

Creating landscape patterns by forest cutting: Ecological consequences and principles

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Abstract

Landscape structural characteristics, such as patch size, edge length, and configuration, are altered markedly when management regimes are imposed on primeval landscapes. The ecological consequences of clearcutting patterns were explored by using a model of the dispersed patch or checkerboard system currently practiced on federal forest lands in the western United States. Thresholds in landscape structure were observed on a gradient of percentages of landscape cutover. Probability of disturbance, e.g., wildfire and windthrow, and biotic components, e.g., species diversity and game populations, are highly sensitive to these structural changes. Altering the spatial configuration and size of clearcuts provides an opportunity to create alternative landscapes that differ significantly in their ecological characteristics. Both ecosystem and heterogeneous landscape perspectives are critical in resource management.

Introduction

How many red spots make a white cow red?

How many clearings make a forest, prairie?

A score? More? A coalescing core?

A threshold reached?

(Landscape Ecology, Forman and Godron 1986)

Geomorphic processes, natural disturbances, and human activities combine to create the richness in spatial pattern visible from the air. In some landscapes, this pattern has been stable for centuries; in others – e.g., primeval forests of the tropics, boreal regions, and the western United States – an onslaught of changes has resulted from forest cutting (Harris 1984; Lovejoy *et al.* 1984). Many specific variables, such as location of roads and patch size, are issues in the cutting operations for both economic and ecological reasons. But emerging ideas in landscape ecology (Risser *et al.* 1984; Forman and

Godron 1986), suggest the pattern created on the landscape by a sequence of cutting operations may be more critical than these specific variables.

Assume that a primeval landscape, say of coniferous or tropical forest, is to be progressively cut. Should we cut small patches and disperse them as much as possible? Should we start at one side and clearcut progressively to the other? Or should we use some other cutting strategy? The answer must reflect the economics of harvesting wood products, the probabilities of major disturbance in the landscape (e.g., windthrow, wildfire, and pests), and desired levels of biotic components (e.g., game, rare species, and threatened habitats).

In this paper we explore the ecological consequences of cutting patterns along a gradient of forest conditions from primeval to completely clearcut landscape. We begin with a simple geometric model to see how spatial patterns (size and density

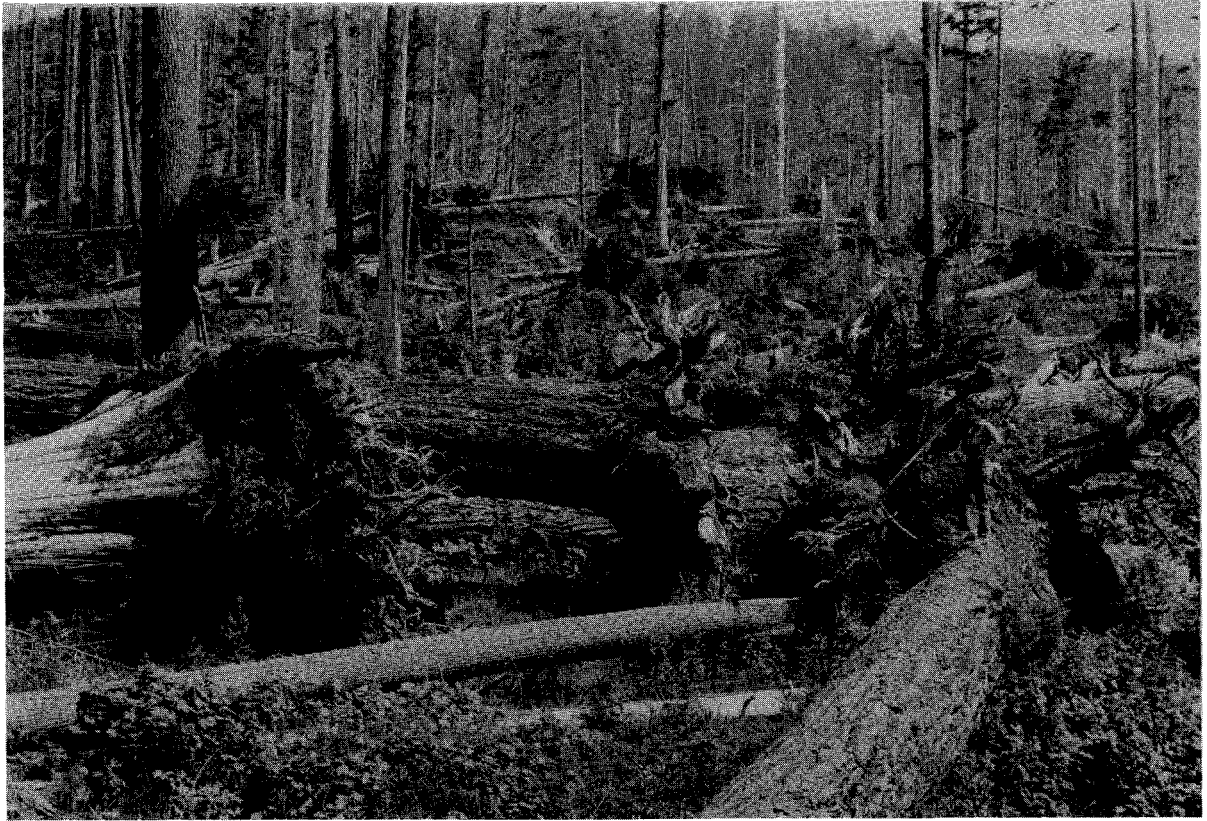


Fig. 1. Nearly a half-billion board feet of timber blew down on 900 ha of forest in the Bull Run drainage of the Mount Hood National Forest, Oregon, during a storm in December 1983; most of the blown down patches were associated with existing clearcuts and roads.

of the patches and length of border) change when small clearcuts are dispersed over the landscape. We examine how susceptibility to disturbance and biotic components, e.g., species diversity, might change along the cutting gradient. Finally, we analyze how these patterns might be controlled by size of cutting unit or different spatial combinations of cutting.

The dispersed patch or checkerboard model is particularly important because variations on this model are widely used in forestry. We thus include some illustrative data from the primeval Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests on federal lands in the Pacific Northwest (USA). For 40 years these landscapes have been cut extensively with a staggered-setting system of clearcutting; 10- to 20-ha patches are interspersed with uncut forest areas of at least equal size (cover) (Smith 1985). Ease of forest regeneration, slash disposal, and access road development were the reasons this approach was originally adopted; the ecological and

economic appropriateness of this system should be reexamined, however, as objectives and techniques change and the fragmentation of the forest landscape continues (Harris 1984). Evidence is accumulating that this system also increases the risk of some types of catastrophic disturbance (Fig. 1).

