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Developing alternative forest cutting patterns: A simulation approach

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Abstract

This study examines effects of different forest cutting patterns on habitat fragmentation in managed forest landscapes. We use computer simulation to conduct experiments in which we examine effects of different cutting patterns, cutting-unit size, and special constraints (*e.g.*, a forest reserve, a stream system, or a road system) on landscape patterns. Fragmentation indices are used to quantify structural changes over the cutting cycle and among different treatments of the experiments. Degree of fragmentation varies greatly among the five cutting patterns used; aggregation of cutting units results in low degree and gradual change of fragmentation. Cutting patterns with larger cutting units and additional landscape constraints also lead to lower degree of fragmentation. Moreover, differences in fragmentation among the treatments are not observed until 30% or 50% of the landscape is cut.

Introduction

Landscape fragmentation is the process of creating an increasingly complex mosaic of patches as a result of disturbances, including human activity. Questions about effects of fragmentation of forest landscapes on wildlife, disturbances, and other ecosystem characteristics have been posed (Harris **1984,** Verner *et al.* **1986,** Franklin and Forman **1987)** and alternative management approaches suggested (Harris **1984,** Franklin and Forman **1987).** However, management alternatives have not been quantitatively evaluated because of difficulties of conducting landscape-level experiments. Guidelines for land managers to minimize fragmentation effects are still lacking (Temple and Wilcox **1986).**

Fragmentation of natural Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] forests on federal lands in the U.S. Pacific Northwest has intensified in the past four decades (Burgess and Sharpe **1981,** Harris **1984,** Verner *et al.* 1986**),** largely because of timber harvesting with the "staggered-setting" clear-cut system. This system, which disperses relatively small cutting-units evenly over a forest landscape, has been challenged for its failure to consider effects of fragmentation (Harris **1984,** Franklin and Forman **1987).** Using a checkerboard model, Franklin and Forman **(1987)** hypothesize that continued implementation of the staggered-setting system could further fragment natural forests, degrade wildlife habitat, and increase susceptibility of residual patches of natural forests to disturbance.

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They suggest instead that cutting units be aggregated, that large blocks of forest habitat be retained until late in the cutting cycle, and that clear-cut units be larger than those currently used. They (Franklin and Forman 1987, Franklin 1989) also argue that live and dead trees should be retained in the cutting units to meet a variety of ecological objectives. However, the proposed hypotheses need to be tested, and their ecological, economic, and other consequences examined for a broader range of landscape patterns.

To illuminate the relations between cutting patterns and forest fragmentation, we used computer simulation and fragmentation indices to evaluate (1) differences in spatial and temporal patterns of forest landscapes created by simulation models that use different rules for locating successive cutting-units, (2) effects of different sizes of cutting units on landscape structure, and **(3)** impacts of additional real-world constraints (forest reserves, streams, and roads) likely to be combined with cutting patterns. In this analysis we deal only with landscape patterns, but not with silvicultural practice within cutting units.

Methods

Landscape simulation models

Computer simulation was used to evaluate alternative landscape patterns, because field experimental and chronological approaches were not feasible due to expense, time requirements, lack of experimental controls, and difficulties of finding suitable study sites (Perry 1988, Baker 1989). The main advantage of computer simulation is that specific forest cutting patterns can be generated under controlled conditions over time. The main limitation is that the reliability of simulation results is highly dependent upon the degree to which the models reflect reality.

We used a computer program, Landscape Spatial Pattern Analysis (LSPA; Li 1989), to study forest fragmentation under different cutting patterns. LSPA generates landscapes with different cutting patterns, measures basic geometric parameters of landscape structure, and calculates various indices of landscape pattern.

In LSPA, we developed five models based on the spatial arrangement of the cutting units (Fig. 1):

(1) The *random patch model* assumed a random distribution of cutting units such that each uncut pixel had an equal probability of being the first pixel of a new patch (Fig. 1a). After the first pixel was selected, contiguous pixels were selected by a random walk model (*i.e.*, each search direction was randomly determined). Size of each unit was determined by randomly adding (or subtracting) **0–9** pixels to the "mean patch size," which was a parameter entered at the beginning of a simulation run.

(2) The *maximum dispersion model* located cut pixels, as evenly spaced and widely dispersed as possible. At each search, a square patch (2 by 2 pixels, **3** by **3**, or 4 by 4) was designated as a cutting unit (Fig. 1b).

(3) The *staggered-setting model* adopted the algorithm of the maximum dispersion model to locate the first pixel of a cutting unit (Fig. 1c). Unit size and search direction were then determined randomly as in (1), but with two restrictions (*i.e.*, restricted random-walk model): (a) no more than **3** pixels were cut consecutively in the same direction without branching, and (b) no two cutting units generated at the same time step were allowed to join.

(4) The *partial aggregation model* divided the landscape into four equal blocks; at each time step, one of the four blocks was randomly selected, and cutting units were confined to the block until it was almost impossible to put cutting units inside the block (Fig. 1d). In each block, the first pixel of a unit was chosen randomly and the unit was then created with the restricted random walk model described in **(3)**. The number of the pixels in a unit (patch size) was randomly determined as in (1).

