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Assessing the spatial implications of interactions among strategic forest management options using a Windows-based harvest simulator

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Abstract

Forest management planners must develop strategies to produce timber in ways that do not compromise ecological integrity or sustainability. These strategies often involve modifications to the spatial and temporal scheduling of harvest activities, and these strategies may interact in unexpected ways. We used a timber harvest simulator (HARVEST 6.0) to determine the sensitivity of landscape pattern to the interactions among three strategic parameters: adjacency constraints, spatial dispersion, and size of harvest units. Adjacency constraints reduced the ability of HARVEST to meet cutting targets by up to 70%, depending on other parameters used, while spatial dispersion had a minimal effect. Adjacency constraints had little effect on patch size except when harvests were clustered. Adjacency constraints increased variability in the amount of forest interior and edge, but had a marginal effect on the total amount. Mean patch size decreased even though the mean size of new patches was greater than the initial mean size, because many small remnant patches were created when harvests did not completely fill some existing stands. A clustered spatial dispersion increased the amount of forest interior habitat. Our description of the intuitive interface of HARVEST 6.0 also shows that HARVEST has advanced from being strictly a research tool to a strategic management planning tool. Published by Elsevier Science B.V.

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1. Introduction

The management of most public and industrial forests is now guided by principles of ecological sustainability (Wallinger, 1995; Baskent and Yolasigmaz, 1999). While the production of commercial wood products remains a major management objective, the maintenance of ecological systems and the preservation of biological diversity have emerged as equally important objectives (Naesset et al., 1997; Andison and Marshall, 1999). Forest management planners must develop strategies to produce timber in ways that do not compromise ecological integrity or sustainability. These strategies often involve new silvicultural and harvesting techniques that are applied at the stand scale, but may also include modifications to the spatial and temporal scheduling of harvest activities (Gustafson, 1996). Such spatial and temporal strategies for achieving ecological goals may interact in unexpected ways, suggesting that these interactions should be studied in a spatial context.

Three important strategic options available to forest management planners are the imposition of adjacency constraints, various spatial dispersion patterns of harvest units, and the size of harvest units. Adjacency constraints are designed to prevent the creation of large harvest openings, and typically do not allow stands to be clearcut if they are adjacent to stands that have themselves recently been harvested. The definition of the term ‘recently harvested’ is specified by a ‘green-up interval,’ given as the minimum age required for all stands adjacent to a proposed harvest unit. Spatial dispersion (e.g. clustered or dispersed) and size of harvest units can have a significant impact on landscape pattern, particularly the amount of forest interior habitat (Gustafson and Crow, 1994). The interactions among these strategic options as they affect landscape pattern have not been well studied.

A dominant ecological characteristic of forests is seral stage. Both managed and unmanaged forests consist of a mosaic of patches of various forest types and seral stages. The size and configuration of these patches have important ecological effects for both plant communities and wildlife habitat (Rudnicky and Hunter, 1993; Quintana-Ascencio and Menges, 1996; Rosenberg et al., 1999). In his book *Land Mosaics*, Forman (1995) calls for retention of large patches as a management goal. However, managed landscapes tend to exhibit a reduction in patch size over time (Crow et al., 1999), suggesting that management planning is necessary to achieve patch size goals.

Another important spatial consequence of intense disturbance (including even-age timber management techniques) in forested ecosystems is the production of edge habitat and a reduction in forest interior habitat. Timber harvest creates internal edges within the forest, which produces ecological edge effects within the adjacent uncut forest. A number of wildlife species appear to be sensitive to the presence of edge habitat (forest that is in proximity to a forest edge), perhaps related to the reduction in forest habitat found within circular home-ranges located near open areas (King et al., 1997), or increased predation or brood parasitism rates in edge habitats (Brittingham and Temple, 1983; Andren and Angelstam, 1988). The impact of these edge effects (positive or negative) depends on the species, as does the distance over which these effects extend into the forest. The effects on vegetation (related to light and microclimate) may extend only a few tens of meters into the forest (Chen et al., 1992). For some forest interior birds, negative effects may extend 100–500 m into the forest (DellaSalla and Rabe, 1987; Andren and Angelstam, 1988; Van Horn et al., 1995). Conversely, some species prefer edge habitat, and their numbers respond positively to the creation of edge habitat (Litvaitis, 1993).

Because the spatial and temporal pattern of timber harvest activities have such a profound impact on the ecological condition of managed forests, and the social acceptability of harvest activity is related to changes in spatial and temporal patterns, strategic research and planning tools to evaluate alternative strategies are needed. Simulation models that produce cutting patterns at landscape scales are used for this purpose, although few have been used in a management context. The conceptual basis for simulation of harvest patterns at landscape scales can be traced back at least to the coarse-grid cutting model developed by Franklin and Forman (1987). More sophisticated pattern-generation models include LSPA (Li et al., 1993), CASCADE (Wallin et al., 1994, 1996), DISPATCH (Baker, 1999), and LANDIS (Gustafson et al., 2000). LANDIS also simulates forest succession, and requires large amounts of input data. LSPA operates on an initially homogeneous map and was used to investigate theoretical relationships between cutting strategies and landscape pattern. Harvest scheduling programs (e.g. FORPLAN, (Johnson and Rose, 1986), SNAP (Sessions and Sessions, 1991), Spectrum (Greer, 1996), and STEPPS (Arthaud and Rose, 1996)) typically have large data requirements, and were not primarily designed to assess the landscape pattern consequences of broad, strategic timber removal alternatives.