Ecosystem theory (Odum 1959; Woodwell and Whittaker 1968; Bormann and Likens 1979), island biogeographic theory (MacArthur and Wilson 1967; Simberloff and Wilson 1970), and geographic spatial theory (Chorley and Haggett 1970; Haggett *et al.* 1977; Ripley 1981) are important foundations for our analysis. Landscape ecology, in contrast, focuses on the ecological structure, functioning, and change of a landscape (Neef 1967; Forman and Godron 1981; Brandt and Agger 1984; Naveh and Liebermann 1984; Risser *et al.* 1984; Forman and Godron 1986) from the small homogenous patch to the large, heterogenous area. In this paper we focus specifically on landscape change, and our

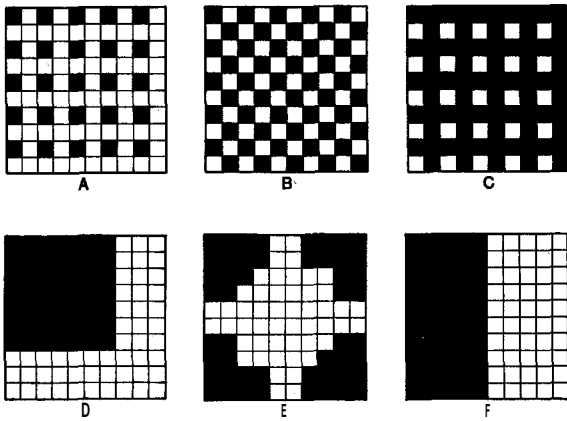


Fig. 2. Patterns of clearcutting developed under various models. (A-C) Progression of clearcutting using the dispersed patch model in which areas are selected for cutting so as to be distributed regularly across the landscape; shown are 25, 50, and 75% cutover points. (D-E) Pattern of cutting at 50% point using single-nucleus, four-nucleus, and progressive-parallel cutting systems.

analysis shows patterns of ecological response to landscape structure, including evidence for thresholds along the continuum of forest cutting intensities. Principles from such analyses can contribute to wise management of our finite remaining forest landscape.

Spatial model

The checkerboard model is designed to disperse the cuttings as evenly as possible across the landscape (Fig. 2). To do that, we made some initial assumptions for our model. The sample area is a 1000-ha² representative of a larger landscape. It is divided into 10-ha cells, one of which is removed by each logging operation. Cells are selected for cutting so that each new cut minimizes the variance in inter-patch distance between it and all other cut patches. The model begins with a completely forested landscape; passes through the 25%, 50% (checkerboard), and 75% cutover points (Fig. 2); and ends with a completely cutover landscape. Only two types of cells are possible – forest and cutover – and once a cell is cut, it remains in that state. The road system is assumed to be complete at the 50% cutover point.

In real landscapes, new forests establish and grow on cutover areas. The pattern in an actual forest is

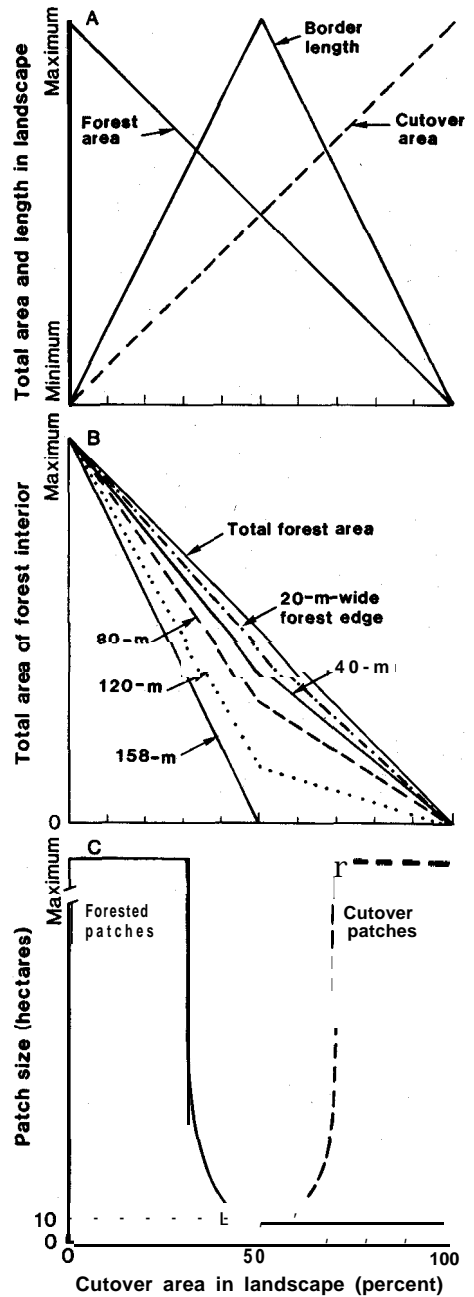


Fig. 3. Changes in landscape characteristics along a landscape cutting gradient based on the regularly distributed dispersed patch cutting or checkerboard model. (A) Total forest area and border length. (B) Total area of forest interior environment for different edge widths. (C) Forest and cutover patch sizes.

also complicated by areas reserved to provide wildlife habitat and recreation and to protect streams. Cutting of all forests within a National Forest landscape will probably never occur.

In the checkerboard model, the total length of

border between forest and cutover areas rises linearly to a peak when the landscape is 50% cut, and drops linearly thereafter (Fig. 3A). This curve approximates the total length of forest edge (Leopold 1933; Dierschke 1974; Thomas 1979; Ranney *et al.* 1981; Morgan and Gates 1982; Forman and Godron 1986) in the landscape if the width of the forest edge is narrow. The forest edge differs significantly in environmental conditions from the forest interior and is a concentrated area for edge species, including many game species.

The total area of forest interior in the landscape, where interior species are concentrated, is related to both the total length of border and the width of forest edge. The forest interior area disappears much more rapidly in cutting landscapes with wide edges (e.g., 120 m) than in those with narrow edges (20 m) (Fig. 3B). With an edge width of over 160 m, no forest interior environment remains after the landscape is 50% cut over; *i.e.*, the 10-ha patches are entirely edge habitat. At boundaries between open areas and forest, the edge width is generally related to the height and structure of the forest. If a measure equivalent to two tree heights is used to estimate the width of recently exposed edges (a conservative rule-of-thumb), the landscape of 80-m-high Douglas-fir trees has no unmodified forest interior conditions left by the time it is 50% cut.

Distinctive patterns for patch size (area) in the landscape also emerge from the model. In the early period of cutting, the average forested-patch size remains equal to the total size of the landscape because the 10-ha cuts are scattered regularly as gaps or clearings within continuous, although increasingly porous, forest. At about the 30% cutover point, the average forest-patch size begins to drop sharply (Fig. 3C) because cuts coalesce into continuous lines of patches dividing the previously continuous forest into sections. Average forested-patch size thus drops rapidly from the 30% threshold to the 50% cutover point; after 50%, the forested-patch size remains constant at 10 ha until the last patch is cut. Variation in forest-patch size — *i.e.*, having different-sized patches in the landscape — exists only in the 30 to 50% cutover interval. Patch size is of central importance in many fields including considerations of biological diversity, nature reserve design, and logging operations

(MacArthur and Wilson 1967; Wilson and Willis 1975; Forman *et al.* 1976; Pickett and Thompson 1978; Gilbert 1980; Cabbage 1983).