(5) The *progressive cutting model* started cutting at a border pixel of the landscape grid and extended in one direction which was randomly determined at each time step (Fig. 1e). The margins of the cutting belt at time step 1 were defined by an input parameter; for the latter time steps, the

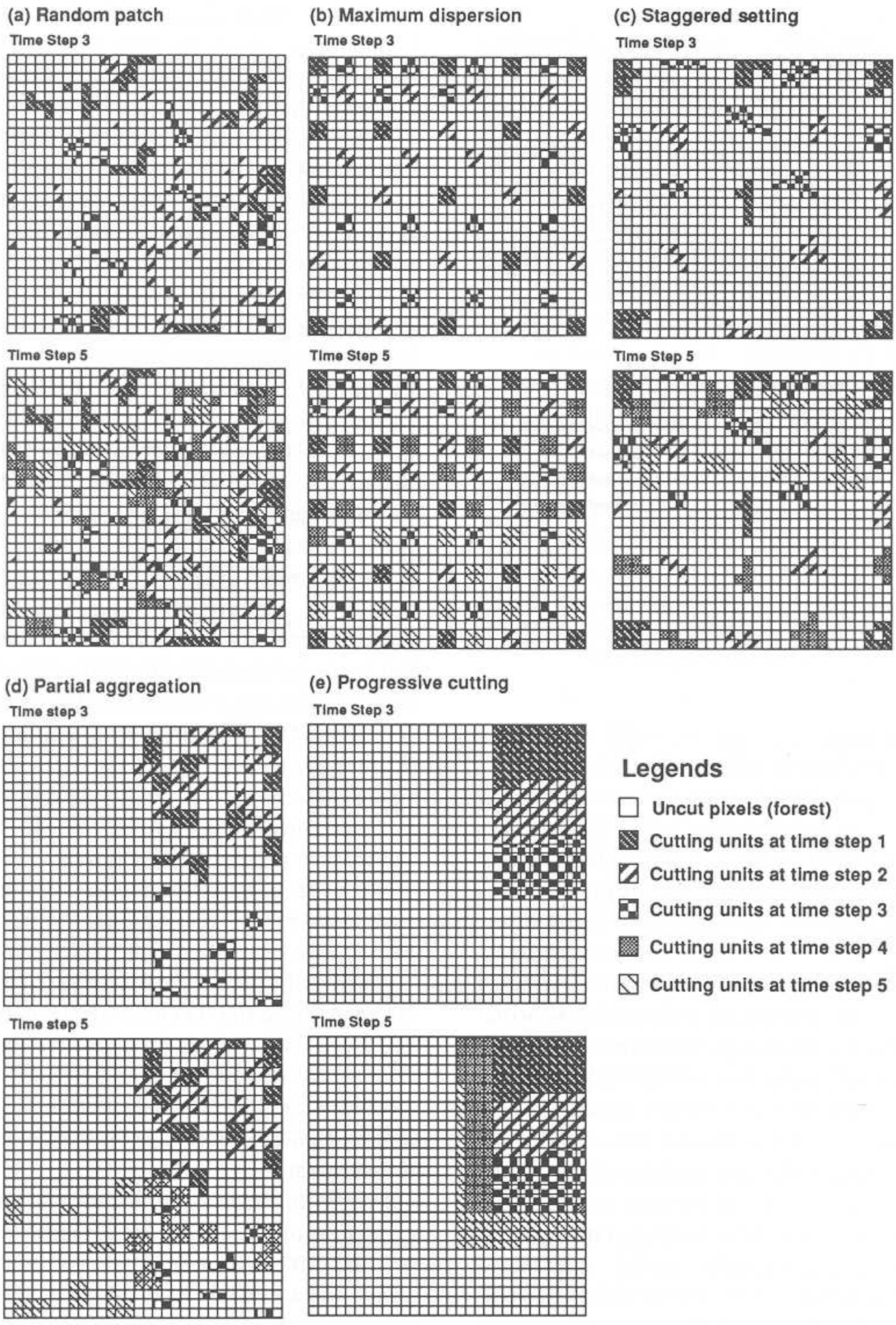

Fig. 1. Example maps generated at time steps 3 and 5 – when the landscape is 21% and 35% cut – by the five landscape models: (a) random patch (RP), (b) maximum dispersion (MD), (c) staggered-setting (SS), (d) partial aggregation (PA), and (e) progressive cutting (PC). Mean cutting-unit size is 4 pixels.

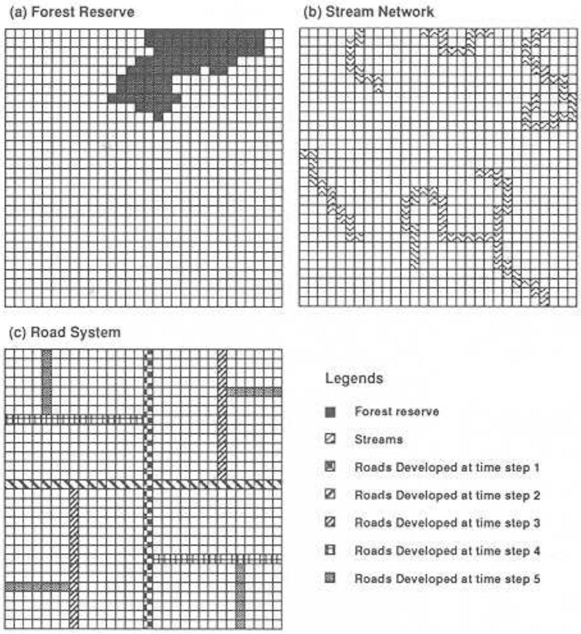

Fig. 2. Examples of the three supplementary models: (a) forest reserve, (b) stream network, and (c) road system.

margins were set to equal the width of the existing cut pixels as a whole in the selected direction. Only one cutting unit was usually created.

