Simulating Spatial and Temporal Context of Forest Management Using Hypothetical Landscapes

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ABSTRACT / Spatially explicit models that combine remote sensing with geographic information systems (GIS) offer great promise to land managers because they consider the arrangement of landscape elements in time and space. Their visual and geographic nature facilitate the comparison of alternative landscape designs. Among various activities associated with forest management, none cause greater concern than the impacts of timber harvesting on the composition, structure, and function of landscape ecosystems. A timber harvest allocation model (HARVEST) was used to simulate different intensities of timber harvest on 23,592-ha hypothetical landscapes with varying sizes of timber production areas and different initial stand age distributions. Our objectives were to: (1) determine the relative effects of the size of timber production areas, harvest intensity, method used to extract timber, and past timber harvest activity on the production of forest interior and edge; and (2) evaluate how past management (in the form of different initial stand age distributions) constrains future timber production options. Our simulations indicated that the total area of forest interior and the amount of forest edge were primarily influenced by the intensity of timber harvest and the size of openings created by harvest. The size of the largest block of interior forest was influenced most by the size of timber harvests, but the intensity of harvest was also significant, and the size of nontimber production areas was important when harvests were numerous and widely dispersed within timber management areas, as is often the case in managed forests. Stand age-class distributions produced by past harvest activity limited the amount of timber production primarily when group selection was used, but also limited clear-cutting when recent harvest levels were high.

Multiple-use management has been the guiding philosophy for sound forest practices since Gifford Pinchot first put forward the idea (Duerr and others 1979). A fundamental assumption underlying multiple-use management is that commodity production (sustained yield) is compatible with other uses and values of the forest, such as recreation and habitat for nongame species. This multiplicity, however, is difficult to achieve in practice (Behan 1990). Because some uses, such as timber harvest and wilderness, are clearly not compatible, planners and managers have traditionally allocated various uses of the forest to separate portions of the landscape. The result has been a piecemeal approach to management, often with unintended cumulative effects, and often creating conditions that do not provide the desired flow of benefits through time (Shands 1988, Crow 1991, Crow and Gustafson 1996). As forested landscapes are becoming more intensively used, the segregation of uses is becoming untenable because the land base is limited. There is a pressing need to integrate timber production with other uses of the land, particularly the maintenance of habitat for nongame species to conserve biodiversity. Some of these species require habitat that is spatially removed from large canopy openings (e.g., forest interior species), others require large contiguous blocks of habitat (e.g., wide-ranging mammals), while still others require habitat in close proximity to canopy openings (e.g., edge species).

A spatial mosaic of forest stands of varying size, shape, age, and composition is created by harvest activities, which determines the extent and spatial distribution of certain habitat conditions. The allocation of stands for harvest is often guided by the prior designation of larger management units and the specific objectives to be achieved for that unit. These objectives might include short-rotation management to optimize wood fiber productivity and provide game habitat, or alternatively, exceptionally long rotations to produce mature forest habitat. At the landscape scale, the spatial distribution of harvest allocations often reflects the spatial distribution of forest types and stands of suitable age for harvest, ownership boundaries, physical barriers, proximity to transportation systems, and many other factors. Considering this mosaic through

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time and space can provide insights on the effects of past management activities on future options.

Another complicating factor facing managers attempting to manage a forest mosaic at large scales is the interspersion of ownerships. Rarely do adjacent landowners manage their properties in concert, acting to achieve mutual goals and objectives related to landscape structure and composition. This may result in all owners producing similar landscape patterns and reducing the diversity of habitats, or, perhaps more commonly, the effectiveness of management activity on one tract is linked to the land use of an adjacent tract. Thus, the landscape context of management activity is often as important as the management itself in achieving landscape structure goals, especially goals for producing the large contiguous blocks of habitat needed by forest interior species and wide-ranging animals. Furthermore, the mosaic of stand types and ages produced by past timber harvests may limit future options to produce desired landscape patterns and composition (Mladenoff and others 1994). Timber harvesting can impose a spatial pattern on a landscape that persists for long periods of time, and there can be significant time lags between changes in rules governing land use and related changes in landscape patterns (Wallin and others 1994). However, it is not known how long the stand age distributions produced by past harvest activity persist. Recent work has suggested that historic landscape patterns are not easily restored, especially on areas of limited extent (Mladenoff and others 1994, Turner and others 1996).

Simulation modeling is especially suited to answer general questions about the spatial implications of interacting processes, especially when manipulative experiments of many factorial combinations are unfeasible. Our interest in this study was the interactions between the spatial aggregation of timber production zones, timber harvest methods, and various forest age-class distributions as produced by forest management in the recent past. Although stochastic spatial models are not useful to predict the spatial location of individual events, they can be used to generate replicate patterns with properties that vary in response to variation in the model inputs. Replicated landscape studies involving extensive removal of trees are generally not feasible, but the study of harvesting strategies on the pattern produced on a landscape are amenable to simulation using spatial models. Modeling allows identification of the management parameters to which spatial pattern is most sensitive, focusing hypothesis testing in an adaptive management environment. In our study, we applied a timber harvest allocation model (HARVEST) to hypothetical landscapes to test the importance of landscape-level management on landscape structure in space and time. We primarily varied the spatial characteristics of the input maps and the intensity of timber harvest applied to those landscapes. Specifically, we conducted simulation experiments that focused on differences in the: (1) spatial configuration of timber production and non-timber-production areas, (2) harvest intensity within the timber production areas, (3) methods of removing timber (large vs small openings), and (4) past harvest activity within the timber production areas. Our objectives were to determine the relative effects of these timber extraction factors on habitat conditions for 2 groups of animals (forest interior species and forest edge species) and to evaluate how past management (in the form of different initial stand age distributions) constrains future timber management options.