The size pattern for cutover patches is the mirror image of the forest pattern; *i.e.*, cutover patches are 10 ha until the checkerboard point when cutover patches begin to coalesce (Fig. 3C). The process continues until a threshold is reached at about 70%; after 70%, the landscape is a continuous cutover area containing remnant 10-ha forested patches. Similarly, different-sized cutover patches are present only in the 50 to 70% cutover interval.

Thresholds for patch density and interpatch distance also appear in the model. At about the 30% cutover point (Fig. 3C), a sharp rise occurs in forest-patch density peaking at the 50% cutover or checkerboard point. Thereafter, patch density decreases linearly to the completely cutover state. The curve for the density of clearcut patches is a mirror image of that for forested patches.

Interpatch distance — the distance that fire, dust, seeds, or mammals must cross to spread to a neighboring forest patch — is zero until the 50% checkerboard point; the corners of all forested patches then touch their neighbors. The first cut thereafter begins the process of isolation or increased interpatch distance. Again, the pattern for the distance between clearings is a mirror image of that for forests.

Several patterns and thresholds of potential major ecological significance appear in the theoretical model when a cutting pattern of regularly distributed squares is assumed. Thresholds are present at 30% (average patch size and patch density), 50% (virtually all characteristics), and 70% (average patch size and patch density).

Development of the patchwork on National Forest lands in the Pacific Northwest shows increasing deviation from the theoretical model as cutting progresses; the results are lower patch densities and border lengths and larger clearcut patch sizes in the real landscape than the model predicts (Table 1). The departures from the dispersed patch cutting pattern in the real landscape result from clearcutting of adjacent forest patches early in the cutting cycle; this is because of road accessibility of these stands and of programs to salvage timber killed by wind or escaped slash fires.

Table 1. Number and mean size of clearcut patches and amount of edge in three National Forest landscapes in relation to percentage of landscape cutover; multiple, adjacent clearcuts are counted as a single patch.

Area and landscape characteristic	Percent landscape cutover					
	10	20	30	40	50	60
H.J. Andrews, Oregon						
Cutover patches (no.)	51	87	93	-	-	-
Cutover patch zone (ha)	11.9	13.8	16.9	-	-	-
Edge length (km)	70.6	128.2	167.5	-	-	-
Bull Run, Oregon*						
Cutover patches (no.)	47	60	-	-	-	-
Cutover patch size (ha)	17.0	22.9	-	-	-	-
Edge length (km)	76.9	118.4	-	-	-	-
South Fork McKenzie, Oregon						
Cutover patches (no.)	26	55	55	53	45	45
Cutover patch size (ha)	25.4	22.4	36.0	49.8	73.3	73.3
Edge length (km)	50.4	124.0	157.2	186.9	204.2	204.2

*Mainstem subbasin.

Disturbance susceptibility

Patterns of patches across the landscape can significantly affect the potential for major forest disturbances, although the nature of the response varies with type of disturbance (Pickett and Thompson 1978; Pickett and White 1985). Here we relate disturbance and ecological response to the geometry of developing clearcut patchwork. Some general patterns of response are apparent, and others are specific to the example from the Pacific Northwest, thus illustrating some of the variability resulting from environment and biota.

The potential for catastrophic windthrow in residual stands of primeval forest relates strongly to the developing landscape patchwork (Fig. 4A) (Ruth and Yoder 1953; Gratkowski 1956; Holtam 1971; DeWalle 1983; Savill 1983). Windthrow susceptibility increases in the model with the amount of edge between cutover area and primeval forest, the isolation of primeval forest in small patches, and increasing wind fetches (Flemming 1968). The initial increase in windthrow potential results from more edge. As cutting progresses and the primeval forest remnants are isolated as IO-ha patches, windthrow potential increases because forest patches are exposed on all sides. Windthrow occurs on corners and along the sides of exposed forest blocks. Wind

fetches progressively lengthen, especially after half of the landscape is cut over. After about 80% of the landscape is cut over, windthrow risk to all remaining patches of primeval forest should be at a maximum, assuming that no significant increase in the wind-firmness of the exposed trees or stands occurs.

The effect of the staggered-setting pattern on fire potential is more complex because it involves both ignition and spread of fire (Fig. 4B). Ignition sources include lightning, human accidents, campfires, cigarettes, and sparks from equipment, and planned ignitions (escaped slash burns). In the primeval landscape, ignition potential is based on natural sources, which can be defined to either include or exclude aboriginal people. In the Douglas-fir region, the potential of natural ignition is relatively low and is primarily from lightning. Sources of wildfire increase rapidly with development of access roads and creation of logging slash from both accidental and planned ignitions; these human-caused ignitions level off once the road system is essentially completed (Fig. 4B).

Once a fire is ignited, the probability of its spreading in residual primeval forest reflects the extent of edge influence in the patch (Fig. 3B). The hypothesized relation assumes that the microclimate of the primeval forest is, because of cooler

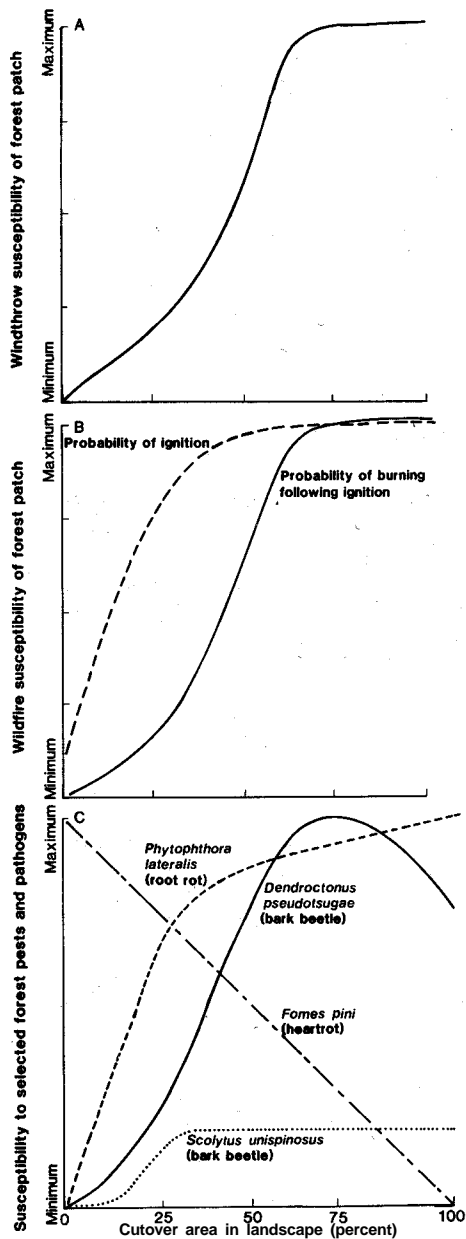


Fig. 4. Susceptibility of forests in the Douglas-fir region to various damaging agents along a landscape cutting gradient as shown by the checkerboard model. (A) Potential for windthrow in residual forest patches. (B) Potential for wildfire ignition and spread. (C) Susceptibility to insect and fungus pests.

and moister conditions, less favorable for fire spread than the cutover area. Drier and warmer conditions induced by adjacent cutover areas would, therefore, increase the probability of a fire spreading to a residual forest patch. The potential

for a fire across the landscape is also affected by the cutting pattern; e.g., wildfire control should be easier in a landscape with greater heterogeneity (including firebreaks, such as roads) or less acreage of primeval forest with its large fuel accumulations.