The timber harvest simulator Harvest was designed as a strategic research and planning tool, allowing assessment of the spatial pattern consequences of broad timber management strategies. One of its most compelling features is its limited input data requirements and ease of use. The model is well suited to evaluate alternative strategies, providing comparable predictions about how the alternatives affect the age (or successional stage) distribution of the forest, the spatial distribution of forest interior and edge habitats, and the patch structure of the resulting forest landscape. With Harvest, the object is not to find a scheduling solution (i.e., determining the order in which stands should be harvested), but to assess the spatial pattern consequences of strategic management options. It has been verified that Harvest can mimic patterns produced by past timber management activity (Gustafson and Crow, 1999). Harvest has been used to investigate the spatial effects of harvesting decisions such as cutblock size, and harvest intensity (total area harvested) (Gustafson and Crow, 1994), and to assess the spatial pattern consequences of strategic management alternatives for the Hoosier National Forest (Indiana) (Gustafson and Crow, 1996, 1999). In this paper we describe capabilities recently added to the model (HARVEST 6.0) to allow simulation of adjacency constraints and various spatial dispersions of cutting units, and use the model to explore the interactions among adjacency constraints, spatial dispersion and harvest unit size as they affect landscape pattern.

Our objectives in this paper are to: (1) describe the capabilities of HARVEST for simulating strategic management alternatives; (2) use HARVEST to determine the sensitivity of landscape pattern to the interactions among three strategic parameters: adjacency constraints, spatial dispersion, and size of harvest units; and (3) discuss the potential utility of HARVEST for forest management planning.

2. Description of HARVEST 6.0

2.1. Overview

HARVEST is a grid cell (raster) model designed to simulate harvest methods that reset the age of forested sites to one, and produce canopy openings at least one cell in size. This includes even-aged timber harvest techniques (e.g. clearcutting, shelterwood, seed tree techniques) and uneven-aged group selection. It is not capable of simulating single tree selection because these treatments do not predictably change forest stand age. This is consistent with its purpose of generating the spatial pattern of canopy openings expected under alternative management strategies.

The management paradigm assumed by HARVEST is that management objectives vary across the land base, depending on constraints and opportunities for achieving the objectives. This paradigm is typically implemented by administratively designating spatial subsets (Management Areas, MA) of the land base for which specific management goals and objectives are described. A MA (having a specific management goal) may be composed of discontiguous subsets. The land base within each MA is further subdivided into stands, which are contiguous spatial units that are relatively homogeneous with respect to seral stage (average forest age) and composition (forest type). HARVEST allows the user to interactively simulate harvest activity targeted to forest type and MA combinations. The user specifies harvest parameters (such as harvest size, rotation age, and adjacency constraints) for a MA and forest type, which are then simulated by HARVEST. The process may be repeated for many such combinations, and for multiple time steps to simulate long-term management activity.

HARVEST now provides a Windows interface and includes a number of features not available in previous versions, including: (1) the ability to specify cutting guidelines by MA and forest type; (2) more flexible and comprehensive control of harvest parameters and adjacency constraints; and (3) generation of harvest units with irregular shapes. HARVEST can also conduct several analyses of the spatial pattern of the landscape both before and after simulated harvest. For example, the patch structure (patches defined by stand age) can be analyzed for the entire map, or by individual MAs. The amount of forest interior and edge habitat can be calculated and displayed according to the definition of interior given by the user. The results of all simulations and analyses can be saved as GIS maps and text files.

2.2. Data input

Input data requirements for HARVEST are minimal, consistent with its use to answer strategic questions. These include a stand age map, a forest type map, a MA map, and a stand ID map. The stand age map has grid-cell values that reflect the age (in years) of the forest in that cell. HARVEST produces a new age map incorporating simulated harvest activity at each time step, where harvested cells take a value of 1 and unharvested cells increase in age by the length of the user specified time-step. The forest type map contains cells whose values represent a specific forest type, or features that provide information for simulation or analysis (e.g. streams and non-forested habitats). The MA map contains cells whose values represent the MA in which that cell falls. The stand ID map is a map of stand ID numbers, and these values are used by HARVEST to track harvest activity in stands, and to implement scheduled re-entries into specific stands.

HARVEST provides control over parameters with strategic management relevance, and that are commonly specified in the standards and guidelines of management plans. These include harvest size distributions, total area harvested, age constraints, spatial dispersion, adjacency constraints, and the width of riparian buffers. These parameters are listed in Table 1, with brief descriptions of their meaning and use. The user interface for specifying the parameters is shown in Fig. 1.

As seen in Fig. 1, the user selects the MA(s) and Forest Type(s) to which the harvest activity being specified will be targeted. There are four fields that allow the user to specify the size distribution of harvests. Size distributions approximate a normal distribution of harvest sizes with the given mean and standard deviation. The user may truncate either tail of the distribution, allowing some control of the shape of the size distribution. Should the user wish harvest unit size to be determined by existing stand boundaries, HARVEST provides a *Fill Stands* option that overrides any size specifications.

HARVEST provides four spatial allocation options: dispersed, clustered, group, and 'oldest first.' Each of these is subject to age and adjacency constraints (i.e. stands that do not satisfy these constraints cannot be cut). HARVEST uses the selected method to select stands for cutting until the target acreage has been harvested, or until no stands remain that satisfy constraints. The *dispersed* method selects stands (of the designated Forest Type(s) within the MA(s)) for harvest independently of each other (i.e. randomly). The *clustered* method chooses a focal stand, and then attempts to harvest the stands that are neighbors of its neighbors (potentially creating a ring of harvested stands, one stand removed from the initial stand). However, these stands may not always be eligible for harvest because they may be in a different MA or forest type, or violate a constraint (such as adjacency). HARVEST attempts to harvest these nearby stands, and then selects a new focal stand and repeats the process. *Group selection* chooses stands using the dispersed method, and then harvests small openings (groups or patches) within those stands. The number of cells (n) harvested in a stand during each entry is calculated by HARVEST as a user-specified proportion (p) of the size of the stand (A):

$n=(A^*p)$. *Oldest first* selects from the stands of the designated forest type within the MA in order of decreasing age. HARVEST can simulate traditional rotation-based cutting, where stands are cut periodically at some specified interval. When the user selects the re-entry feature associated with a dispersion method, HARVEST ensures that re-entries occur automatically, using the parameters set during the initial entry.