Methods

HARVEST, A Timber Harvest Allocation Model

To implement our study, we used a timber harvest allocation model (HARVEST) (Gustafson and Crow 1994, 1996) that places harvest units on a landscape according to parameters controlling harvest size, total area harvested, and rotation interval, and is constrained by the designation of timber management zones (portions of the landscape where harvest is allowed). The model produces landscape patterns that have spatial attributes resulting from the initial landscape conditions and the management parameters. The model does not attempt to optimize timber production or quality, but instead, stochastically mimics the allocation of stands for harvest by forest managers, within the constraints of the broad management strategies. Modeling this process allows experimentation to link variation in management parameters with the resulting landscape patterns and the distribution of forest age classes.

HARVEST was constructed to allow the input of specific rules to allocate forest stands for even-age harvest (clear-cuts and shelterwood) and group selection, using parameters commonly found in National Forest Plan standards and guidelines. These include harvest size distributions, total area harvested, rotation length (understood by HARVEST to mean the minimum age of stands that can be harvested), silvicultural method (even-age or group selection), and the width of buffers that must be left around harvests. An important capability of HARVEST is the ability to allocate harvests only in portions of the landscape that are designated for harvest. A number of simplifying assumptions were made in the development of HARVEST to enable it to quickly simulate harvest activity over a relatively large area. The first is that harvest allocations within timber production zones typically take a spatially random distribution over the 10-year time-step of the model. However, this assumption does not nullify the spatial constraints most important in management planning: harvest allocations are constrained by the locations of existing stands that are older than the rotation length and by the boundaries of management zones. The spatially random assumption is based on an analysis of stands reaching rotation age and past harvest allocations. Using nearest-neighbor analysis (Davis 1986) on ten subsets of Hoosier National Forest (HNF; located in southern Indiana, USA) stand maps (mean size of subsets = 3366 ha, SD = 1062 ha), the observed mean nearest-neighbor distance between stands of similar age was compared to the distance expected if stands were randomly distributed, and a z statistic was computed. The null hypothesis that stands are randomly distributed could not be rejected at the 95% confidence level for eight of the ten subsets (see Gustafson and Crow 1996).

Experimental Design

Simulations were conducted on a series of hypothetical landscapes to avoid the confounding spatial effects of existing land-use patterns. The hypothetical landscapes were each 512 × 512 pixels (i.e., 23,592 ha), and we assumed that each pixel represented 0.09 ha (30 × 30 m). We conceived managed forest landscapes as being divided into timber production zones (timber harvest is allowed) and non-timber-production zones (timber harvest is not allowed). We expected the size of zones to be important because the potential for large contiguous blocks of forest interior is greater in large management units. Three levels of ZONESIZE were created by dividing the landscapes into zones and assigning alternating zones as non-timber-production areas. Sizes of contiguous non-timber-production areas were varied by dividing the landscape in half (H), into quarters (Q), and into sixteenths (S) (Figure 1). These patterns are analogous to those created by delineation of timber and non-timber-production management zones or where adjacent owners pursue different management objectives. Because the amount of area harvested has an effect on forest fragmentation, two levels of harvest intensity (INTENS) were simulated (2600 ha/decade and 1300 ha/decade). These values fall within the parameter space of real management alternatives simulated elsewhere (Gustafson and Crow 1996). Two timber removal methods (METHOD) were simulated, each creating canopy openings by complete removal of all trees: large openings analogous to clear-cutting (CC), and clusters of small openings similar to those produced by group selection (Group) (Table 1).