The responses of pests and pathogens to a developing patchwork are highly species specific, which reflects the interactions of their life histories (including dispersal mechanisms) and environment (including host distribution) (Fig. 4C). In the Douglas-fir landscape of the Pacific Northwest, some bark beetles, such as *Dendroctonus pseudotsugae*, require mature or old-growth trees as host and often reach outbreak populations after broad-scale **blowdown** events. Populations breed in freshly felled trees and attack standing trees. The probability of outbreaks of such a pest should parallel the risk of **blowdown** (Fig. 3C) until late in the cutting cycle when host trees of the necessary size become increasingly scarce (Fig. 4C). Other beetles – such as *Scolytus unispinosus*, which typically uses smaller, competitively stressed trees – might show an increase proportional to the area in regenerated stands of susceptible age (Fig. 4B). Heart rot fungi, such as *Fomes pini*, are most common in old forests and should decrease in importance with decreasing area of primeval forests (Figs. 3A and 4C). But a root rot fungus dispersed by human activities, such as *Phytophthora lateralis*, might expand its role as the road system is developed and the landscape is cut over (Zobel *et al.* 1985) (Fig. 4C). The point is that no general pattern of pest or pathogen response to the developing landscape pattern emerges. Each pest has its own response to changing landscape geometry.

Cutting patterns and intensities affect other types of disturbances, such as landslides. Potential for landslides is affected by both road networks and clearcuts; in the Pacific Northwest, the relative contributions may be nearly equal in the long run (Swanson and Dyrness 1975; Ziemer 1981). Major impacts of checkerboard cutting are that it requires essentially the entire road system to be operational throughout the cutting cycle and maintains a constant proportion of the landscape in clearcuts of an age vulnerable to landslides; the period between loss of the old root network and establishment of a new root network typically has the highest risk of landslides.

Disturbances observed in landscapes of dispersed clearcuts in the Pacific Northwest appear to substantiate at least some of the hypothetical patterns. Windthrow has long been recognized as a chronic problem in such landscapes (Ruth and Yoder 1953; Gratkowski 1956). The possibility that dispersed patchcutting might lead to extensive catastrophic blowdown (Fig. 1) has not been generally understood. On the H.J. Andrews Experimental Forest in western Oregon, about 4% (250 ha) of the residual forest area has suffered serious windthrow (> 10% of the stand volume) during the last 35 years. All this windthrow was adjacent to existing clearcuts or road clearings. The only significant wildfire (4 ha) in this landscape during the last 35 years occurred when a slash fire escaped from a clearcut.

The Bull Run River drainage in the Mount Hood National Forest in western Oregon provides strong evidence of the potential for catastrophic disturbance created by the checkerboard pattern (Fig. 1). We analyzed windthrow patterns on a 37,000-ha area including the Bull Run and adjacent tracts. Major windstorms in this area in December 1973 and 1983 blew down forests of 482 ha and 899 ha, respectively. Nearly 1/2-billion board feet of timber fell in the 1983 blowdown. About 48% of the 1973 and 81% of the 1983 blowdowns were adjacent to existing clearcuts and roads; both are statistically significant relations; About one-fourth of the clearcut-related 1983 blowdown was associated with clearcuts created in previously unlogged landscapes to salvage the 1973 blowdown; such areas might be considered natural rather than management-related blowdown. All significant wildfire damage to forests within Bull Run has resulted from escaped slash burns, further indicating the contribution of management activities to disturbance potential. Similar patterns of catastrophic windthrow and wildfire have occurred in the patchcut landscapes of the southern Gifford Pinchot National Forest in southern Washington; the major wildfire in this region during the last 40 years was the West Point fire, which burned both regenerated forest and residual old-growth patches within a highly fragmented area.

Large, protected reserves within such fragmented landscapes also suffer disturbance (Pickett and Thompson 1978; Forman 1979). In 1980, forty-five

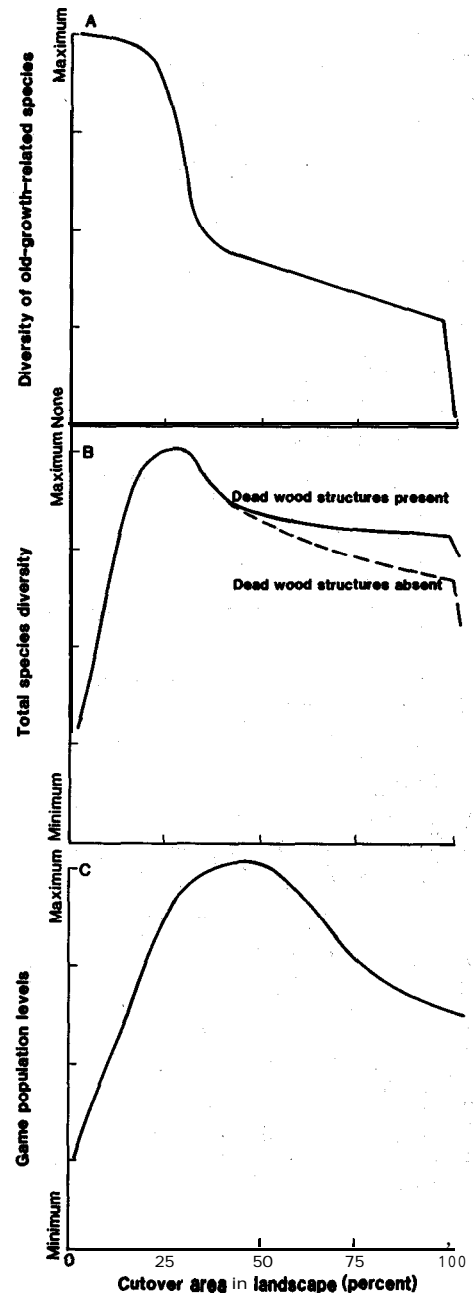


Fig. 5. Changes in biotic characteristics of a Douglas-fir forest landscape along a cutting gradient as shown by the checkerboard model. (A) Diversity of species dependent on a forest interior environment. (B) Total species diversity in the landscape (including forest and cutover area) when standing dead trees and fallen logs are present and when they are not within cutover areas of the landscape. (C) Total game populations in the landscape.