HARVEST allows age constraints to be specified either as a minimum stand age or as a minimum time since the stand was last harvested. The area (acreage) to be cut can be specified in one of three ways: (1) as a percent of the area of the forest type(s) in the MA(s); (2) as a percent of the area of the forest type(s) in the MA(s) that also satisfies all constraints (amount of *available* forest type); or (3) as an area entered by the user. This provides flexibility for different planning entities (e.g., federal or private) to simulate harvest targets using different approaches to the specification of harvest area.

Table 1
Parameters controlled by the user in HARVEST 6.0

Parameter	Range	Description
MA	Values in map	Specifies targeted Management Area
FT	Values in map	Specifies targeted Forest Type
Mean harvest size	≥ 1 cell	Specifies mean of size distribution
S.D. in harvest size	≥ 0.0 cell	Specifies width of size distribution
Minimum harvest size	$\leq$ mean	Truncates left tail of size distribution
Maximum harvest size	$\geq$ mean	Truncates right tail of size distribution
Fill stands	On/off	Whether to use existing stand boundaries to determine harvest opening size
Spatial dispersion method	Dispersed, clustered, group selection, oldest first	Controls how harvest openings are distributed spatially
Reentry interval	≥ 0 years	Rotation length (optional)
Group proportion	≥ 0.0	Proportion of stand area harvested in each group selection entry
Minimum age for harvest	> 0 years	Stands must be at least this old to be cut
Area to harvest	> 0 cell	Specifies how many cells will be cut
Adjacency constraint	On/off	Specifies whether adjacency constraints (see text) will be enforced
Green-up interval	> 0 years	How old stands must be to allow an adjacent stand to be cut (when Adjacency constraint = on)
Riparian buffers	On/off	Specifies whether riparian buffers are required
Riparian buffer width	Multiple of cell width	Specifies the width of riparian buffers (when Riparian buffers = on)

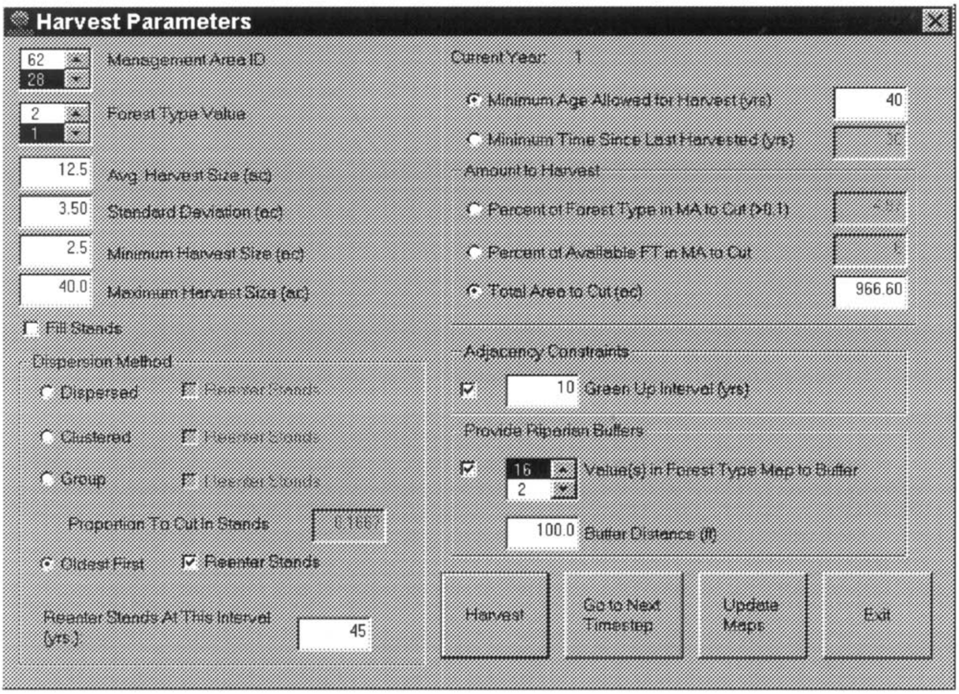

Fig. 1. HARVEST 6.0 user interface showing the dialog box used to specify harvest strategies targeted to specific MA(s) and forest type(s).

An adjacency constraint prohibits harvest units from being placed adjacent to existing openings, thereby increasing the total size of the opening. The green-up interval defines what constitutes an existing opening. It is given in years, and represents the time that must pass before a harvested stand has regrown sufficiently to no longer be considered an opening. Riparian buffers are uncut strips left adjacent to water, or other features. HARVEST allows the user to specify whether or not to leave these buffers, how wide they must be, and the land cover features that are to be buffered (e.g. streams, lakes, roads).

2.3. Model assumptions

A number of simplifying assumptions were made in the development of HARVEST to reduce input data requirements, maintaining its ease of use as a strategic planning and research tool. (1) Forest age is used as a surrogate for merchantability. It is assumed that the likelihood that a stand of a given forest type will be harvested is related solely to its age. However, we know that stocking density, size class, site conditions, accessibility and operability are all factors that influence stand growth and harvest decisions in reality. Nevertheless, this simplifying assumption is reasonable in a strategic planning context. (2) When HARVEST does not select stands using the *Oldest First* method, stands are selected at random from the stands of the given forest type that are older than the minimum age for harvest. Over a time period of a decade or more, this mimics the pattern found in real managed forests (Gustafson and Crow, 1999). For shorter time periods this may not be the case. (3) Forest type does not change, even over long time periods. This may be unrealistic for certain forest types under even-age management. However, if the treatment types targeted by the user to specific forest types are compatible with those types, then this should not be a problem. If the user is interested in how forest composition might change under alternative management strategies, then HARVEST is not the tool to use. (4) Stand boundaries do not change, even when the harvest boundaries are significantly different than the original stand boundaries. The original stand boundaries are maintained solely for bookkeeping purposes. This normally does not create problems, but has the potential to create a logistical limit to harvest activity if simulated harvests are generally much smaller than the original stands. (5) Operability is assumed to be constant across the landscape among stands within MAs where harvest is allowed, so that issues related to roads are not a constraint. Stands can be eliminated from the input age map if operability or access is a known limitation, to preclude simulated harvest activity in them.