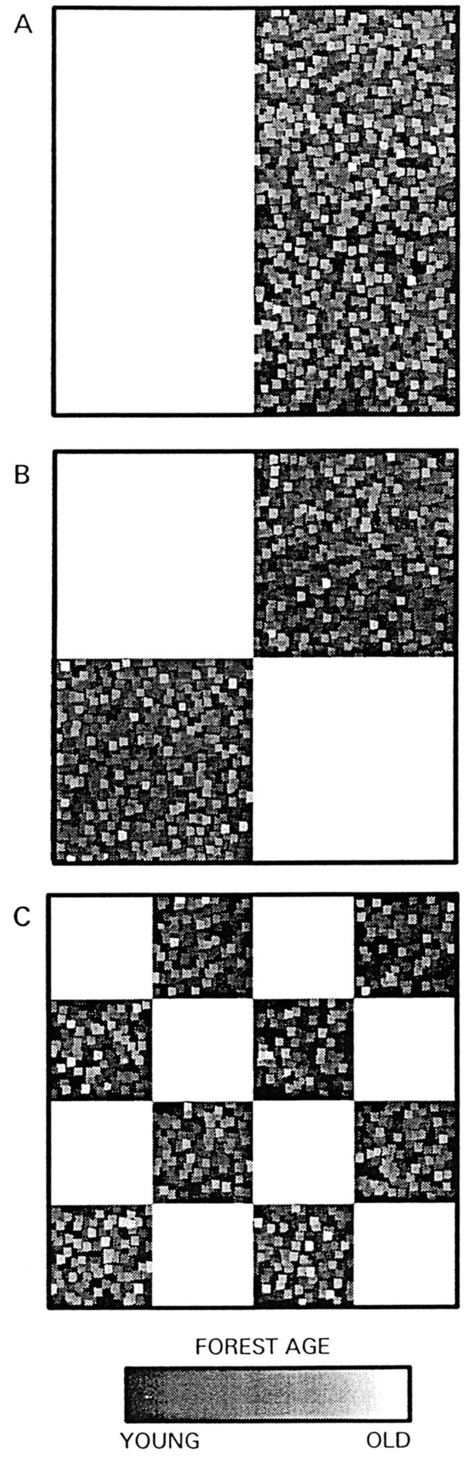

Figure 1. Examples to aid visualization of initial conditions for the simulation experiments for (A) bimodal age distribution, landscape divided in half, (B) normal age distribution, landscape divided in quarters, and (C) inverse-sigmoid age distribution, landscape divided in sixteenths. Old forest is 141–150 years old. See Figure 2 for histograms of the age distributions.

Table 1. Harvest allocation parameters used in hypothetical landscape simulations

Model parameter	Method	
	Clearcut	Group
Mean harvest opening size (ha)	7.02	0.22
Maximum opening size (ha)	10.0	0.4
	Intensity	
	High	Low
Total harvested / decade (ha)	1179.6	389.2
Harvest rate / decade (%)[a]	10.0	3.3
Rotation length (years)	80	80

[a]Represents percent of forest on all timber management blocks that was harvested each decade.

We expected group selection to greatly increase forest fragmentation, because more openings are produced to harvest a given amount of timberland. The primary effect of the age distributions produced by past management history was expected to be a temporary restriction of timber supply, particularly for distributions with little area in age classes reaching rotation age (e.g., inverse sigmoid, Figure 2c). Variation in past timber harvest activity was represented by three initial stand-age distributions (AGE-DIS).

Initial age-class distributions (AGE-DIS) for our simulation experiments reflected three arbitrary scenarios of past management history. The normal age-class distribution represents a scenario of high harvest levels 40–100 years before present (BP), but declining markedly between 40 years BP and the present. The bimodal age-class distribution represents a scenario of two historical peaks in harvest rates, at 21–30 years BP and 81–90 years BP, with a large decrease in the most recent decade, and is similar to that found on the Hoosier National Forest (Gustafson and Crow 1996). The inverse-sigmoid scenario represents an historically steadily increasing level of timber production with a rotation length of approximately 80–100 years. To ensure independence of replicates, we used HARVEST to generate maps of initial conditions for each replicate of each scenario. This was done by simulating 150 years of past harvest activity for each scenario by varying the total area harvested each decade to produce maps having the stand-age distributions shown in Figure 2a–c. The initial stands had a mean size of 9 ha (100 pixels) and were randomly distributed within the timber management blocks. These maps were used as the starting conditions for our experiments (see Figure 1 for examples).

We conducted the experiment by simulating 15 decades of harvest within timber management blocks for the complete $3 \times 2 \times 2 \times 3$ factorial (ZONESIZE $\times$ INTENS $\times$ METHOD $\times$ AGEDIS). The experimental design modeled the simultaneous application of two management prescriptions (i.e., timber production vs closed canopy forest) on alternating management units. This is representative of a number of scenarios where land allocations to different land uses are made across the landscape. Timber harvest was not allowed in non-timber-production zones, and we assumed that a closed canopy condition prevailed on these areas. On timber production zones, harvests were simulated according to the METHOD, with the total number of cells harvested determined by the INTENSITY.

Three replicates of each simulation were produced. All scenarios required 30-m buffers to be left between adjacent harvests and between harvests and the edge of timber production areas. Group-selected stands were tracked for reentry at 30-year intervals and remained in group selection throughout the simulations. In some cases the past management history (e.g., stand-age distribution) caused a shortage of timber in some decades (Table 1) due to rotation length requirements, so we recorded the area that was actually harvested in each decade.

We assumed that all cells harvested created a canopy opening for 20 years. We examined the resulting pattern of forest edge (forest adjacent to a harvest opening) and forest interior (forest >210 m from an edge or opening). This definition of interior was based on studies of forest interior birds (DellaSalla and Rabe, 1987; Andren and Angelstam, 1988). A different definition of interior would change the absolute magnitude of interior and edge, but the relative difference among treatments would remain the same. Maps of forest interior and forest edge were produced using a GIS proximity function, and the area of forest interior, the size of the largest contiguous block of forest interior, and the length of forest edge were calculated.