In these five cutting models we did not consider landscape features other than the spatial arrangement of cutting units. However, constraints such as existing distribution of vegetation age classes, topography, stream networks, and road systems, may profoundly affect cutting pattern in managed forests. Because incorporating the numerous structural features greatly complicates landscape modeling, we selected three factors (as supplementary models): a forest reserve, a stream network, and a road system. The forest reserve was a randomly selected area of contiguous pixels in which cutting was prohibited (Fig. 2a). The stream network (Fig. 2b) was created by a self-avoiding, random-walk model. This random-walk model constructed stream channels that (1) initiated randomly at a pixel from which a linear system of pixels one pixel wide was continuously developed, (2) could randomly change direction, but never go backward, and (3) terminated when it ''stepped outside'' the landscape boundary or met with another branch. Cutting of stream pixels was prohibited. The road system was created following a fixed pattern illustrated in Figure 2c; development of the road system started at time step 1 and completed at time step 5. Cutting was allowed only if one of the pixels in a cutting unit was next to a road pixel or a pixel cut at previous time steps. Thus, reserves and streams prohibited cutting in some parts of the landscape, whereas roads constrained cutting patterns.

Three sets of simulation experiments were conducted. In each set, all variables were held constant except the property to be examined. The first set used all five cutting models to examine effects of cutting pattern on landscape characteristics through space (spatial pattern) and time (temporal pattern). The second set used the random and partial aggregation models to study the effects of cutting-unit size on landscape geometry; only mean patch size varied (4 and 16 pixels). The third set incorporated the three supplementary models. A forest reserve was included in the random and partial aggregation models; a stream network in these two models; and a road system in the staggered-setting model. The forest reserve and stream network each covered 10% of the total area, and the road system 15%. We used fewer models in the second and third simulation experiments to simplify the graphic presentation of results.

We used 10 simulation time steps in each experimental run of landscape pattern development; at each time step, 7% of the total area was cut (*i.e.*, 7% was cut at step 1, 14% at step 2, and so on to 70%). A single run was used for the maximum dispersion model; ten replicate model runs were performed for all other models, because they were stochastic so that simulation results may differ among replicates. However, variation in landscape measures among those replicates was small (Li 1989). Within each experimental run, cutting units created at different time steps (ages) were considered as different patch types. A simulated landscape was a grid of 34 by 34 pixels (limitation of personal computers).

Indices of fragmentation

Fragmentation has not been clearly defined as an ecological concept, not even in the principal publications on the subject (*e.g.*, Burgess and Sharpe 1981; Harris 1984; Verner *et al.* 1986). In an ecological context and for quantification, we here define fragmentation as the processes of increasing the number of landscape pieces, decreasing interior habitat area, increasing the extent of forest-opening edges, or increasing isolation of residual forest patches. Our study concerns fragmentation of natural forests, although all habitats may be subject to fragmentation.

Many fragmentation indices have been designed and used (Li 1989; also see Romme 1982; Rosenberg and Raphael 1986; O'Neill *et al.* 1988; Ripple *et al.* 1991). Four indices were selected in this study to represent different aspects of fragmentation (Li 1989).

(1) Edge density, a good indicator of fragmentation, is defined as the length of edge per unit area, here measured as meters per hectare.

(2) Area-weighted shape index (AWS) is defined as:

$$AWS = \sum_{i=1}^{t} A_i SI_i / A$$

$$SI_i = 0.25\, P_i/(A_i)^{1/2}$$

where t is the total number of patches, A_i the area of forest patch i, SI_i the shape index of patch i (*i.e.*, the standard shape is square; Patton 1975, Forman and Godron 1986), P_i the perimeter (*i.e.*, edge length) of patch i, and A the total area of forest patches. This index uses patch (cutting unit) size as a weighting factor – larger patches are assumed to have greater effect on overall landscape structure (Li 1989). Therefore, a higher AWS value indicates that more irregular shaped cutting-units dominate the landscape.

(3) Romme's (Romme 1982) relative patchiness index (RPI) is defined as:

$$RPI = 100 \sum_{i=1}^{t} \sum_{j=1}^{t} E_{ij} D_{ij} / N_b$$

where t is the total number of patch types, E_{ij} the number of boundary units (in units of pixel edge length) between patch types i and j, D_{ij} the dissimilarity value for patch types i and j, and N_b the total number of boundary units (Romme 1982; Li 1989). RPI is strongly dependent on the dissimilarity matrix and thus on definition of habitat types. The dissimilarity matrix, $[D_{ij}]$, can be obtained either subjectively (*e.g.*, by expert judgment) or objectively (*e.g.*, using scores of the first ordination axis or other dissimilarity measures); we determined the matrix subjectively, with old-growth forest and first-year clear-cut as the two extremes (maximum value of 1). This index, a measure of over-all landscape fragmentation, considers regrowth of patches (cutting units) by assigning different values to units of different ages. A higher RPI value indicates the presence of many habitat types in juxtaposition with one another, resulting in a high contrast, complex landscape.

(4) An interior area fragmentation index (IAF), is defined as (Li 1989):

$$IAF = 1 - (A_{in}/A)$$

where A_{in} is the forest interior area, and A the total forest area. A, was calculated by assuming edge to be one pixel (*i.e.*, scale of edge effect is 1-pixel) and subtracting all edge pixels from the total forest area. An interior pixel is any forest pixel that is more than one uncut pixel away from cut pixels. This index is scaled from 0 to 1. An IAF value of 1 indicates a forest landscape whose interior habitat is completely fragemented, that is, all pixels of forest patches are edge-pixels (*i.e.*, adjacent to clear-cut pixels).