216-ha 'spotted owl management areas' were set aside for protection of *Strix occidentalis* (Xantus de Vesey) in the Gifford Pinchot National Forest.

A windstorm in 1983 caused ' . . . 215 acres [86 ha] of blowdown in six spotted owl management areas, including 75 acres [30 ha] in one core . . . [resulting in] having to make adjustments in five areas, combine two other areas into one, and relocate one management area. Blowdown appeared greatest adjacent to harvest units, particularly in locations where habitat had already been fragmented by timber harvesting' (Ruediger 1985).

Biotic components

The checkerboard system of clearcutting affects many ecological characteristics of the landscape and creates potential for major disturbances. It may, for example, affect diversity of species, occurrence of species requiring interior forest conditions, and populations of game animals. Biological diversity and maintaining interior species dependent on old-growth forest are increasingly important issues for National Forests (e.g., Franklin *et al.* 1981; Harris 1984; Meehan *et al.* 1984; Brown 1985).

The diversity of forest-interior species declines with progressive cutting of the primeval forest (Fig. 5A). An initial, gradual decline is likely as the result of a loss of solitary predators during the early cuttings. We expect that the first large loss of species considered obligate interior-forest dwellers will coincide with the major reduction in the size of primeval forest patches that occurs between 30 and 50% cutover (Fig. 3C). This theory assumes that the 10-ha patch size is under the minimum area required for some interior species (Forman *et al.* 1976; Robbins 1980; Lovejoy *et al.* 1984; Gutierrez and Carey 1985). Species loss may be the result of an unsuitable forest microenvironment, competitive interactions with edge or opening species, or an insufficient total area of suitable foraging habitat. The lichen *Lobaria oregana*, for example, depends on a strictly interior microclimate (Franklin *et al.* 1981), and the spotted owl requires a minimum total old-growth area for foraging (Gutierrez and Carey 1985). The second large loss of species will occur when the last primeval forest patch is cut. The assumption is that some forest interior species, such as certain salamanders and forest herbs, can survive in a 10-ha patch. The gradual decline in species diversi-

ty between the two major episodes of species loss reflects the combined effects of chance extinction of some species from patches and the declining number of forest patches.

Some variation in the shape of the curve for loss of interior species (Fig. 5A) is possible, depending on minimum patch sizes (total or interior) for the species present, the patch size selected for cutting, and the width of critical edge conditions. If each interior species could persist in a 10-ha patch of primeval forest, a continuous curve of interior species loss would be expected as random events and declining patch numbers take their toll. The magnitude of interior species loss would be lessened if some species could colonize regenerating forests on cutover land.

Total species diversity should increase during the initial phases of cutting an old-growth forest landscape (Fig. 5B). Clearcutting results in the addition of many pioneer organisms that find the disturbed, open environment suitable for colonization. Species diversity for vascular plants in the Douglas-fir region is, for example, highest in the early successional stages preceding canopy closure (Franklin and Dyrness 1973). An initial episode of total species loss occurs with fragmentation of the primeval forest, and a second episode occurs when the last primeval forest patch is eliminated, as described above. The presence of dead-wood structures (i.e., standing dead trees and fallen logs) is a key factor in survival of many animal species (e.g., Brown 1985; Harmon *et al.* 1986). Thus, the magnitude of the loss of total species diversity depends on the presence or absence of dead-wood structures in the cutover landscape (Fig. 5B).

Most game species favor the open, early stages of forest succession and, therefore, probably will increase rapidly with the early cuttings (Fig. 5C) (Leopold 1933; Thomas 1979). Many of these species also make heavy use of edges or use two ecosystem types, forest and open. The maximum game population in the forest and cutover patchwork is expected at about the 50% cutover point. Population declines follow as the amount of edge decreases and the high-quality protective cover and winter habitat provided by the primeval forest are lost (see Alaback 1984 and Schoen *et al.* 1984; Brown 1985).

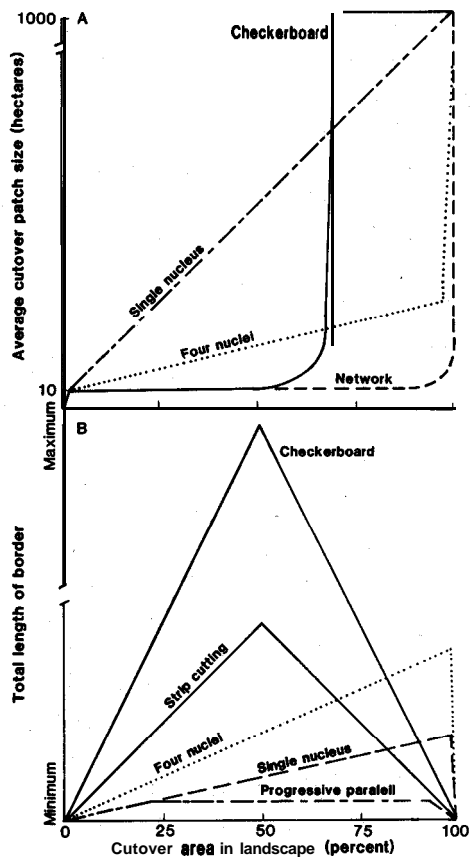


Fig. 6. Contrasting effects of different spatial cutting models for a landscape. The single-nucleus model indicates progressive, contiguous cutting from an initial central point, and the four-nucleus model is similar with four regularly distributed initial points. The network model makes 10-ha cuts regularly distributed in an initially established network of narrow forest corridors. The progressive-parallel model has progressive contiguous cuts of strips parallel to one side of the landscape. (A) Average cutover patch size. (B) Total length of forest border between forest and cutover.

Patch configuration and size

The analyses to this point are based on the checkerboard model — equal-sized cutting units distributed regularly across the landscape. We now generate alternative major cutting models to compare with the checkerboard. We consider five alternative spatial configurations of the basic 10-ha cutting unit: (a) 'single-nucleus model', where an initial central patch is progressively enlarged by contiguous cutting; (b) 'four-nucleus model', where four evenly spaced initial-cut patches are similarly enlarged; (c)

'network model', where cuts are regularly distributed within an initially defined network of narrow, forested line corridors; (d) 'strip-cutting model', where regularly distributed parallel strips, 316 m wide, are cut; and (e) 'progressive parallel model', where 316-m-wide contiguous strips are progressively cut parallel to one edge of the landscape (Fig. 2). We also explore the effects of different clearcut sizes.