To determine the relative impact of the four sources of variation (ZONESIZE, INTENS, METHOD, and AGE-DIS) on landscape pattern, we conducted an analysis of variance (ANOVA) to test for treatment effects on the total area of forest interior, size of the largest block of forest interior, and total forest edge. All variables were tested for homogeneity of variance and normality, and transformed as necessary to satisfy ANOVA assumptions. Each initial landscape and replicate was generated with a unique random number seed. Because forest openings only persisted on the landscape for two decades, we used every third decade in the analysis (2 observations per rotation). Although this

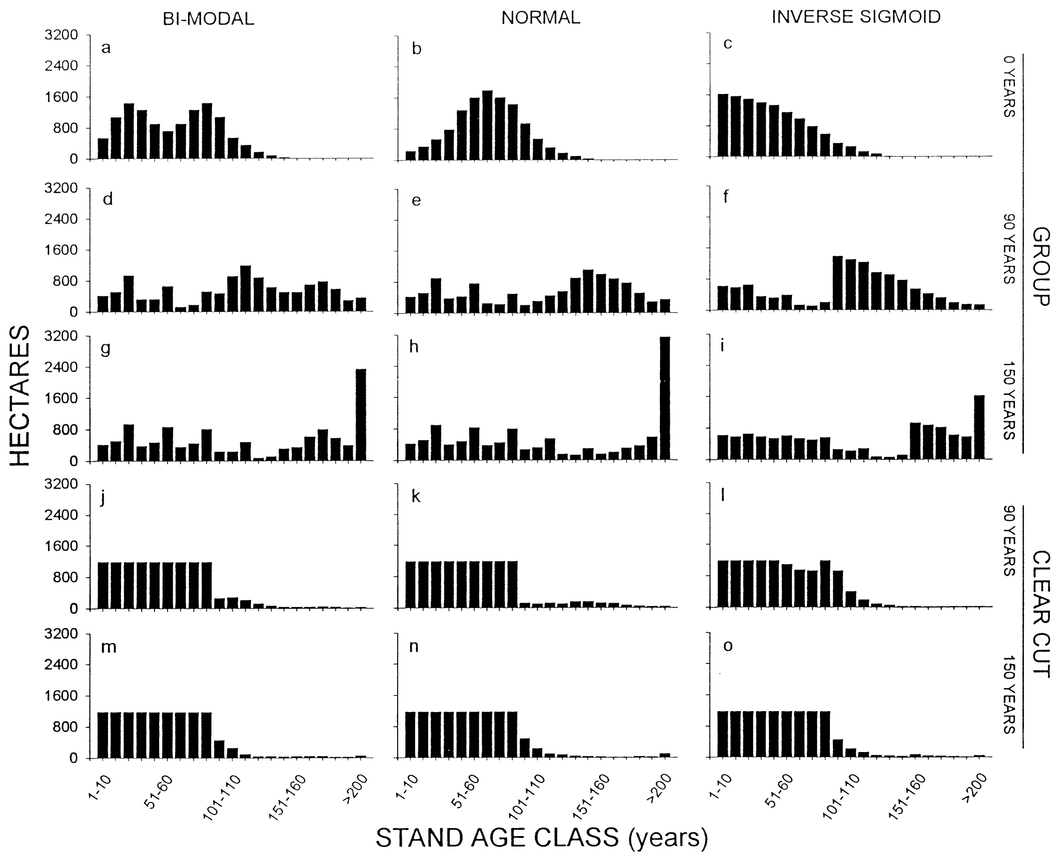

Figure 2. Changes in stand age class distributions of timber production areas through time under high-intensity group selection and high-intensity clear-cutting. Stands in non-timber-production areas are *not* shown but would contribute substantially to older age classes through time, as non-timber-production areas comprised half of each hypothetical landscape.

eliminated inclusion of the same opening in more than one observation, each opening precluded allocation of harvests in that location for a period of time equal to the rotation length, and therefore the observations we used were not strictly independent. However, the limitation of the initial stand age-class distribution on harvest allocations lasts only for a single rotation, and we would be unable to measure the effects of initial stand age-class distribution without using more than one observation per rotation. To account for the temporal trends in spatial pattern measures (e.g., Figures 3 and 4), we included the simulated time periods (DECADE) in the analysis, using a log transformation of decade.

Results

Effects of Harvest Strategy

The total area of forest interior produced on the hypothetical landscapes was primarily influenced by the timber harvest strategies (METHOD and INTENS). The results of the ANOVA sums of squares revealed that METHOD explained 42.2% of the total variance in forest interior, INTENS explained 28.7%, and the interaction of METHOD and INTENS explained an additional 22.0%. ZONESIZE, AGE-DIS, and the other interaction terms each explained $<2\%$ (Table 2).

