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The effects of timber harvesting on the structure and composition of adjacent old-growth coast redwood forest, California, USA

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Abstract

Data collected across timber harvest boundaries on nine sites within the Redwood National and State Park management area in California, USA, were used to estimate the effective size of old-growth coast redwood preserves. Fourteen variables related to stand structure and composition, wildlife habitat, and physical environment were significantly correlated to distance from the timber harvest boundary using multiple regression analysis. A maximum depth of edge influence of 200 m was determined for variables exhibiting a significant correlation to the distance from the harvest edge. A spatial analysis using ArcView indicated that 53% of the old growth preserved within the study area was influenced by edge conditions, leaving 47% as effective old-growth.

Introduction

Timber harvesting can affect adjacent forest stands by altering solar radiation and microclimate along the edge of the disturbance and by exposing trees to the dangers of windthrow and crown die-back (Matlack 1993; Young and Mitchell 1994; Murcia 1995; Peterken 1996). The character of the remaining forest is altered along its edge, reducing the effective size of a preserve (Schonewald-Cox and Bayless 1986; Chen et al. 1992; Brothers 1993; Burke et al. 1998; Russell et al. 2000). An understanding of the extent to which edge effects reduce the effective size of old-growth forest stands is essential to the proper management of forests, the design of preserves, and the implementation of buffer zones.

The removal of canopy cover through timber harvesting has been so prevalent in the coast redwood forest type that very little of the original forest remains (Russell 2000). What remains is in small isolated preserves. In most cases these preserves are surrounded by land managed for timber. The boundary between the preserved forest and managed areas is not static. Biotic and abiotic factors within managed areas can alter characteristics of adjacent stands. The interface between the two communities (managed and preserved) is referred to as the edge and is distinct in terms of composition and structure.

A discussion of effective old-growth size by Harris (1984) focused on a single factor. Heightened wind velocity was measured for a distance of approximately two to three tree heights into old-growth stands. Harris suggests that the distance of edge influence could be based on a 'three tree height' rule of thumb. Further, he suggests that since most old-growth islands have irregular shapes the 'three tree height' rule is inadequate for preserves with irregular shapes. Harris also discussed the importance of the matrix in which an old-growth island exists. The effective size of old-growth preserves can be increased if the preserve is surrounded by late seral second-growth stands.

The importance of matrix is also discussed in Janzen's (1983) investigation of a forest preserve in Costa Rica. He suggests that the integrity of residual pristine forest may be better preserved if the residual forest is surrounded by managed lands, such as monoculture agricultural systems, rather than second-growth forest. He argues that exotic species are more likely to invade from species-rich regenerating forest, while the unsuitability of most agricultural plants to forest interior conditions makes their invasion unlikely. His analysis is limited, however, by his single variable approach. Variables other than species composition may also be impacted by adjacent agriculture. The single-variable approach is effective only when managing specifically for that variable. It is not necessarily the most useful approach in determining the effective size of preserves.

A multiple-variable approach was used to determine the influence of edge on the effective size of preserves by Franklin and Foreman (1987). They suggest that the total edge within a landscape unit should be minimized in order to protect 'interior species and amenity values' of residual old-growth patches. These conclusions were reached by applying a simple geometric model of timber harvest configurations to a hypothetical landscape. The effect of harvest patterns was analyzed in terms of potentials for disturbance, such as blowdown and landslide, and biotic factors such as species diversity that were correlated to distance from the edge.

A model for determining the effective size of a preserve was developed by Laurence and Yensen (1991) by refining portions of an earlier model developed by Patton (1975). Laurence and Yensen's model used two factors to predict core area. A shape index term was combined with edge function (the depth of the edge influence of an unspecified variable or variables) to determine the affected area. The affected area was then subtracted from the total area to determine the core area. Applying this model to tropical forest fragments in Australia, Lawrence (1991) plotted the relationship of several variables with distance from the edge. The variables that exhibited the greatest depth of edge influence were selected for use in the model. This model is useful in comparing the relative edge effect on preserves with different shapes and can easily be adapted to a multivariable approach.