Results

Spatial and temporal patterns

Overall, landscape fragmentation increased or fluctuated most with the maximum dispersion, random patch, and staggered-setting models, was moderately affected by the partial aggregation model, and was virtually unchanged by the progressive cutting model (Fig. 3).

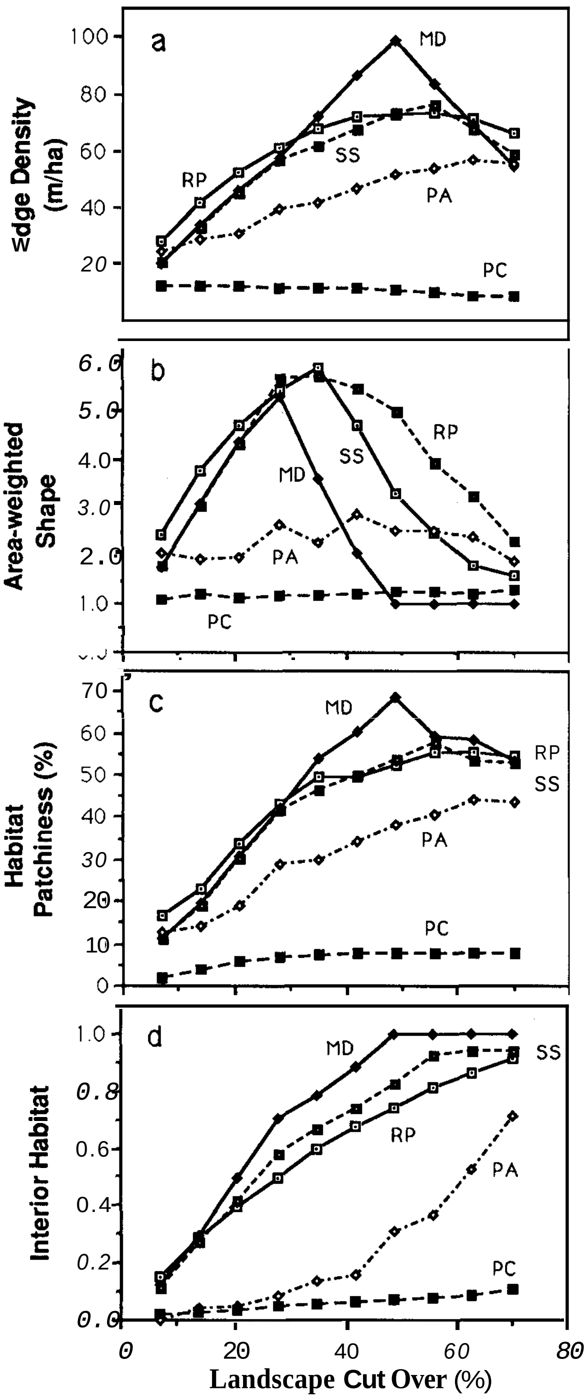

Fig. 3. Comparison **of** the five landscape models by the four fragmentation indices (a-d). Percentage **of** landscape cut over on horizontal axis corresponds to simulation time steps 1–10(*e.g.*, 7% **is** at step **1**; 70% at step 10). For this and subsequent figures, see Fig. 1 caption for **full** model names and abbreviations.

Edge density increased most in the maximum dispersion model, peaking when 50% of the landscape cut (Fig. 3a). The random patch and staggered-setting models were strongly, but less dramatically affected. In contrast, edge density of the partial aggregation model increased gradually with cutting but did not clearly peak; that for the progressive cutting model was extremely low and varied little.

The average forest patch shape fluctuated more dramatically for the maximum dispersion, random patch, and staggered-setting models (Fig. 3b). For the first model, AWS values peaked when the landscape was 30% cut, but dropped to their minimum at 50% cut when all units were 4-pixel squares. Values for the other two models peaked when the landscape was 35% cut and then dropped sharply; no apparent minimum was reached. As with edge density, AWS values for the partial aggregation model fluctuated only moderately, and those for the progressive cutting model remained unchanged.

Habitat patchiness closely followed the trends revealed for edge density (Fig. 3c). The maximum dispersion, random patch, and staggered-setting models differed little until **30%** of the landscape was cut. Thereafter, RPI values for the first model peaked at 50% cut and declined; those for the latter two models closely paralleled one another (by slowly increasing after 35%, leveling off at 50% cut). RPI values for the partial aggregation model climbed steadily, also leveling off at 50% cut. Again, values for the progressive cutting model changed little.

The amount of fragmented forest interior area increased rapidly, then leveled off, for the maximum dispersion, random, and staggered-setting models (Fig. 3d). In contrast, IAF for the partial aggregation model rose gradually until 40% of the landscape was cut, then accelerated sharply. As with all the other fragmentation indices, IAF values for the progressive cutting model were virtually unaffected.