When considering the size of the largest block of interior forest, we expected ZONESIZE to have a significant effect because potential contiguous blocks of interior may be fragmented due to the underlying management area pattern. METHOD explained 35.0% of the variance in the sums of squares, while INTENS and ZONESIZE explained 17.5% and 16.0%, respectively. The interaction of METHOD and INTENS explained an additional 11.1% and the interaction of METHOD and ZONESIZE explained 5.5%. The other effects and interactions each explained $<1.5\%$ of the variance (Table 3). ZONESIZE became important under scenarios that tended to fill each timber management area with openings and fragmented forest interior into blocks, reflecting the underlying management area

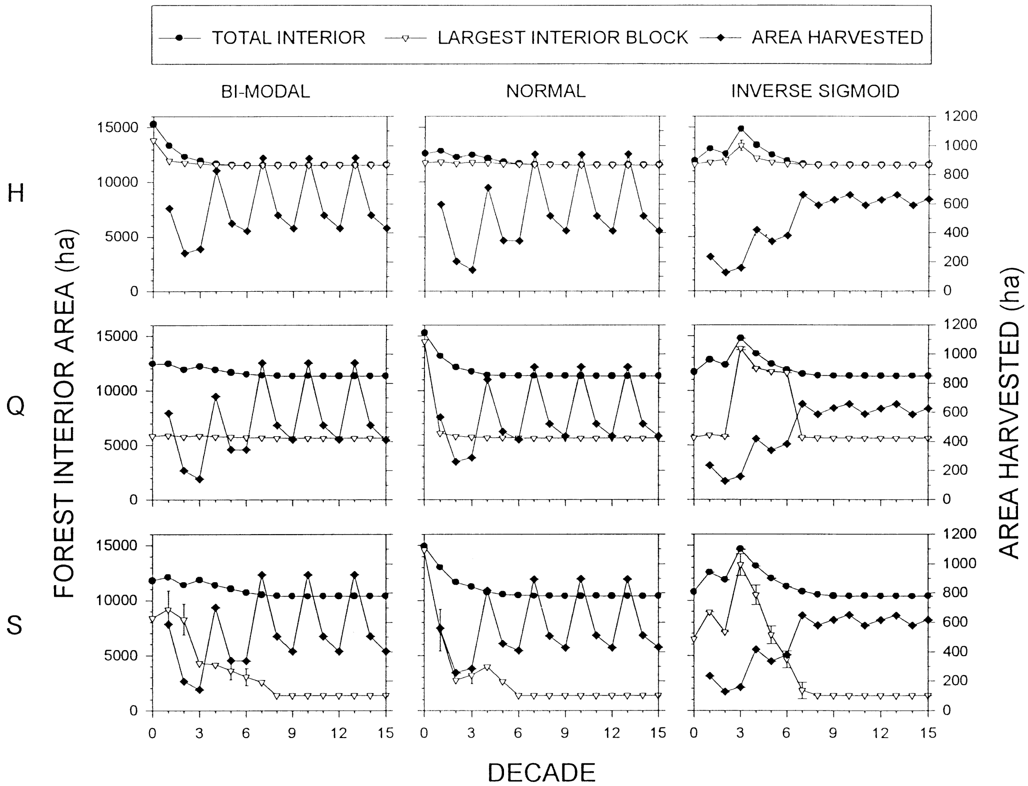

Figure 3. Changes in the total amount of forest interior and the size of the largest block of forest interior through time under a high-intensity, group-selection harvest regime. Plotted on the right axis is the area actually harvested each decade. Letters on the left indicate how the hypothetical landscape was divided to fragment the management areas: H = half; Q = quarters; S = sixteenths. Error bars indicate one standard deviation and generally are smaller than the width of the symbols.

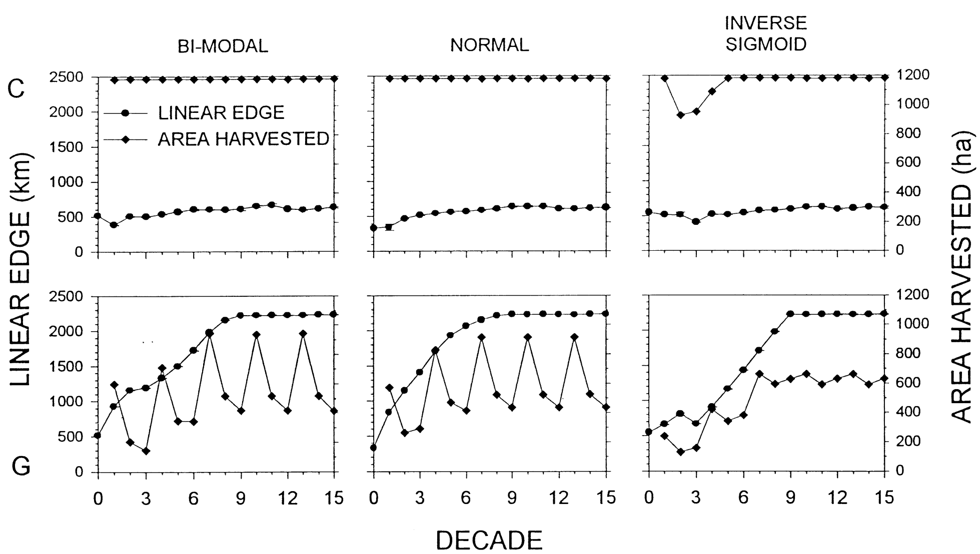

Figure 4. Changes in linear forest edge through time under a high-intensity harvest regime on a hypothetical landscape divided into two management areas (half). Plotted on the right axis is the area actually harvested each decade. Letters on the left indicate clear-cuts (C) and group selection (G). Error bars indicate one standard deviation and generally are smaller than the width of the symbols.