3. Methods

To achieve objective 2, we used HARVEST to conduct simulation experiments on a 34 053 ha portion of the Pleasant Run Unit of the Hoosier National Forest, Indiana (Fig. 2), using 1988 stand maps for initial conditions. We designed these simulation experiments to determine the effect of adjacency constraints and spatial dispersion on: (1) the ability to meet a cutting target; (2) on mean patch size (defined by age class); and (3) the amount of forest interior and forest edge habitat. We varied the use of adjacency constraints (constraint [i.e. harvest is not allowed adjacent to stands <20 years of age] vs. no constraint), the spatial dispersion of harvests (clustered vs. dispersed), and harvest size in a full factorial design. We included variation in mean harvest size (1.8 vs. 18 ha) because harvest size has a dominant effect on spatial pattern, particularly the amount of forest interior (Gustafson and Crow, 1994). The cutting target was held constant at 1058 ha/decade (8% of the forest within the study area), and we simulated 8 decades of harvest activity. All simulations used a minimum stand age of 80 years for harvest, and required 30 m riparian buffers. Three replicates of each simulation were generated because similar studies have shown that the variability in the resulting patterns is quite low (Gustafson and Crow, 1994; Gustafson, 1996). We plotted the number of hectares actually harvested, mean patch size, area of forest interior habitat, and area of forest edge habitat against time. For this analysis, we defined forest interior habitat as forest >210 m from a harvested opening (age <20 years) or non-forested habitat. We conducted an analysis of variance to determine the relative effect of each of the parameters we varied. The time steps were included in the analysis to account for the potential correlation of measures of forest pattern in successive decades.

4. Results

The analysis of variance showed that harvest size was the most important factor in determining the ability to meet cutting targets, but that the adjacency constraint was also significant (Table 2). Adjacency constraints reduced the ability of HARVEST to meet cutting targets by up to 70% of the target, depending on other parameters used, while spatial dispersion had a minimal effect (Fig. 3, Table 2). The effect was not consistent through time, as adjacency constraints interacted with the availability of stands of sufficient age as time progressed. The ability to meet cutting targets was sensitive to adjacency constraints, because this constraint removes some stands from eligibility for harvest in each time step. Smaller harvest size also reduced the ability to meet cutting targets, because small (1.8 ha) harvests consumed the available stands before the targets were reached.

Adjacency constraints had little effect on patch size (Fig. 4, Table 2). Patch size was related primarily to harvest unit size as might be expected (Table 2). However, mean patch size decreased even when the mean size of new patches was greater than the initial mean size, because many small remnant patches were created when harvests did not completely fill existing stands.

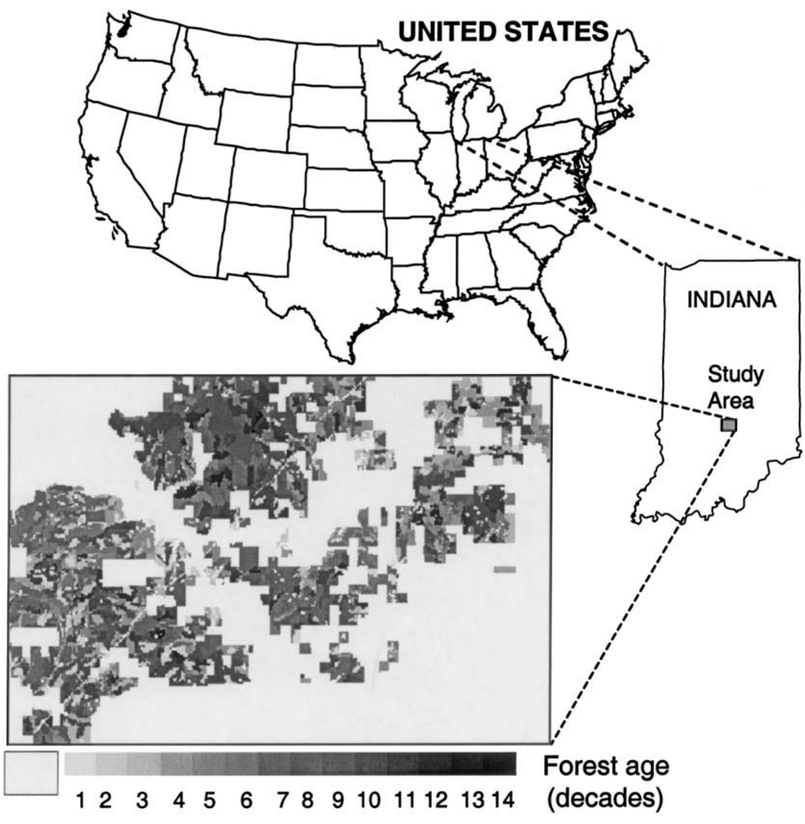

Fig. 2. Location of the study area and the initial conditions age map used in the simulations.