Effects of cutting-unit size

Using large cutting-units consistently produced less fragmented landscapes (Fig. 4), although the rand-

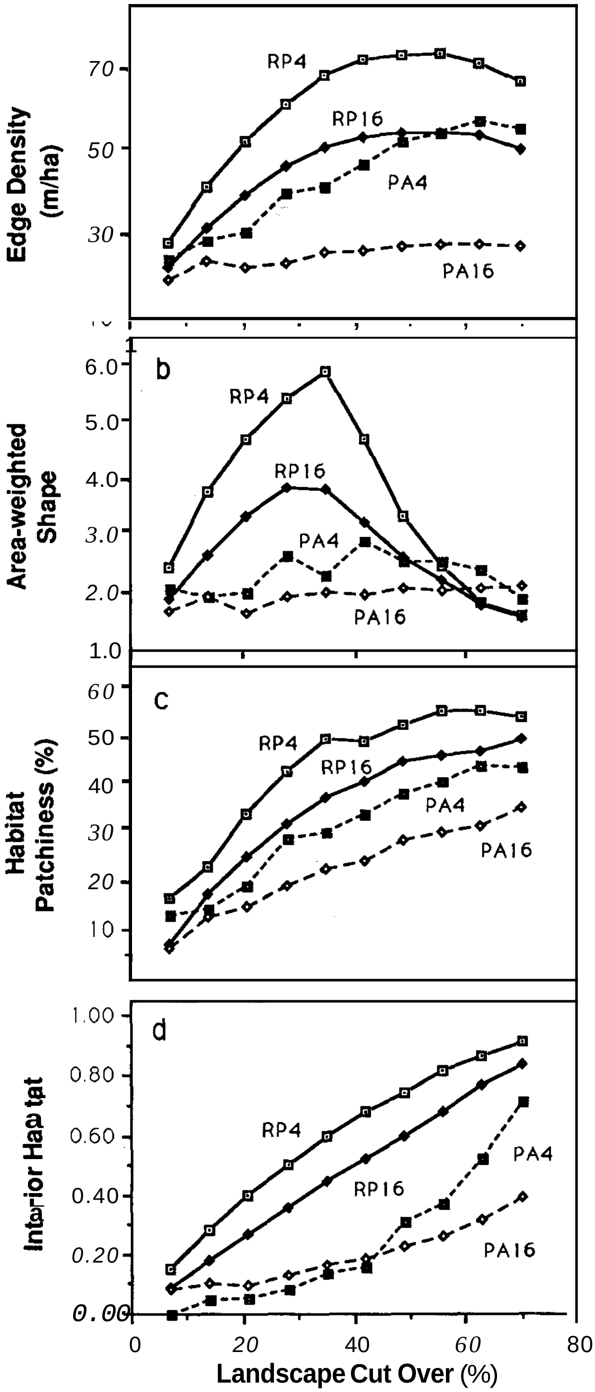

Fig. 4. Comparison of the RP and **PA** models by mean cutting-unit **size (4** and 16 **pixels).**

om patch model always created more fragmentation than the partial aggregation model regardless of cutting-unit size. Moreover, the random patch model with smaller (4-pixel average) cutting-units always fragmented the landscape most, the partial aggregation model with larger (16-pixel) cutting units least.

Edge density for the partial aggregation model with larger units did not change as the percentage of landscape cut increased (Fig. 4a), and there was little difference between the random model with larger units and the partial aggregation model with smaller units.

Irregularly shaped clear-cuts fragmented less of the landscape when cutting units were larger (Fig. 4b), but only before 50% of the landscape was cut. As with the edge density, AWS values for the partial aggregation model with larger cutting-units changed little as percentage of area cut increased.

Habitat patchiness was diminished when larger cutting-units were used (Fig. 4c). However, overall, the landscape became patchier (RPI values increased) regardless of cutting pattern or cutting-unit size.

Interior forest habitat was less fragmented when cutting units were larger (Fig. 4d), but not until 50% of the landscapes was cut. IAF values for the random patch model steadily increased regardless of cutting-unit size; those for the partial aggregation model accelerated sharply for smaller cutting-units when roughly 40% of the landscape was cut.

Effects of additional landscape constraints

Setting aside a reserved area affected interior forest area more than the other aspects of landscape fragmentation (Fig. 5.1). Indeed, interior fragmentation was considerably less (IAF values were lower) for both the random patch and partial aggregation models when a forest reserve was included.

Effects on landscape fragmentation varied when a stream network was included in the random patch and partial aggregation models (Fig. 5.2). For both models, edge density was greater with stream network included until 40-45% of the landscape was cut. This outcome was expected because of the edges added by cutting rules associated with streams. The decline in edge at 40–45% may have been due to stream channels constraining the cut-