The cutting configuration from the checkerboard model produces a constant average cutover-patch size of 10 ha until the landscape is 50% cut; this is followed by a steep rise and leveling off of clearcut patch size near the 70% point, where a cutover landscape contains remnant 10-ha forest patches (Fig. 6A). In contrast, the single-nucleus model produces a steady increase in size of the single cutover patch, and the four-nucleus model produces a steady but smaller increase in size of the four cutover patches until they coalesce near the end (Fig. 6A). Average size of cutover patches in the network model remains at 10 ha until the forested corridors of the network itself are cut. Thus, if minimizing the average size of cutover patches (e.g., to minimize wind fetch or desiccation of soil) is an important planning and management criterion, then clear differences among the models emerge. In addition, individual models differ in response between a slightly cutover and an extensively cutover landscape.

The average patch size during a cutting cycle also differs markedly for the different cutting approaches. In the checkerboard model, the average patch size remains high up to the 30% -cutover point, drops steeply, and levels off at 10 ha at the 50%-cutover point (Fig. 3C). The single-nucleus and the progressive-parallel models produce a steady decrease in forest patch size from beginning to end. The four-nucleus model also follows this curve initially because the four cuts are simply gaps within a single, huge forest patch. At some point beyond the 50%-cutover point, the cut patches in this model coalesce, and the average size of the remaining forest patches drops sharply. If maintaining large forest patches is critical in management to protect interior species or headwaters of stream systems, then clear differences in cutting configuration are evident.

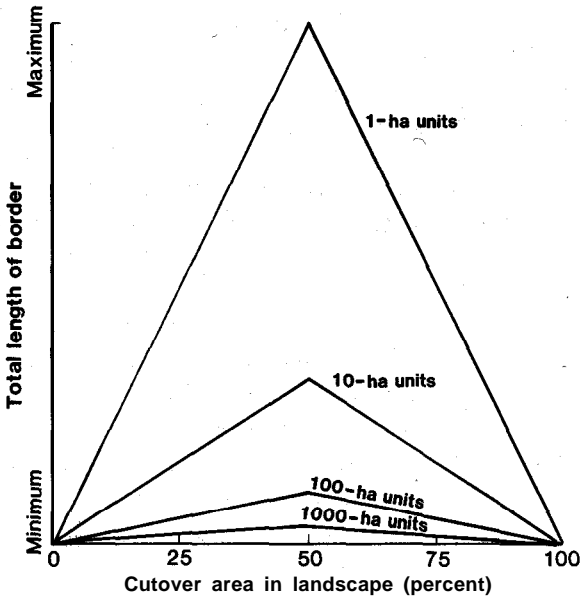


Fig. 7. Total length of border between forest and cutover area with different cutting-unit sizes. Based on the checkerboard model and an unlimited-size grid.

The cutting configurations have major effects on the total length of border between forest and cutover area, which is often critical in managing for game populations or windthrow susceptibility. Strip cutting results in half of the border length of the checkerboard model (Fig. 6B). The single- and four-nucleus models produce less total border length except just before coalescence at the end, and the progressive-parallel model 'produces the minimal average total length of border.

We can also vary the size of the cutting units from 1 to 1000 ha in a checkerboard model and gauge possible effects. The average forest-patch size remains unchanged up to 30%-cutover point because the cuts are gaps in an extensive landscape (Fig. 3C). Forest-patch size drops from the 30 to 50% points, and then levels off as remnant woods equal to the cutting unit size are scattered through the cutover landscape. The total length of border between forest and cutover areas peaks at the 50% point for all cutting unit sizes (Fig. 7). Much less border results, however, from the larger cutting-unit sizes than from using 1- or 10-ha cuts for a given area of cutover. These patterns of patch size and border length resulting from different cutting-unit sizes have major implications for critical ecological processes,

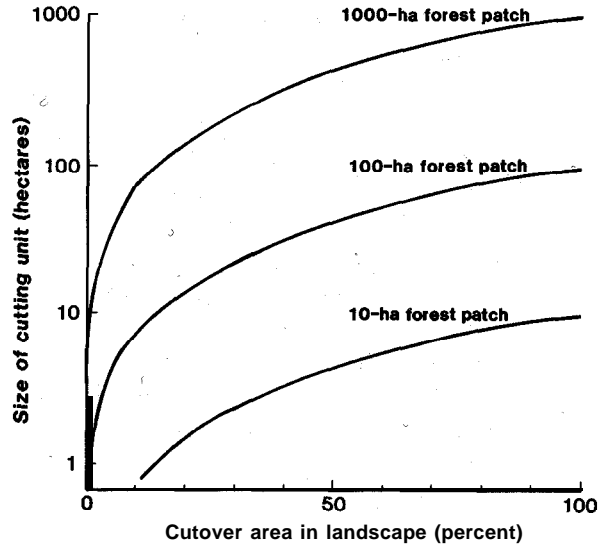


Fig. 8. Disappearance of large patches as a result of using different cutting-unit sizes in the checkerboard model. Cuts are distributed regularly by using an unlimited-sized grid. For example, the last square, 100-ha forest patch (middle curve) disappears when the landscape is only 1% cutover, if 1-ha cutting units are used. Using 10-ha cutting units removes the last large patch (same curve) at 15% cutover, also early in a cutting cycle. Using 100-ha cuts retains a 100-ha forest patch until the last cut in a landscape grid.

including disturbances and biotic components.

Because many interior species need large patches (Forman *et al.* 1976; Robbins 1980; see Alaback 1984 and Schoen *et al.* 1984), knowing when the last large patch of a certain size will disappear along a landscape cutover gradient is critical. The checkerboard model told us that the last square 100-ha forest patch without cut gaps will disappear when the landscape is only 15% cut (Fig. 8). Using a 100-ha cutting unit, the last 1000-ha forest patch will disappear at this same 15%-cutover threshold. The initial steep slope of the curves up to the 15% threshold (Fig. 8) reflects the rapid loss of large, intact forest patches. The single-nucleus, four-nucleus, and progressive-parallel models retain large patches much farther into the cutting cycle than does the checkerboard model.

A critical but unknown number of large patches appear necessary, however, to maintain maximal species diversity, retain genetic diversity, and provide stability in the face of disturbance to a single patch (Forman *et al.* 1976; Pickett and Thompson 1978; Game and Peterken 1984). As noted above,

the last large patch disappears at about the 15%-cutover point. In addition, the last two, three, or several large square patches disappear sequentially just before the 15% cutover point. Thus, in a dispersed-patch cutting pattern, major spatial landscape characteristics with attendant ecological effects change suddenly and rapidly early in the cutting cycle.

Yet another cutting strategy is to use more than one size of cutting unit in a landscape. When 1-ha and 10-ha cuts are mixed such that equal areas result (e.g., forty 1-ha and four 10-ha cuts each equal 40 ha), the total length of border between forest and cutover areas is midway between the border length for just 1-ha cuts and for just 10-ha cuts. Thus, many planning and management options for minimizing border length (to control windthrow) or maximizing border length (to enhance game) are available by using a mixture of clearcut sizes.

Differences in cutting configuration and basic cutting-unit sizes (or mixtures of different sizes) are critical in understanding the ecology of a landscape and in forest planning and management. Changes in these factors drastically alter the spatial patterns of a landscape along a cutover gradient.