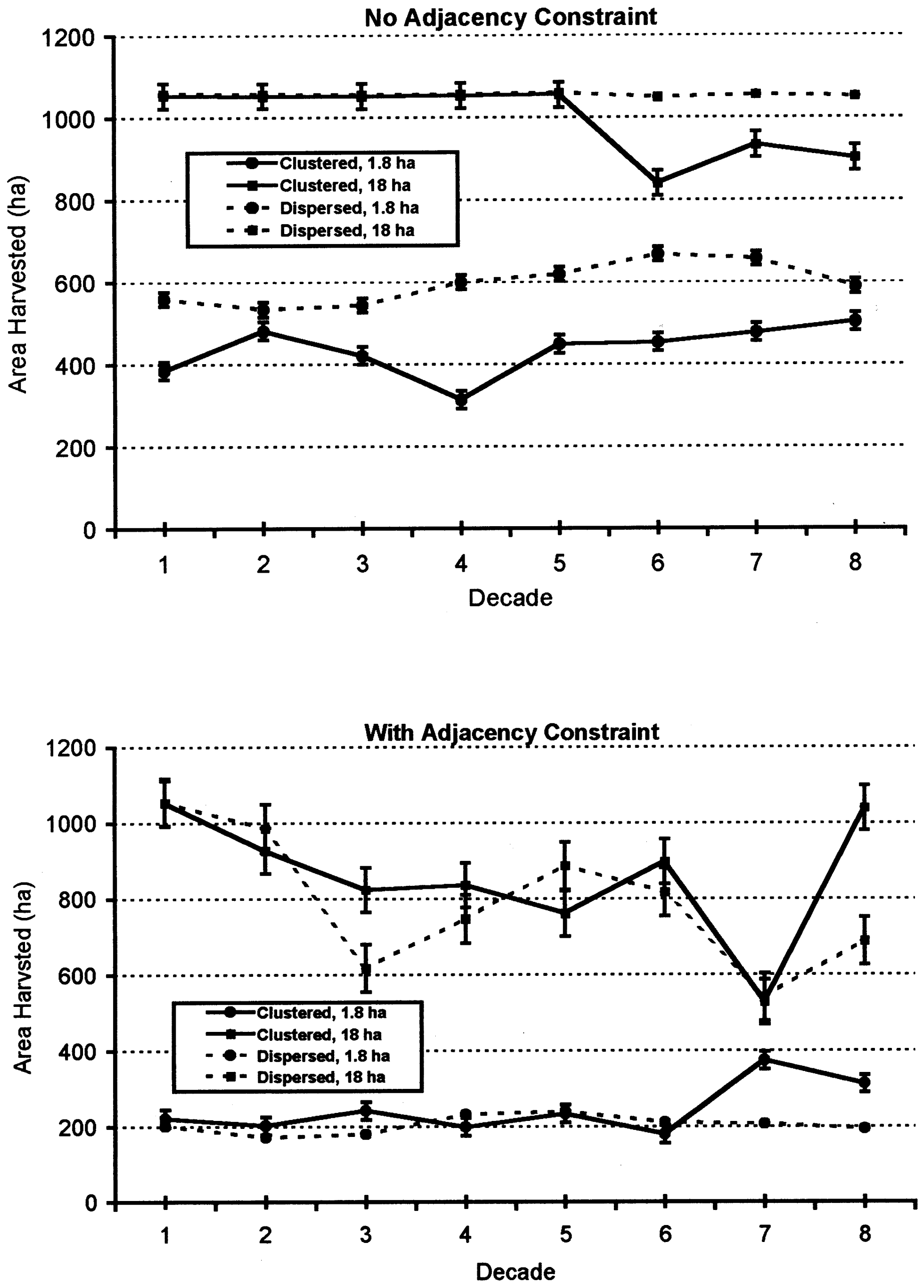

Fig. 3. Effect of harvest size, spatial dispersion and adjacency constraints on the ability to meet a cutting target of 1058 ha (8% of forest area within the study area). Error bars show 1 S.E.

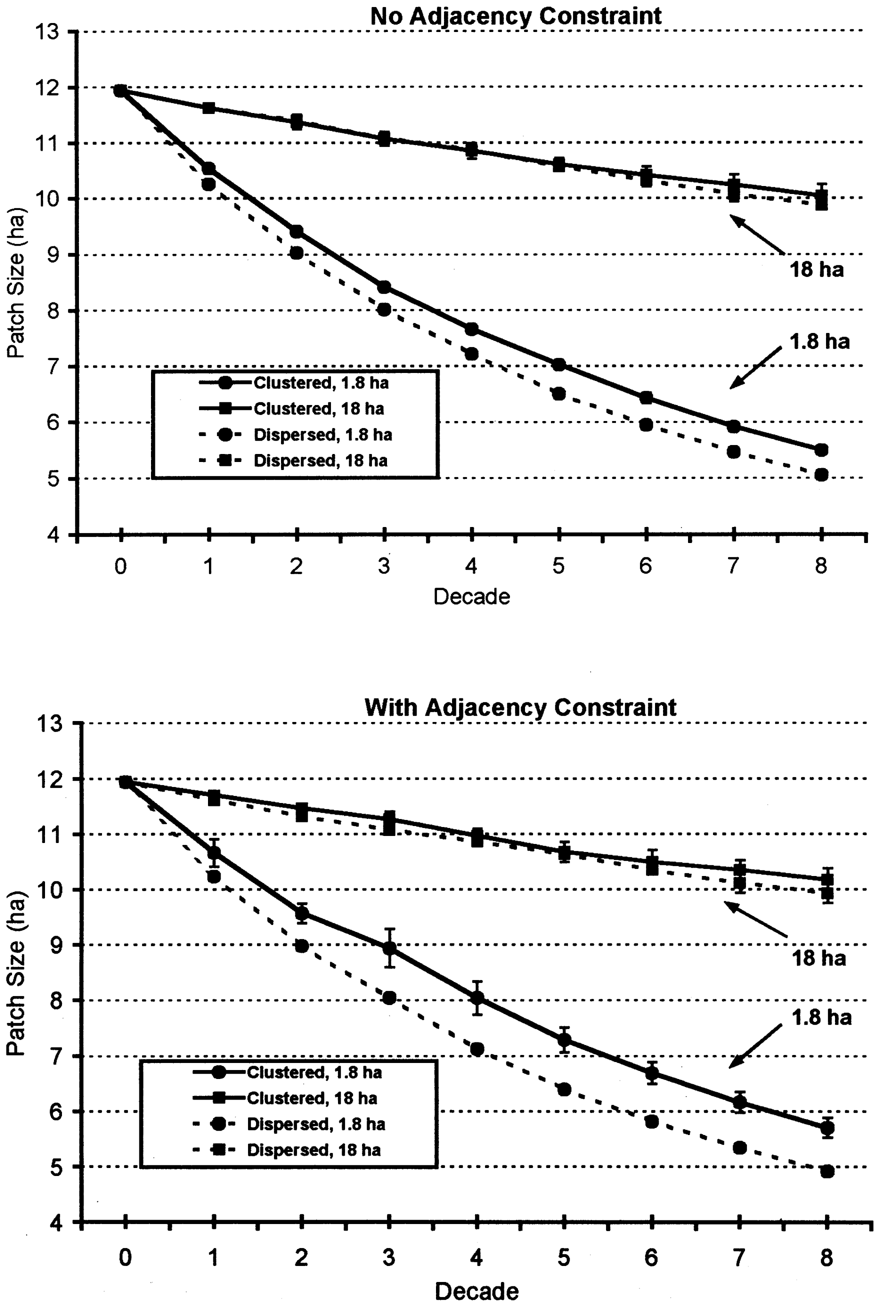

Fig. 4. Effect of harvest size, spatial dispersion and adjacency constraints on mean patch size. Error bars show 1 S.E.