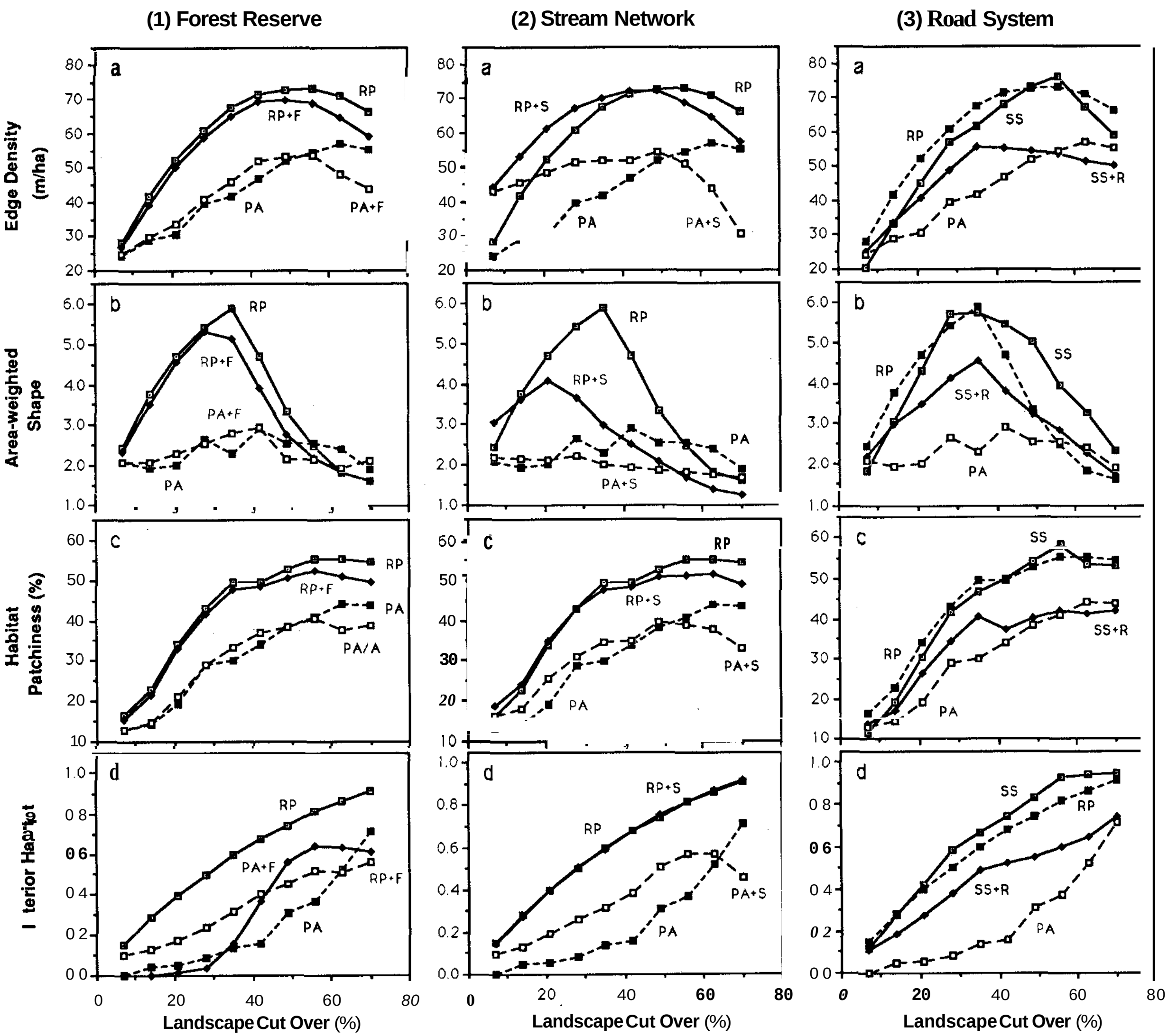

Fig. 5. Effects of adding 1) a forest reserve (F), 2) a stream network (S), and 3) a road system (R), to some of the landscape models. In 3), the RP and PA models are included to show the magnitude of change caused by including roads.

ting process. The presence of streams affected forest patch shape more profoundly for the random patch model; **AWS** values were far lower with streams. Including streams had little effect on habitat patchiness because the dissimilarity values between stream and cut pixels were assumed to be similar to those between forest and clear-cut. Interior forest fragmentation was not affected when screams were mcruded in the ranaom patch model; however, fragmentation was greater with than without streams for the partial aggregation model.

Landscape fragmentation decreased with every index when a road system was introduced to the staggered-setting model (Fig. 5.3). Edge density with roads peaked when 35% of the landscape was cut, then declined slightly; that without roads peaked at 55% cut, then dropped drastically. Trajectories with and without roads paralleled one another, differed only in magnitude, for each of the other three indices.

Discussion

Spatial and temporal patterns

Landscapes can differ significantly in fragmentation when different cutting patterns are used. Fragmentation was low in the progressive cutting and partial aggregation models, but high in the staggered-setting, random, and maximum dispersion models (Fig. 3). The main difference among the landscapes created by the five cutting models lies in the degree of aggregation of cutting units; with more aggregation of cutting units, there is less fragmentation. In order of decreasing aggregation, the models are ranked: progressive, partial aggregation, random, staggered-setting, and maximum dispersion. Generally speaking, the random patch model yielded values of landscape measures which were usually between values for the maximum dispersion model (*i.e.*, regular pattern) and values for the partial aggregation and progressive models (*i.e.*, aggregated pattern). This result agrees with the general theory of spatial pattern development that adding constraints to landscape structure leads to departure from a random pattern (*e.g.*, Ludwig and Reynolds 1988).

The timing of changes in fragmentation varied markedly when different cutting patterns were used (Fig. 3). Changes in the landscapes created by the maximum dispersion, random, and staggered-setting models were more dramatic than the partial aggregation model, which displayed gradual development of fragmentation, and the progressive cutting model, which showed little change. For example, fragmentation of interior forest habitat by the staggered-setting model increased steadily and reached a maximum at about 55% of the landscape cut, while the same type of fragmentation for the partial aggregation model increased slowly before 40% of the area cut, but then accelerated without reaching a maximum at the end of the simulated cutting cycle (Fig. 3d). Habitat patchiness for most models leveled off at about 50% of the area cut (Fig. 3c). This suggests that fragmentation, in terms of contrast between neighboring pixels, may remain somewhat constant after landscape cut-over percentage reaches a certain point, although new patches are still being created. The reason for the constant habitat patchiness is that patchiness index is a measure of fragmentation of the whole landscape and the fragmentation effects of new cutting were offset by re-growth of patches cut earlier. We conclude that the temporal pattern of forest fragmentation varies among cutting patterns.