Table 2. Analysis of variance of forest interior[a]

Source	*df*	SS	% TSS[b]	F	Prob > *F*	R^2
	Total area of forest interior habitat (ha)					
ZONESIZE	2	4.513E+09	0.93	79.33	0.0001	
INTENS	1	1.393E+11	28.72	4897.62	0.0001	
AGE-DIS	2	2.435E+09	0.50	42.80	0.0001	
METHOD	1	2.045E+11	42.16	7190.67	0.0001	
LOG (DECADE)	4	1.032E+10	2.13	90.70	0.0001	
ZONESIZE * INTENS	2	4.515E+08	0.09	7.94	0.0004	
ZONESIZE * METHOD	2	8.601E+08	0.18	15.12	0.0001	
AGE-DIS * METHOD	2	9.979E+08	0.20	17.54	0.0001	
METHOD * INTENS	1	1.067E+11	22.02	3751.09	0.0001	
Error	518	1.473E+10	3.04			
Total[c]	539	4.850E+11	100.00			0.97

[a]ANOVA comparing the effects of management area size (ZONESIZE), timber harvest intensity (INTENS), timber harvest method (METHOD), and the initial age-class distribution of forest stands (AGE-DIS) on the total area of forest interior habitat (forest >210 m from the nearest opening) on the landscape. Analysis is based on three replicates of simulations on hypothetical landscapes, and includes every third decade.

[b]Percent of total sums of squares.

[c]Insignificant interactions are not shown, so that *df* and sums of squares do not sum to total.

Table 3. Analysis of variance of the largest block of forest interior[a]

Source	*df*	SS	% TSS[b]	*F*	Prob > *F*	R^2
	Size of largest block of forest interior habitat (ha)					
ZONESIZE	2	3.019E+11	16.02	442.52	0.0001	
INTENS	2	3.289E+11	17.46	963.97	0.0001	
AGE-DIS	2	2.772E+10	1.47	40.63	0.0001	
METHOD	1	6.590E+11	34.98	1931.60	0.0001	
LOG (DECADE)	4	2.607E+10	1.38	19.10	0.0001	
ZONESIZE * INTENS	2	1.868E+10	0.99	27.38	0.0001	
ZONESIZE * METHOD	2	1.039E+11	5.51	152.30	0.0001	
ZONESIZE * AGE-DIS	4	1.377E+10	0.73	10.09	0.0001	
AGE-DIS * METHOD	2	1.674E+10	0.88	24.54	0.0001	
METHOD * INTENS	1	2.087E+11	11.08	611.68	0.0001	
Error	514	1.754E+11	9.31			
Total[c]	539	1.884+12	100.00			0.91

[a]ANOVA comparing the effects of management area size (ZONESIZE), timber harvest intensity (INTENS), timber harvest method (METHOD), and the initial age-class distribution of forest stands (AGE-DIS) on the size of the largest block of forest interior habitat (forest >210 m from the nearest opening) on the landscape. Analysis is based on three replicates, and includes every third decade.

[b]Percent of total sums of squares.

[c]Insignificant interactions are not shown, so that df and sums of squares do not sum to total.

pattern (Figure 5). This situation usually occurred with high-intensity cutting using group selection (illustrated in Figures 3 and 5C). The clear-cutting strategy produced fewer openings, and allowed enough forest interior to remain within timber management areas to preserve the connectedness of interior habitat across more of the landscape (Figure 5B).

The amount of edge was influenced most by the cutting METHOD (Figure 4), as opening size determined the relative amount of edge. METHOD explained 76.9% of the variance in forest edge, while INTENS explained 9.3%. ZONESIZE and AGE-DIS explained <0.01% (Table 4). Edge generally accumulated through the first rotation (Figure 4), and log DECADE explained 5.2% of the variance.

Effects of Past Management History

The differences in stand age-class distributions produced by past management history had little effect on the amount of forest interior and edge (Tables 2–4). However, age distributions produced by past harvesting can place constraints on timber production capabilities through time. Clear-cutting was the least constrained by past management activity, being limited by lack of