Table 2
Percent of total sums of squares attributed to each treatment in an analysis of variance conducted on simulation results

Treatment (levels)	Interior habitat	Edge habitat	Patch size	Area cut
Time period (decade) (1–8)	6.7*	0.36	28.0*	0.86
Dispersion method (dispersed, clustered)	21.9*	23.1*	0.69*	0.19
Harvest unit size (1.8 ha, 18 ha)	55.5*	60.2*	63.2*	68.7*
Adjacency constraint (yes, no)	0.05	0.03	0.03	13.4*
Dispersion × harvest size	11.1*	11.7*	0.35*	0.20
Harvest size × adjacency	0.09	0.06	0.001	0.47
Dispersion × adjacency	0.005	0.009	0.07	1.5*
Dispersion × harvest size × adjacency	0.004	0.002	0.02	0.07
R^2	0.95	0.95	0.92	0.85

* Relationship between treatment and response variable was significant ($\alpha = 0.01$).
Each ANOVA was calculated using 192 observations (three replicates of each treatment combination at each of eight time periods), with 14 degrees of freedom.

Adjacency constraints increased variability in the amount of forest interior, but they had a marginal effect on the total amount (Fig. 5). Clustered spatial dispersion increased the amount of forest interior habitat. Larger (and therefore fewer) harvest openings also increased forest interior (Figs. 5 and 6). Adjacency constraints also increased variability in the amount of edge habitat, but had a marginal effect on the amount (Fig. 7). Clustering decreased the amount of edge habitat. Larger harvests decreased the amount of edge habitat because of their smaller perimeter to area ratios. Harvest unit size and spatial dispersion of harvests had the greatest effect on the amount of forest interior and edge habitat (Table 2).

Our results also illustrate the interactions between the size of harvest units, adjacency constraints and the spatial dispersion of harvest units on the response variables. The ability to meet the area to be harvested target (1058 ha) was significantly dependent on the combination of harvest size, adjacency constraints and spatial dispersion (Table 2, Fig. 3). Patch size, and the area of interior and edge habitat were significantly dependent on the interaction between harvest size and spatial dispersion, with less of an interaction with adjacency constraints (Table 2, Figs. 4, 5 and 7).

5. Discussion

Simulation experiments using HARVEST can determine the effects of strategic management decisions on spatial pattern. In our example, we generated answers to strategic questions about the effects of the size of harvest units, adjacency constraints, and the spatial dispersion of harvest units. Our experiment showed that changing harvest size in order to change the scale of patchiness (grain) of seral stages across the landscape does not provide a straightforward result. The legacy of