Some apparent thresholds of landscape change emerged from these simulation results. Differences in fragmentation caused by the different cutting patterns may not be observable until 25–30% (or 50% in some cases) of the landscape was cut (Fig. 3). The reason is that the forest matrix is still intact in the early stages of fragmentation and an increment of cutting in the mid rotation is more likely to break forest patches into separated pieces than is the case early in the rotation. The implications of this result are two-fold. First, comparative field studies of fragmentation in landscapes where these thresholds have not been reached may not be appropriate, because the major differences in fragmentation effects are not yet manifest. This may be evident in the findings by Rosenberg and Raphael (1986); they studied effects of fragmentation on vertebrate species in northwestern California Douglas-fir forests, and found that the majority of wildlife species studied did not show any negative response to fragmentation. Second, it may be possible to change the course of fragmentation, if the thresholds have not been exceeded. Many forests on federal lands in the western US are just reaching the 30–40% cut-over point. Fragmentation may be reduced by implementing the alternative forest management strategies discussed in this paper and in Harris (1984), Franklin and Forman (1987), and Maser *et al.* (1988).

Effects of cutting-unit size

Landscapes are less fragmented when larger cutting units are used. Use of larger cutting-units to lessen fragmentation effects has been suggested (Franklin and Forman 1987), but the ecological consequences at the landscape level have not been analyzed in field studies or detailed modeling exercises. In this study, we used two simulation runs with different cutting-unit sizes to examine effects of cutting-unit size alone on forest fragmentation; a general trend was observed that an increase in the size of cutting units led to a decrease in forest fragmentation (Fig. 4). For example, an increase in cutting-unit size could offset the differences between the random and partial aggregation models; edge density of the random model with larger units was similar to that of the partial aggregation model with smaller units (Fig. 4a). In other words, increasing cutting-unit size can have effects on fragmentation (*e.g.*, edge density) similar to aggregation of cutting units. This result supports the speculation of Franklin and Forman (1987) that larger cutting-units may have ecological benefits. Larger size of cutting units will reduce edge density created by cutting. However, the size of cutting units is also constrained by other environmental considerations, such as delay in forest recovery and increases in the magnitude of peak stream flow events and sediment production associated with forest cutting. Thus, cutting-unit size should reflect a balance among all ecological consequences.

Effects of additional landscape constraints

Landscape constraints affect cutting patterns. The three landscape constraints considered here (forest reserves, streams, roads) generally led to lower degrees of fragmentation (Fig. 5). Forest reserves play a major role in preservation of interior forest habitat important to many species (Whitcomb *et al.* 1981; Harris 1984; Forman and Godron 1986; Temple 1986; Wilcove *et al.* 1986). Changes in habitat patch size have been recognized as a major component of fragmentation by many people (*e.g.*, Harris 1984, Lovejoy *et al.* 1986; Temple and Wilcox 1986). Our results indicate that setting aside a large track of forest land for cutting at later stages of the cutting cycle can strongly affect the extent of interior forest habitat in random and partial aggregation cutting systems.

Stream networks can be used to define boundaries of cutting units. Retaining riparian vegetation preserves both special riparian habitats and a network of corridors (Forman and Godron 1986; Noss 1987). Many studies have shown that corridors are important, integrated parts of sustained landscapes (Harris 1984; Forman and Godron 1986; Noss 1987). Unfortunately, the fragmentation indices used here do not directly measure effects of corridors on fragmentation.

Road systems induce higher aggregation of cutting units, but at the same time break the landscape. The road constraint was included mainly to examine its effects on dispersion of cutting units. Comparison of the staggered-setting model with and without roads to the random patch and partial aggregation models without roads depicted the magnitude of changes caused by inclusion of roads. Landscape fragmentation for the staggered-setting model without roads was close to that for the random model; landscape fragmentation for the staggered-setting model with roads was close to that for the partial aggregation model. In other words, roads forced greater aggregation of cutting units.

Modeled patterns and management practices

How well do the five cutting pattern models examined here represent actual management practice? The representativeness differs among the five models. The random patch and maximum dispersion models are used primarily for comparison; they are far from realistic. The maximum dispersion model was used by Franklin and Forman (1987). On the contrary, the progressive cutting, staggered-setting, and partial aggregation models are intended to be somewhat realistic.

The progressive cutting model is an extreme case of aggregation. Since it is essentially a single-patch cutting model (*i.e.*, one patch at each time step), the progressive cutting model should only imitate forest cutting at a small scale. In addition, the simulations were run for 10 time steps that result in 70% of the landscape cut. For cutting systems typical for federal lands of the Pacific Northwest up to 1990, such time steps would amount to a 5–7 year increment. The progressive cutting system is modeled here to proceed at the same cutting rate as the other four models. However, some private lands at the spatial scale modeled here have been cut progressively within one or two such time steps. Thus, the progressive cutting model used here only represents actual management practice to limited extent.

The staggered-setting model was meant to represent the real cutting system used in the federal lands in the Pacific Northwest. However, the original model was close to the maximum dispersion model, because the staggered-setting model did not use any realistic constraints, except for the patch shape. Road access is a significant constraint on development of dispersed cutting patterns where ground-based and cable logging systems used. Therefore, only those models that reasonably consider the road constraint are realistic. Given these factors and the influence of complex topography on the shape of individual units, the most realistic model of forest pattern development used here is the staggered setting system with road constraints.

The partial aggregation model was intended to serve as an alternative to the staggered-setting cutting system. What distinguishes the two models is the degree of aggregation. The degree of aggregation is higher in the partial aggregation model than in the staggered-setting model. The concentration of cutting units in one of the blocks at a time actually mimic the logging operation that is constrained not only by road access but also by economics of operation. In this case, the partial aggregation model may be as realistic as the staggered-setting model with road constraints.