Landscape ecology and forest management implications

These models are simplified for identifying underlying patterns and principles. In the real world, many constraints limit the creation of particular land-use patterns. Topography (e.g., drainage pattern and the length, evenness, and steepness of slopes) limits the possibilities. Broad geographic patterns (e.g., differences in frequency of high winds between coastal and inland regions) and localized site conditions (e.g., poorly drained soils) strongly affect the absolute risk of catastrophic events like windthrow and fire (Ruth and Yoder 1953; Forman 1979). The existing 'vegetation mosaic also influences the size and distribution of patches imposed on the landscape, particularly where much of the landscape is composed of forests currently unsuited to cutting. Nevertheless, the theoretical analyses we have presented clearly show

that ecological consequences can differ drastically depending on the pattern imposed on a landscape by land-use activities. Data from at least one forest region support us.

The number, size, and arrangement of the patches in a mosaic created by forest managers strongly influence the degree to which management objectives are fulfilled. Our checkerboard approach maximizes the high-contrast edge between primeval forest and cutover areas and demonstrates thresholds in patch size and interior environment when the original forest matrix is fragmented between 30 and 50% cutover. Disturbances and biota may be altered dramatically with these structural changes, certainly at the scale of forest patch (10 ha) and tree heights (dominant heights of 80 m) typical of the Douglas-fir region. Alternative approaches will result in different ecological responses.

We suggest a two-point guide for managers of natural landscapes (e.g., Federal timberlands in the Douglas-fir region) based on this landscape analysis and on other ecological considerations. First, reduce the emphasis on dispersing small clearcut patches through the forest landscape. The fragmentation that results does not enhance many resource values. Approaches featuring progressive or clustered cuts from scattered nuclei should be considered. In this way, the risks of disturbance associated with edges and the amount of maintained road systems can be reduced. The size of a cluster of cuts would depend on management objectives and landscape characteristics. Networks of corridors and small forest patches should be retained within the clustered cutover areas to provide additional cover and edge for game species, reduce wind fetches and erosion, and enhance interpatch movement of species.

Second, identify and reserve large patches of primeval forest in the landscape for maintenance of interior species and amenity values. It is urgent because many current cutting programs are rapidly reducing the size of available patches. Clearcutting generally must be avoided within the reserved patches because of the substantial vulnerability that results from placing even small cuts within a reserved tract (Ruediger 1985). Finally, other evidence suggests that connections between reserved

tracts, such as forest corridors, may be critical to long-term protection of the landscape (Neef 1967; Forman and Godron 1981; Brandt and Agger 1984; Naveh and Liebermann 1984; Forman and Godron 1986).

We have demonstrated the importance of evaluating the spatial and long-term consequences of human-imposed landscape patterns. As land-management prescriptions are developed, consideration must be given to how ecological conditions in a patch are affected by the position of the patch within the landscape: How do the surroundings affect a patch and vice versa? This contrasts with an exclusive focus on the individual stand or homogeneous ecosystem. Management programs must similarly balance long- and short-term considerations. The checkerboard approach worked reasonably well during the first decades of cutting in the Douglas-fir region but appears increasingly unsatisfactory thereafter. The circumstances originally leading to its adoption have also changed. Basic road systems are now largely present, and tree planting has replaced natural regeneration. The consequences of the patch-cutting pattern will also have a strong and persistent effect on management of future cutting cycles.

Summary

Economic, sociological, and ecological concerns must be considered in any analysis of cutting systems. Significantly higher management costs, for example, are associated with the checkerboard system. A basic road network must be created for the entire landscape early in the cutting cycle and be continuously maintained because silvicultural activities are dispersed rather than concentrated. Unit-area costs for management activities in the Douglas-fir region, such as slash burning, tree planting, and stand thinning, can be reduced by geographical concentration and increased patch size. On the other hand, extensive clearcutting of a drainage basin over a short time could create severe problems, such as floods after rain-on-snow storms (Harr and Berris 1983).

Across major portions of the globe, human ac-

tivities are imposing new patterns on natural or seminatural landscapes. The effects of agricultural clearing and forest cutting in the tropical forests of South America and southeastern Asia are critical examples, as are arid lands being placed under irrigation. Major collaborations are needed among scientists, planners, managers, and the public to utilize landscape perspectives in development of land-use policies and imposition of management regimes.

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References

- Alaback, P.B. 1984. A comparison of old-growth and second-growth forest structure in the western hemlock-Sitka spruce forests of southeast Alaska. *In* Fish and Wildlife Relationships in Old-Growth Forests. pp. 219-226. Edited by W.R. Meehan, T.R. Merrell Jr. and T.A. Hanley. American Institute of Fisheries Research Biologists, Morehead City, North Carolina.
- Bormann, F.H. and Likens, G.E. 1979. Pattern and Process in a Forested Ecosystem. Springer-Verlag, New York.
- Brandt, J. and Agger, P. (eds.) 1984. Proceedings of the First International Seminar on Methodology in Landscape Ecological Research and Planning. Roskilde Universitetsforlag *Georuc.*, Roskilde, Denmark.
- Brown, E.R. (ed.) 1985. Management of Wildlife and Fish Habitats in the Forests of Western Oregon and Washington. Publ. R6-F&WL-192-1985. U.S. Department of Agriculture,