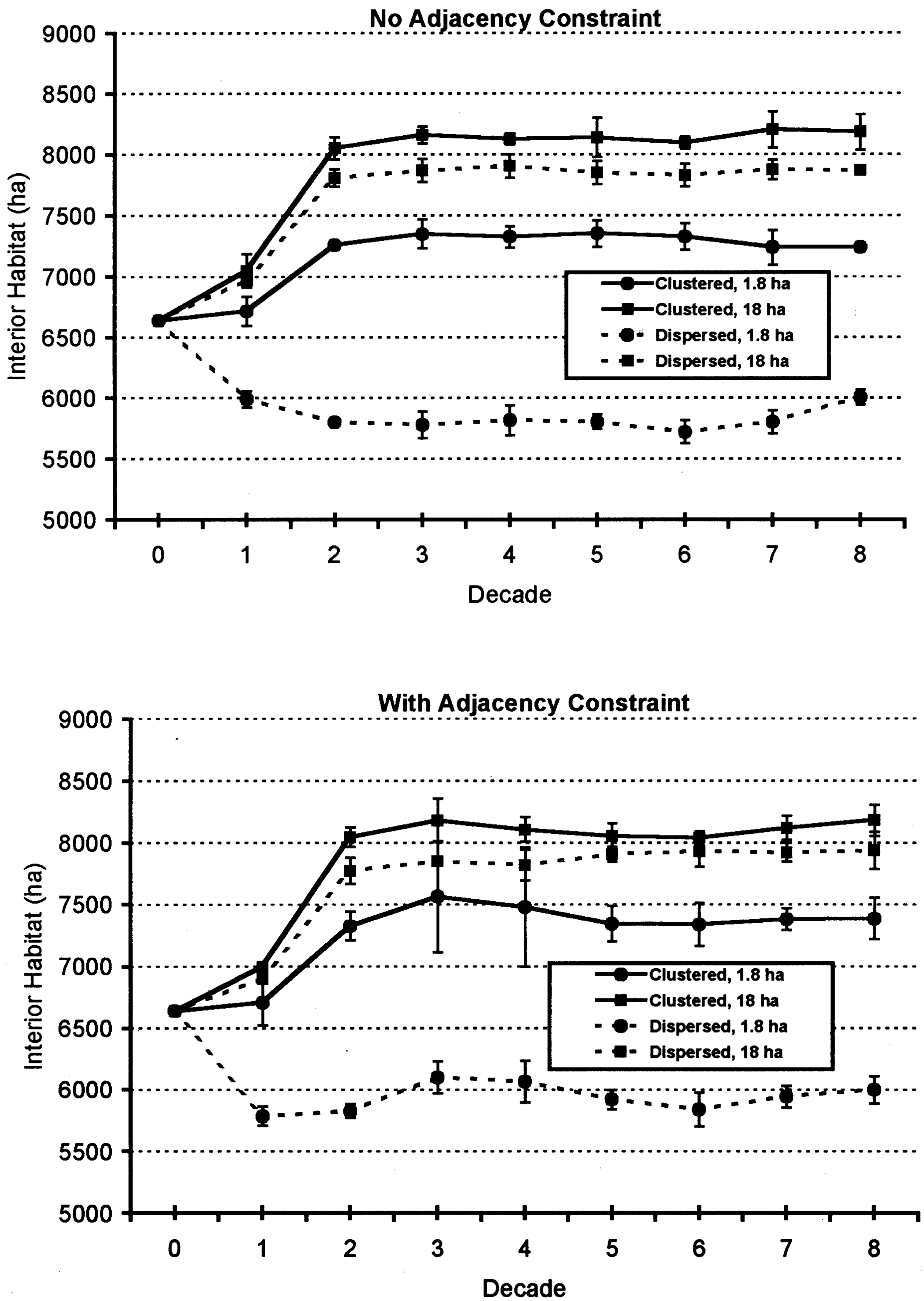

Fig. 5. Effect of harvest size, spatial dispersion and adjacency constraints on the amount of forest interior (forest > 210 m from an opening). Error bars show 1 S.E.

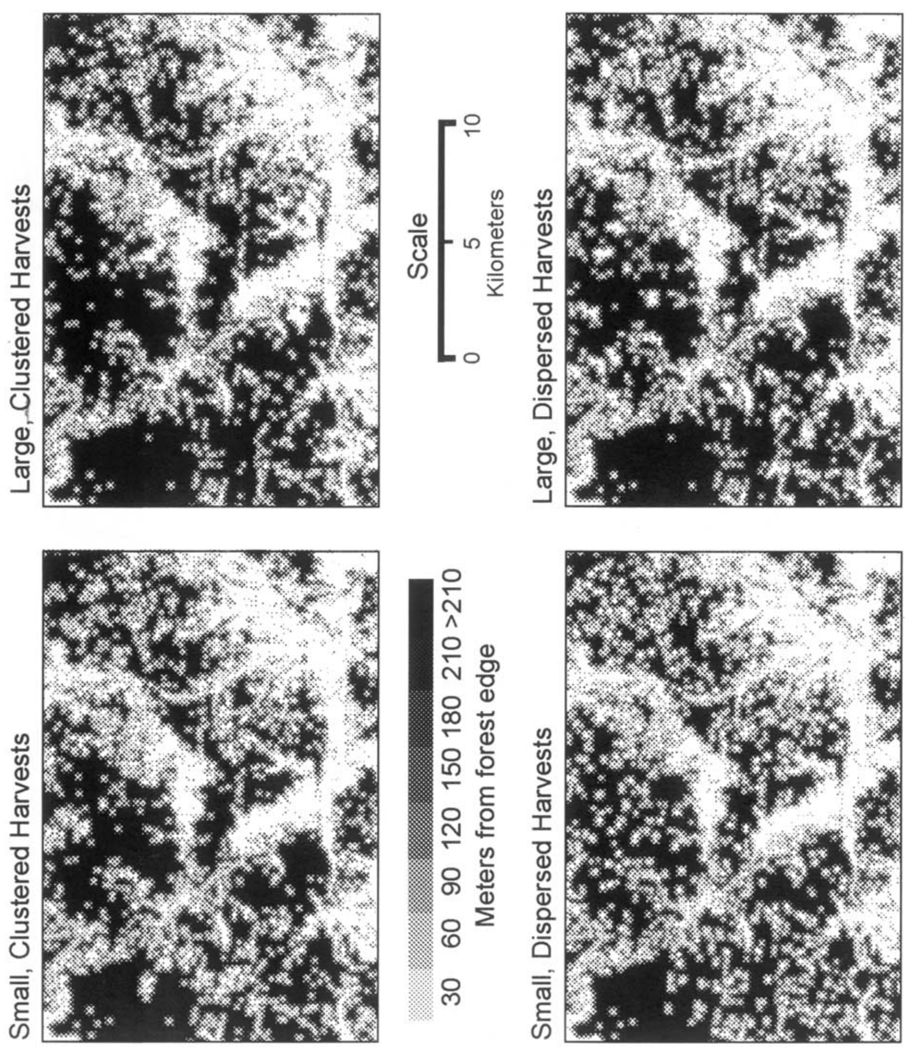

Fig. 6. Maps showing the spatial configuration of forest interior and forest edge habitat after simulating 8 decades of timber harvest activity. Forest interior habitat was defined as forest >210 m from a forest opening (stands <20 years old, or non-forest habitat). Parameters used to produce the maps are given above each map. A total of 1058 ha was cut in each decade for each scenario, and adjacency constraints were not enforced for any of the maps.