Similar results were determined using a GIS (geographic information system) model to automate the same functions carried out by the core area model (Ripple et al. 1991). The precise area of influence was readily defined and calculated. However, the developers of this approach did not address the question of what variables should be used to measure depth of edge influence. For the purpose of the paper, a conservative two-tree height rule was used, and the depth of influence was set at 100 m.

The goal of this study was to determine the effects of timber harvesting on the structure and composition of adjacent old-growth coast redwood (*Sequoia sempervirens*) forest. A wide variety of variables related to species diversity and occurrence, development of understory and overstory species, wind damage to exposed trees, effects on wildlife habitat, and abiotic factors were measured to determine the depth of edge influence. The depth of influence determined from field data was then used to estimate the effective size of old-growth redwood preserves using GIS analysis.

Methods

Data were collected along 360 m transects randomly located across the boundaries between regenerating stands and adjacent old-growth on nine sites in the redwood forest region of Northern California, USA. A stepwise regression analysis of this data was used to identify the depth of influence of the regenerating stands on adjacent old-growth. Effective size of preserves was predicted on the basis of the depth of influence of measured variables.

Study area and site characteristics

Nine sites were sampled within the Redwood National and State Parks management area in Northern California (Table 1). Sites were located where a distinct boundary separated harvested and old-growth stands. An effort was made to choose sites where the old-growth components were as similar as possible in terms of structure and composition. Three sites were selected in each of three post-harvest age groups (20, 30, and 50 years since harvest) in order to illustrate effects of time on the composition and structure of vegetation.

Sampling strategy

Ten transects were randomly located on each site, perpendicular to the boundary of the timber harvest. Transects were sampled 200 m into old-growth stands, and 120 m into regenerating stands. Circular 20-meter diameter sample plots were set at 40-m intervals along transects, with five plots on each transect located within the uncut forest and four plots located in the regenerating stands (Figure 1). Within these plots occurrence and percent cover of each shrub species, and occurrence, number, and dbh (diameter at breast height) of each of the following size classes of trees

Table 1. Characteristics of study sites.

Name of study site	Year of harvest	Elevation (m)	Average Slope (%)	Aspect	Harvest Area (ha)	Orientation of cut
Emerald Creek	1974	120–180	37.6	SE	17.6	NW
Dedication Grove	1972	120–180	23.7	SE	65.8	NW
Tall Trees	1973	150–215	28.6	SW	17.6	E
Lady Bird Johnson	1964	180–240	21.7	NW	70.1	NW
Lady Bird Johnson	1965	180–240	34.2	NW	8.78	N
Walker Road	1966	75–180	36.1	E	34.4	N
Liefler Loop	1948	75–180	33.5	E	17.4	N
Wilson Creek	1948	180–240	32.9	NE	44.5	N
Lady Bird Johnson	1945	240–300	38.3	S	101.0	S

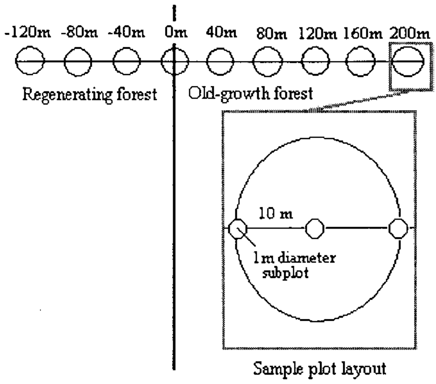

Figure 1. Diagram of plot and transect layout used to sample old-growth and regenerating stands on nine sites in Redwood National Park.

was recorded: mature trees (dbh < 50 cm), pole size trees (dbh = 10–50 cm), sapling size trees (height > 1 m, dbh < 10 cm). Trees exhibiting bark removal and claw marks were recorded as bear damaged. Overstory and sub-canopy canopy cover were measured with a spherical densiometer. Total height was estimated for the canopy, sub-canopy, and shrub layers. Trees displaying crown dieback were recorded using the line intercept method.