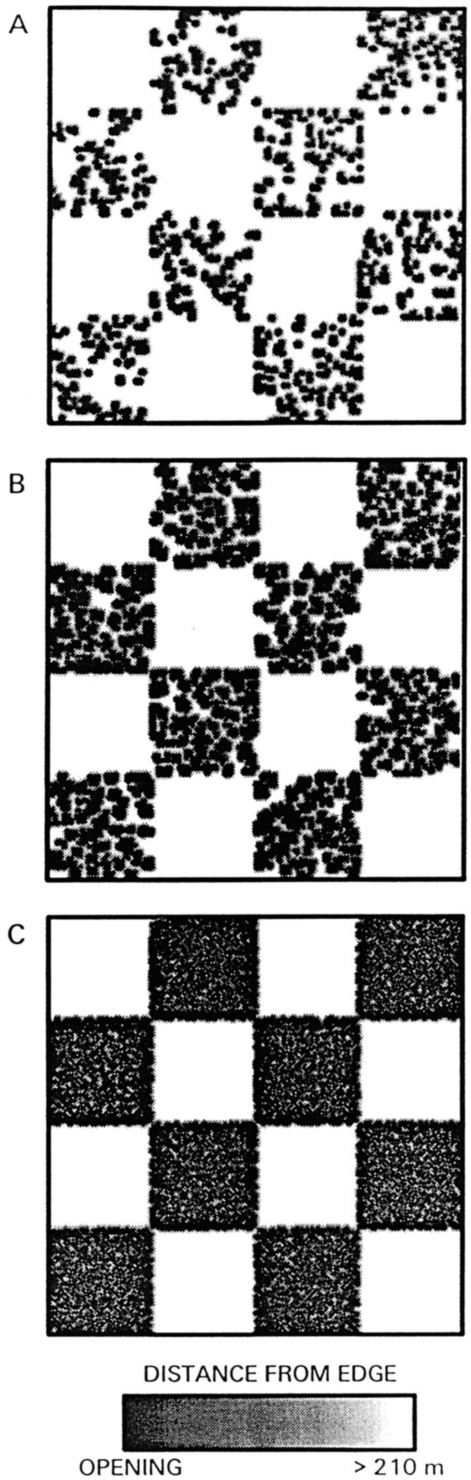

Figure 5. Examples of the spatial configuration of forest interior (white) and openings (cells <20 years old, shown in black) on the normal age-class distribution landscape that was divided into sixteenths, at (A) the start of the simulation (0 years); (B) the end of the simulations (150 years) under a high-intensity, clear-cutting scenario; and (C) the end of the simulations (150 years) under a high-intensity, group-selection scenario.

stands of rotation age only under the inverse sigmoid initial age distribution (Figure 4). Group selection requires many more stands to reach a given level of timber production because each entry into a stand results in only about one-sixth of the stand being harvested. When harvest intensity was high, target levels of timber production (1180 ha / decade) were never met (Figure 3), and when intensity was low, target levels could not be met for a period of time that depended on the initial age-class distribution (not shown). Timber production levels oscillated under group selection (Figure 3), as stands were selected for group selection during the first three decades, and then reentered at three-decade intervals. Generally all stands greater than rotation age were allocated in the first decade, and in subsequent decades relatively fewer such stands were available. Additional stands were allocated as they reached rotation age, but the pattern established in the first three decades persisted throughout the 15 decades simulated. Note the subtle differences in the pattern of area harvested established in the first three decades among the three initial age-class distributions (Figure 3). The inverse sigmoid distribution resulted in the lowest timber harvest capability initially, and the bimodal distribution allowed the highest initial timber production levels (Figure 3).

The stand-age distribution legacy of historical disturbance (cutting) persisted in some form throughout the 150 years simulated under all scenarios (Figure 2) except high intensity clear-cutting (Figure 2j–o). At low levels of harvest, the initial distribution of stand ages remained evident 150 years later in the distribution of older stands (not shown). When low points in the distribution of stand ages reached the rotation age (80 years), target harvest levels could not always be reached, resulting in anomalies in the distribution that also persisted through time. For example, the oscillating timber harvest levels resulting from high-intensity group selection (Figure 3) resulted in uneven age-class distributions that persisted through time (Figure 2).

The age-class distributions shown in Figure 2 do not include stands outside timber production areas, where stand age was not explicitly modeled. Non-timber-production areas comprised half (11,796 ha) of each hypothetical landscape, and these areas were assumed to be closed canopy forest throughout the simulations. It is safe to assume that these forests would be at least 20 years of age at the start of the simulations and that these non-timber-production areas would therefore provide over 11,000 ha of forest greater than 170 years by the end of each simulation. This mature forest is not included in the histograms of Figure 2, and interpreta-

Table 4. Analysis of variance of forest edge[a]

	Total linear forest edge (m)					
Source	*df*	SS	% TSS[b]	*F*	Prob > *F*	R^2
ZONESIZE	2	6.894E+06	0.002	0.08	0.9250	
INTENS	1	2.836E+10	9.29	641.53	0.0001	
AGE-DIS	2	1.379E+09	0.45	15.60	0.0001	
METHOD	1	2.349E+11	76.94	5312.66	0.0001	
LOG (DECADE)	4	1.580E+10	5.18	89.36	0.0001	
AGE-DIS * METHOD	2	9.974E+08	0.33	11.28	0.0001	
METHOD * INTENS	1	5.727E+08	0.19	12.95	0.0003	
Error	522	2.308E+10	7.56			
Total[c]	539	3.053E+11	100.00			0.92

[a]ANOVA comparing the effects of management area size (ZONESIZE), timber harvest intensity (INTENS), timber harvest method (METHOD), and the initial age-class distribution of forest stands (AGE-DIS) on the total linear forest edge on the landscape. Analysis is based on three replicates and includes every third decade.

[b]Percent of total sums of squares.

[c]Insignificant interactions are not shown, so that *df* and sums of squares do not sum to total.

tion of this figure should be limited to effects on age distributions in timber production areas only.

