas were similar and are not shown.

parameters (total forest interior, mean interior patch size and total linear edge), the model indicated that rates of change with time were higher at the coarser resolution. Differences in rates of change were due to differences in measurable edge because of larger cells at the 100 m resolution, and the fact that smaller openings could not be detected. The general trends, however, were similar between the two resolutions, suggesting that these trends are scale invariant.

As with all models, simplifying assumptions were made in the simulations that affected the outcome. In this case, holding the treatments constant over a long period created extremely skewed age class structures (Figures 6 and 7). Although management always involves adjustments, the extreme cases presented here provide useful comparisons. Another simplifying assumption, that of holding private lands in a constant state of canopy coverage throughout the simulation, probably reduced fragmentation at the landscape level. Studies involving broader questions of context and interaction between adjacent public and private lands have been conducted or are underway (e.g. Gustafson and Crow, 1994). Disturbances other than harvesting were not included in our simulations to avoid confounding our analysis with the effects of management alternatives. The stochastic allocation of stands is a simplistic representation of a complex decision-making process. Based on our analysis of past allocations (Table 1), it is reasonable to expect that the spatial patterns produced by our simulations provide reliable general principles about the effect of these management alternatives on forest spatial pattern through time.

In the case study presented here, substituting uneven-age management in the form of group selection for even-age management and reducing harvest levels produces both economic as well as ecological consequences. Yet the substantial reductions in harvest levels do not necessarily result in substantial increases in forest interior or substantial decreases in forest edge. Furthermore, oak–hickory forests may be difficult to maintain without clearcutting (Johnson, 1993). Public land managers must also consider many other ecological concerns as well, such as water quality, disturbance-dependent communities, backcountry recreational opportunities and invasion of exotics. It is the balancing of various ecological and economic values that is the challenge to public land managers. If the public limits management options in the HNF, this social (and thus political) consideration may override the ecological and economic factors. HARVEST provides a tool to link policy (planning) with changes in landscape characteristics (structure), commodity production, and other potential benefits and values that are spatially dependent. Such a tool may enable managers to better understand management consequences and to defend their decisions to the public and other professionals.

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