- Forest Service, Pacific Northwest Region, Portland, Oregon.
- Chorley, G.A. and Haggett, R.J. 1970. *Social and Economic Models in Geography*. Methuen, London.
- Cubbage, F.W. 1983. Tract size and logging costs in southern pine. *J. For.* 81: 430-433.
- DeWalle, D.R. 1983. Wind damage around clearcuts in the ridge and valley province of Pennsylvania. *J. For.* 81: 158-159.
- Dierschke, H. 1974. Die naturräumliche Gliederung der Veredener Geest. *Forsch. Deutsch. Landeskunde* 177: 1-113.
- Flemming, G. 1968. Die windgeschwindigkeit auf waldumgebene freiflächen. *Arch. Forstwes.* 17: 5-16.
- Forman, R.T.T. (ed.) 1979. *Pine Barrens: Ecosystem and Landscape*. Academic Press, New York.
- Forman, R.T.T., Galli, A.E. and Leck, C.F. 1976. Forest size and avian diversity in New Jersey woodlots with some land use implications. *Oecologia* 26: 1-8.
- Forman, R.T.T. and Godron, M. 1981. Patches and structural components for a landscape ecology. *BioScience* 31: 733-740.
- Forman, R.T.T. and Godron, M. 1986. *Landscape Ecology*. John Wiley & Sons, New York.
- Franklin, J.F. and Dyrness, C.T. 1973. *Natural Vegetation of Oregon and Washington*. Gen. Tech. Rep. PNW-8. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.
- Franklin, J.F., Cromack, K., Jr., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F. and Juday, G. 1981. *Ecological Characteristics of Old-Growth Douglas-Fir Forests*. Gen. Tech. Rep. PNW-118. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.
- Game, M. and Peterken, G.F. 1984. Nature reserve selection strategies in the woodlands of central Lincolnshire, England. *Biol. Conserv.* 29: 157-181.
- Gilbert, L.E. 1980. The equilibrium theory of island biogeography: fact or fiction? *J. Biogeogr.* 7: 209-235.
- Gratkowski, H.J. 1956. Windthrow around staggered settings in old-growth Douglas-fir. *For. Sci.* 2: 60-74.
- Gutierrez, R.J. and Carey, A.B. (eds.) 1985. *Ecology and Management of the Spotted Owl in the Pacific Northwest*. Gen. Tech. Rep. PNW-185. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.
- Haggett, P., Cliff, A.D. and Frey, A. 1977. *Locational Analysis in Human Geography*. Wiley, New York.
- Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack Jr., K. and Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. In *Advances in Ecological Research*, Vol. 15, pp. 133-302. Academic Press, New York.
- Harr, R.D. and Berris, S.N. 1983. Snow accumulation and subsequent melt during rainfall in forested and clearcut plots in western Oregon. In *Proceedings of Western Snow Conference, 51st Annual Meeting, Vancouver, Washington, 19-21 April 1983*, pp. 38-45. Colorado State University, Ft. Collins, Colorado.
- Harris, L.D. 1984. *The Fragmented Forest*. University of Chicago Press, Chicago.
- Holtam, B.W. (ed.) 1971. *Windblow of Scottish Forests in January 1968*. Bull. 45. [Brit.] Forestry Commission.
- Leopold, A. 1933. *Game Management*. Scribners, New York.
- Lovejoy, T.E., Rankin, J.M., Bierregaard, R.D., Jr., Brown, K.S., Jr., Emmons, L.H. and Van der Voort, M.E. 1984. Ecosystem decay of Amazon forest remnants. *In* *Extinctions*. pp. 295-325. Edited by M.H. Nitecki. University of Chicago Press, Chicago.
- MacArthur, R.H. and Wilson, E.O. 1967. *The Theory of Island Biogeography*. Princeton University Press, Princeton, New Jersey.
- Meehan, W. R., Merrell, T.R., Jr. and Hartley, T.A. (eds.) 1984. *Fish and Wildlife Relationships in Old-Growth Forests*. American Institute of Fisheries Research Biologists, Morehead City, North Carolina.
- Morgan, K.A. and Gates, J.E. 1982. Bird population patterns in forest edge and strip vegetation at Remington Farms, Maryland. *J. Wildl. Manage.* 46: 933-944.
- Naveh, Z. and Liebermann, A.S. 1984. *Landscape Ecology, Theory and Application*. Springer-Verlag, New York.
- Neef, E. 1967. *Die Theoretischen Grundlagen der Landschaftslehre*. Geographisch-Kartographische Anstalt Gotha. Hermann Haack, Leipzig.
- Odum, E.P. 1959. *Fundamentals of Ecology*. Saunders, Philadelphia, Pennsylvania.
- Pickett, S.T.A. and Thompson, J.N. 1978. Patch dynamics and the design of nature reserves. *Biol. Conserv.* 13: 27-37.
- Pickett, S.T.A. and White, P.S. (eds.) 1985. *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, New York.
- Ranney, J.W., Bruner, M.C. and Levenson, J.B. 1981. The importance of edge in the structure and dynamics of forest islands. *In* *Forest Island Dynamics in Man-Dominated Landscapes*. pp. 67-96. Edited by R.L. Burgess and D.M. Sharpe. Springer-Verlag, New York.
- Ripley, B.D. 1981. *Spatial Statistics*. Wiley, New York.
- Risser, P.G., Karr, J.R. and Forman, R.T.T. 1984. *Landscape Ecology: Directions and Approaches*. Special Publ. 2. Illinois Natural History Survey, Urbana, Illinois.
- Robbins, C.S. 1980. Effect of forest fragmentation on bird populations. *In* *Management of North Central and Northeastern Forests for Nongame Birds*. pp. 198-212. Edited by R.M. DeGraaf and K.E. Evans. Gen. Tech. Rep. NC-51. U.S. Department of Agriculture, Forest Service, North Central Experiment Station, St. Paul, Minnesota.
- Ruediger, W.C. 1985. Implementing a spotted owl management plan: the Gifford Pinchot National Forest experience. *In* *Ecology and Management of the Spotted Owl in the Pacific Northwest*. pp. 10-13. Edited by R.J. Gutierrez and A.B. Carey. Gen. Tech. Rep. PNW-185. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.
- Ruth, R.H. and Yoder, R.A. 1953. *Reducing Wind Damage in the Forests of the Oregon Coast Range*. Res. Pap. 7. U.S. Department of Agriculture, Forest Service, Pacific Northwest

- Forest and Range Experiment Station, Portland, Oregon.
- Savill, P.S. 1983. Silviculture in windy climates. For. Abstr. 44: **473-488**.
- Schoen, J.W., Kirchhof, M.D. and Wallmo, O.C. 1984. Sitka black-tailed deer/old-growth forest relationships in southeast Alaska: implications for management. **In** Fish and Wildlife Relationships in Old-Growth Forests. pp. 315-319. Edited by W.R. Meehan, T.R. Merrell, Jr. and T.A. Hanley. American Institute of Fisheries Research Biologists, Morehead City, North Carolina.
- Simberloff, D.S. and Wilson, E.O. 1970. Experimental zoogeography of islands: a two-year record of colonization. Ecology 51: 934-937.
- Smith, D.E. 1985. Principles of Silviculture. 8th ed. John Wiley & Sons, New York.
- Swanson, F.J. and Dyrness, C.T. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range. Geology 3: 393-396.
- Thomas, J.W. (ed.) 1979. Wildlife Habitats in Managed Forests: The Blue Mountains of Oregon and Washington. Handbook 553. U.S. Department of Agriculture, Washington, D.C.
- Wilson, E.O. and Willis, E.O. 1975. Applied biogeography. In Ecology and Evolution of Communities. pp. 522-534. Edited by M.L. Cody and J.M. Diamond. Belknap Press, Cambridge, Massachusetts.
- Woodwell, G.M. and Whittaker, R.H. 1968. Primary production in terrestrial ecosystems. Amer. Zool. 8: 19-30.
- Ziemer, R.R. 1981. Roots and the stability of forested slopes. **In** Proceedings, Erosion and Sediment Transport in Pacific Rim Steeplands Symposium, Christchurch, New Zealand, 1981 January, Publ. 132, pp. 343. International Association for the Advancement of Science, Institute of Hydrology, Washington, D.C.
- Zobel, D.B., Roth, L.F. and Hawk, G.M. 1985. Ecology, Pathology, and Management of Port-Orford-Cedar (*Chamaecyparis lawsoniana*). Gen. Tech. Rep. PWN-184. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.