Discussion

Land managers are often faced with the challenge of achieving multiple-use objectives, including commodity outputs, recreational opportunities, and maintenance of biological diversity. Conflicts between human resource needs and the habitat needs of certain species are becoming more prominent. In many cases, the species of greatest concern are those that require large contiguous blocks of habitat with a high proportion of interior conditions (Sanders and others 1991). This habitat characteristic is clearly spatial in nature. Our results demonstrate that, of the four factors examined (timber production zone size, harvest intensity, silvicultural method, and past management history), silvicultural method (more specifically, the number of harvest openings) was the most critical in determining the size of blocks of habitat interior. When the density of openings produced within timber production areas is high, as is usually the case, the size of non-harvested areas is critical in the generation of large blocks of forest interior. Consequently, managers seeking to provide significant interior habitat should seek to aggregate management activity so that the fragmenting effects of timber harvest are not spread across the landscape at any point in time. This aggregation can also have a temporal component, reducing the amount of land that must be permanently reserved from harvest, yet providing large areas of relatively old, undisturbed forest (Gustafson 1996). These results contrast with past timber management policies that sought to disperse cutting activity across the landscape (Franklin and Forman 1987, Wallin and others 1994).

Diverse habitats can be produced by various management activities, but managers must carefully consider the scale at which they designate management areas. When large contiguous blocks of habitat are rare and important, managers should resist the temptation to designate more, smaller, management areas spread across more of the land-base, and designate fewer, but larger units to create habitat diversity at landscape scales. This practice would not increase the total area managed for interior, nor decrease the land base in commodity production, but would maximize the effectiveness of non-timber-production allocations. A practice of sequentially rotating timber production and non-timber-production among management areas over very long time periods (at a scale of centuries) could maintain a constant area of forest interior habitat while sustaining a relatively high level of timber production (Gustafson 1996). The use of larger cutting units, although perceived by the public to be detrimental to forest habitat values (Brunson and Reiter 1996), would preserve greater amounts of interior forest and generate less edge than the use of more, smaller cutting units (Gustafson and Crow 1994) by reducing the number of openings produced at the landscape scale. It could be argued that a more effective strategy for maintaining forest interior would be to reduce harvest levels in timber production management areas, but we believe that such a strategy is not socially or politically sustainable in the long term, perhaps creating a pendulum effect of high timber harvesting in areas currently managed for closed canopy forests. Our results support consolidation of ownership and location of contiguous habitat management units in areas with the least fragmented ownership. An example of a landscape design that balances timber production and the preservation of old-growth interior forest is presented by Mladenoff and others (1994).

Conversely, the production of edge and a mixture of age classes is primarily affected by disturbance method and intensity, and the size of management areas is of little consequence (Table 4). Small openings have high perimeter–area ratios, so disturbance at small scales (such as group selection) appears to be effective when management objectives are to maintain edge and early successional habitats. Production of these habitat conditions can be achieved by harvesting in smaller, dispersed management areas. Although the creation of forest interior habitat has recently had many proponents, there are still many species of concern that require early successional habitats that are difficult to maintain without even-age management in at least part of the landscape (Litvaitis 1993).

The historical context of management on a site has the potential to constrain future timber harvest activity in the long-term and may limit other forest values in the short-term, depending on the nature of the disturbance and the resulting stand structure (Wallin and others 1994). In our simulations, the effects of different initial stand-age distributions due to past harvesting history were limited to reductions in harvest levels in decades when there was insufficient area of forest older than the rotation length. These limitations produced consequences for forest interior and edge environment. For example, forest interior increased for several decades under the inverse sigmoid scenario because very little harvest was possible initially (Figure 3). The legacy of initial age-class distributions can persist on the landscape for long periods of time in the absence of high disturbance rates (by harvest, fire, insects, etc.).

Conclusions

Timber harvesting can profoundly affect the structure of forested landscapes in both space and time. Past timber harvest activity and the spatial arrangement of current timber production areas produces consequences for achieving management goals. The use of the spatially explicit model HARVEST provided insights about those consequences. Timber harvest method (METHOD) and intensity (INTENS) explained the most variation in both the amount of forest interior and forest edge. Group selection produced less interior and more edge than clear-cutting at a given harvest intensity, and the interaction of intensity with harvest method was also important for explaining variation in forest interior. A high intensity of harvest eliminated much less interior when large openings were used to extract the timber than when small group selection openings were used.

The effects of management area size appear to be most important when attempting to sustain high levels of timber production while maintaining relatively large blocks of forest interior habitat on the same landscape. The legacy of past timber management activity may result in constraints to current timber production goals such that target harvest levels can not always be achieved.

These results illustrate the importance of considering the historical context of land management, and both the spatial and temporal configuration of timber extraction, and its effects on non-timber forest resources when developing harvest schedules (Cox and Sullivan 1995). Application of these principles to real land management situations requires creativity, as complex ownership patterns, permanent landscape units (e.g., roads, streams), and management logistics produce additional constraints on management options. Nonetheless, management planning that explicitly considers the spatial and long-term temporal consequences of management activity is required to produce desired outcomes and benefits in perpetuity (Gustafson 1996). Simulation tools such as HARVEST can provide valuable insight into how the interactions of multiple timber harvest parameters affect landscape conditions through time.

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