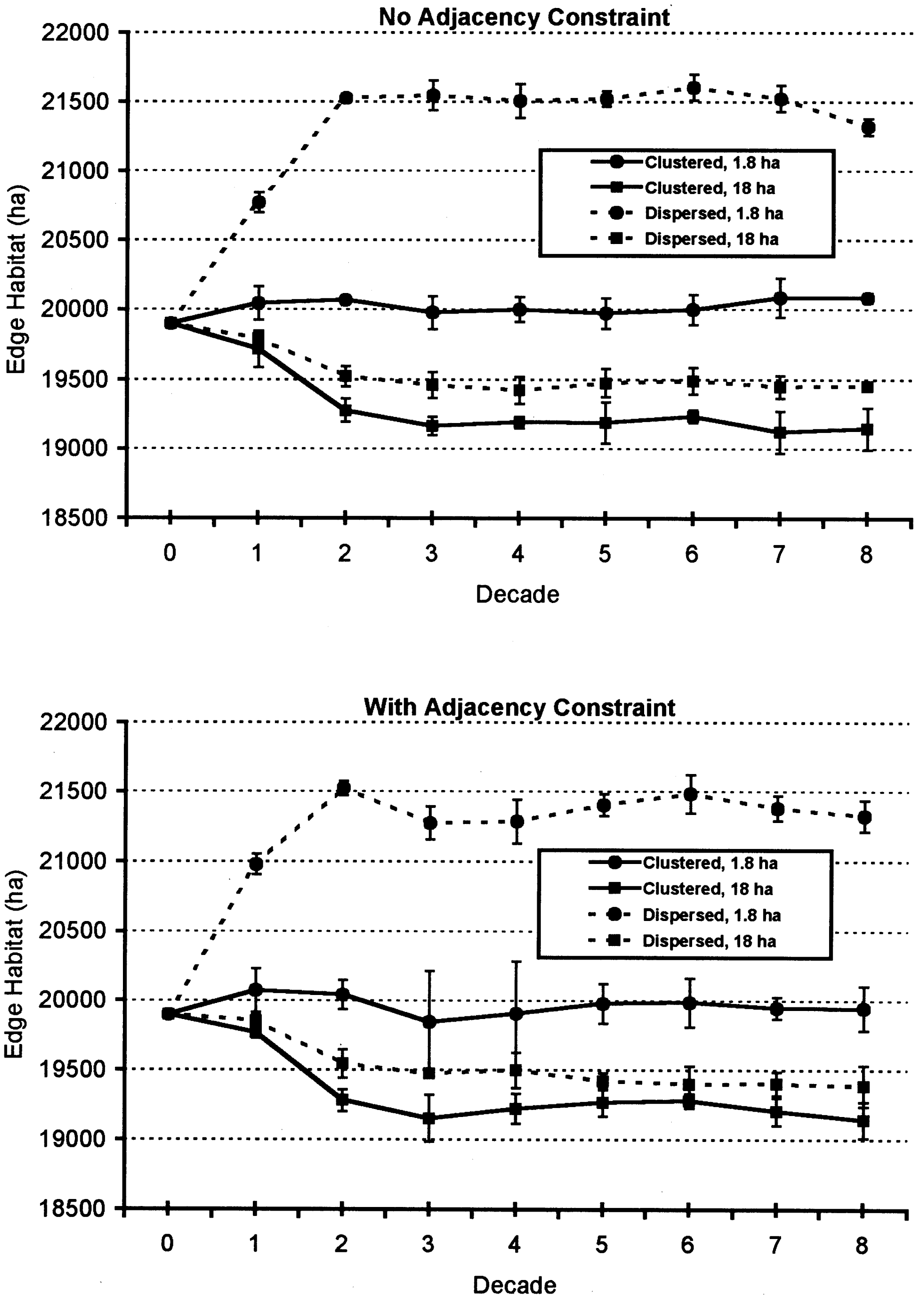

Fig. 7. Effect of harvest size, spatial dispersion and adjacency constraints on the amount of edge habitat (forest < 210 m from an opening). Error bars show 1 S.E.

the prior pattern persists for a long time, and the size of patch fragments between harvested patches appear to have a more important effect on the average patch size than the patches produced by current harvesting. Note that the average patch size declines from the original 12 ha even when the average harvest unit is 18 ha (Fig. 4). Our results also showed that adjacency constraints had minimal effect on average patch size and amount of forest interior and edge habitat. However, adjacency constraints did limit harvest levels over the course of many decades. At higher levels of harvest (i.e. a higher percentage of forests cut each decade) there would be an even greater effect on spatial pattern, and also a greater limitation on achieving those higher cutting targets. It should be noted that different initial conditions might also limit the ability to meet cutting targets if recent harvest rates were high (Gustafson and Crow, 1998). Our results also showed that a clustered dispersion of harvests produced a greater area of forest interior habitat, consistent with other findings (Li et al., 1993; Gustafson and Crow, 1994). A previous study demonstrated that changes in the area cut in each time period produces a positive linear increase in linear forest edge, and a negative exponential decrease in forest interior habitat (Gustafson and Crow, 1994). Finally, we found significant interactions among the size of harvest units, adjacency constraints, and the spatial dispersion of harvest units in determining the landscape patterns produced by harvest strategies. It may be important for managers to understand these interactions to avoid unintended spatial effects when implementing management strategies.

The intuitive interface of HARVEST, coupled with its more flexible parameter specification, has advanced HARVEST from being strictly a research tool to a strategic management planning tool. Its limited input data requirements and ease of use make it feasible for forest managers and their staff to conduct their own 'what-if' analyses as they formulate management alternatives and strategic direction. Although the questions HARVEST addresses are limited to those related to the spatial pattern of canopy closure and seral stages, these questions are increasingly important to many stakeholders of managed forests. The input maps can be produced from spatial data commonly maintained by forest managers. The output maps from HARVEST (Erdas 7.5 format) can be input directly into many GIS systems and to the widely used spatial pattern analysis software Fragstats (McGarigal and Marks, 1995) for additional analysis. Important ecological conditions such as the amount and location of forest interior habitat, the juxtaposition of habitats of different ages, and the size of patches can be assessed strategically using HARVEST, and related to the wildlife species that are impacted by these conditions. As an example of this, District biologists on the Chequamegon-Nicolet National Forest in Wisconsin are using HARVEST to evaluate the habitat fragmentation effects of even-aged management as part of an Environmental Impact Statement study. At a broader level, novel strategic approaches such as dynamic zoning (Gustafson, 1996, 1998) and patch cutting can now be developed and evaluated for spatial pattern effects by forest management planners themselves.

HARVEST also remains a useful research tool, now more easily accessible to researchers other than its developers. Research software typically is poorly documented and is difficult for other researchers to use. We have invested resources to overcome this limitation for HARVEST, in hopes that it will become part of the toolbox for investigators studying the interactions between forest management and landscape pattern.

Version 6.0 of HARVEST and the User's Guide are available without charge from the North Central Research Station Web site (http://www.ncrs.fs.fed.us/4153/) under 'Products.'

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