Fragmentation and its measures

The ecological significance of fragmentation has been elucidated (Harris **1984;** Verner *et al.* **1986;** Wilcove *et al.* **1986).** Fragmentation is the leading factor to species loss, locally or globally (Wilcox and Murphy **1985,** Lovejoy *et al.* **1986;** McLellan *et al.* **1986;** Temple and Wilcox **1986;** Wilcove *et al.* **1986).** The importance of fragmentation demands monitoring its development in managed landscapes, which in turn requires quantitative measures of fragmentation. There are many aspects of forest fragmentation. As defined above, forest fragmentation occurs when: the number of forest "islands" increases; the shapes of those "islands" become more irregular; the area of interior forest habitat shrinks; forest corridors are broken and forest patches isolated. This working definition of fragmentation should prove useful because it facilitates quantification.

Indices have been designed to measure different aspects of fragmentation (Li **1989;** also see Romme **1982;** Fahrig and Merriam **1985;** Forman and Godron **1986;** O'Neill *et al.* **1988).** Li **(1989)** recognizes seven categories of fragmentation measures: **(1)** number of patches (or patch density), **(2)** patch shape (*e.g.*, AWS), **(3)** interior habitat area (*e.g.*, IAF), **(4)** patch isolation or connectivity (mostly distance measures), **(5)** contrast of landscape mosaics (*e.g.*, RPI), **(6)** the physical attributes of landscapes (*e.g.*, edge density, the largest patch size), and **(7)** landscape diversity (*e.g.*, richness, dominance). Ripple *et al.* **(1991)** also identify a set of measures – most of them covered by Li's seven categories – to analyze maps of real landscapes. Although each category of these fragmentation measures is intended to characterize one aspect of fragmentation, most of them are correlated because many indices are computed from a small number of primary measurements (*e.g.*, patch size and shape, edge length). When the effect of a particular aspect of fragmentation is of concern, one should use indices specifically designed for that aspect; otherwise, one should use a combination of indices for different fragmentation aspects. Our results suggest that the measures used in this study are useful, because they have a large range of values and differentiate well these landscapes with different degrees of fragmentation.

Management implications

Our results are consistent with the observation of Franklin and Forman **(1987)** that the widely used staggered-setting clear-cut system is more likely to result in a high degree of forest fragmentation. Spatial arrangement and average size of cutting units regulate and greatly affect the degree of fragmentation by forest management. Aggregation of cutting units and increase of cutting-unit size can lead to lower fragmentation and less change in forest fragmentation over time. At the local scale, setting aside a large forest tract for later cutting can delay and reduce fragmentation effects. Forest managers should consider aggregation of cutting units, larger cutting-units, and forest reserves in design of new landscape management systems.

This paper addressed questions about forest landscape patterns primarily from the standpoint of wildlife habitat. Of course, many other aspects of landscape function must be considered in design of managed landscapes and selection of desired fragmentation patterns. For example, an important factor that led to original use of the dispersed cutting system was the desire to disperse effects of cutting on stream flow, sediment production, and stream and riparian habitats. Rapid progressive cutting over a large drainage basin may create low levels of forest fragmentation, but concentrate cutting impacts on these landscape processes and features. Therefore, any successful landscape design should be based on a balance among resource objectives and impacts of management. As an important element in determining this desired balance, we must assess the sensitivity of particular landscapes to alteration of stream flow, sediment production, and other landscape processes and features. Also, aspects of management other than cutting patterns, such as levels of retention of live trees and downed woody materials in cutting units and the extent and arrangement of riparian management zones, play important roles in the sensitivity of drainage basins to undesired management impacts. However, quantitative understanding of these relationships is still too weak to model with any realism.

Future research should concentrate on two areas. First, fragmentation discussed in this study focused only on forest patterns; the functional aspects (*e.g.*, effects of fragmentation on wildlife species) should be addressed. Effects of fragmentation on wildlife species have been documented by many people (*e.g.*, Whitcomb *et* al. 1981; Harris 1984; Wilcox and Murphy 1985; Lovejoy *et* al. 1986; McLellan *et al*. 1986; Temple and Wilcox 1986; Verner *et* al. 1986; Wilcove *et* al. 1986). However, most previous studies have focused primarily on fragmentation effects in single patches (*e.g.*, Lovejoy *et* al. 1986). Thus, research is needed to establish the relationships between changes in landscape structure (*e.g.*, fragmentation) and wildlife and other biological and physical responses at the landscape scale.

Second, we only considered the forest cutting process to the point of 70% of the total area. Future research should track seral (age) classes through the first full rotation and the next cycle of forest cutting (*i.e.*, beyond 100% of cut over) and, thus, consider the recovery of forest landscapes. Patterns of seral classes in the period of conversion from natural to managed forest may differ from those developed through a cycle of cutting in a landscape where no natural forests of advanced ages are being cut. In the model used here, for example, during the first cutting rotation all residual blocks are older than the rotation age (considering that they were of rotation age at the beginning of cutting and have aged since then), but in the second rotation these blocks are all younger than rotation age. Simulation of alternative patterns through a full cutting cycle and beyond may help managers recognize abrupt periods of change in landscape structure that may affect habitat function, public perception of visual quality of landscapes, and other important qualities. Given that fragmentation will continue in most of forest landscapes (*e.g.*, Simberloff 1988), forest managers must try to alleviate fragmentation effects by using new forest management strategies based on landscape perspectives.

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