Within each 20-meter plot, three circular nested subplots (2 m diameter) were used to sample herbaceous species and seedling sized trees (height < 1 m). Subplots were located with one at plot center and one on each side of the larger plot where the transect intersected the plot boundary. Within each subplot the occurrence and percent cover of each herbaceous species was recorded along with the species and number of all seedling sized trees.

the data collected on sample plots was used to quantify sample variables including species richness (number of species per hectare) and Shannon diversity (Pielou 1975), the height of canopy layers, percent cover and cover class of canopy layers, density of size classes, dominance of major tree species (calculated from dbh), frequency of observed crown dieback, and frequency of all species occurring on sample plots.

Variables were selected for further analysis based on their correlation to distance from the timber harvest boundary, using a standardized z-test. Variables with a p-value of 0.05 or less were used, except in cases of covariance. Where a correlation coefficient greater that 0.5 was found for two variables, the variable with the greatest p-value was removed.

Determining the depth of influence

Variables that were highly correlated to distance from the boundary were plotted on a linear scale. A third order polynomial curve was applied to the distribution of each variable. This curve was then analyzed using a procedure adapted from Oosting (1948). A ratio of the x and y axes was used to determine the angle of a tangent line. The point where this tangent line intersected the curve was the confidence point for depth of influence. For the greatest accuracy, Oosting suggests a ratio of 5% rise to 10% run. The tangent point then indicates where a 5% increase in the value of the sample variable occurs over 10% of the distance of the transect. Less than a 5% slope is therefore assumed to be zero. This results in a conservative estimate for the depth of influence, thereby increasing the confidence in that estimate.

Using ArcInfo 7.2 a 200-m negative buffer was placed around the inner edge of all old-growth red-

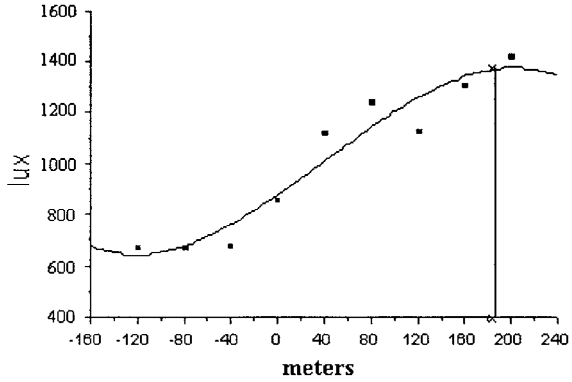

Figure 2. Solar radiation and distance from the edge measured across timber harvest boundaries in Redwood National and State Parks ($R^2 = 0.242$, $p < 0.0001$). Depth of influenced estimated using a procedure adapted from Oosting (1948). The scale on the x-axis refers to distance from the edge as positive in the direction of the old-growth forest and negative in the direction of the regenerating areas. The zero mark represents the timber harvest boundary.

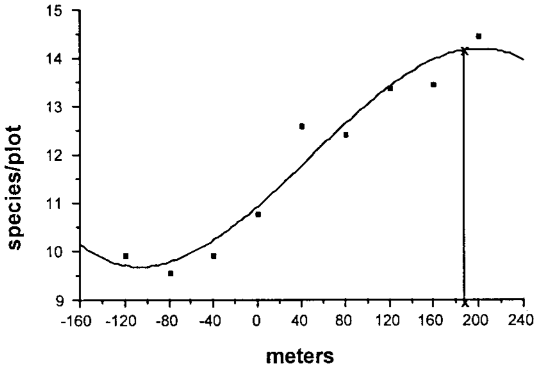

Figure 3. Species richness and distance from the edge measured across timber harvest boundaries in Redwood National and State Parks ($R^2 = 0.197$, $p < 0.0001$). Depth of influenced estimated using a procedure adapted from Oosting (1948). The scale on the x-axis refers to distance from the edge as positive in the direction of the old-growth forest and negative in the direction of the regenerating areas. The zero mark represents the timber harvest boundary.

wood polygons in Redwood National and State Parks. Since there are small second growth stands within the old-growth groves an additional 200-m positive buffer was placed on these second growth polygons. The buffered coverage was converted into a shape file and brought into ArcView 3.2 for calculation of total buffer area and map production.

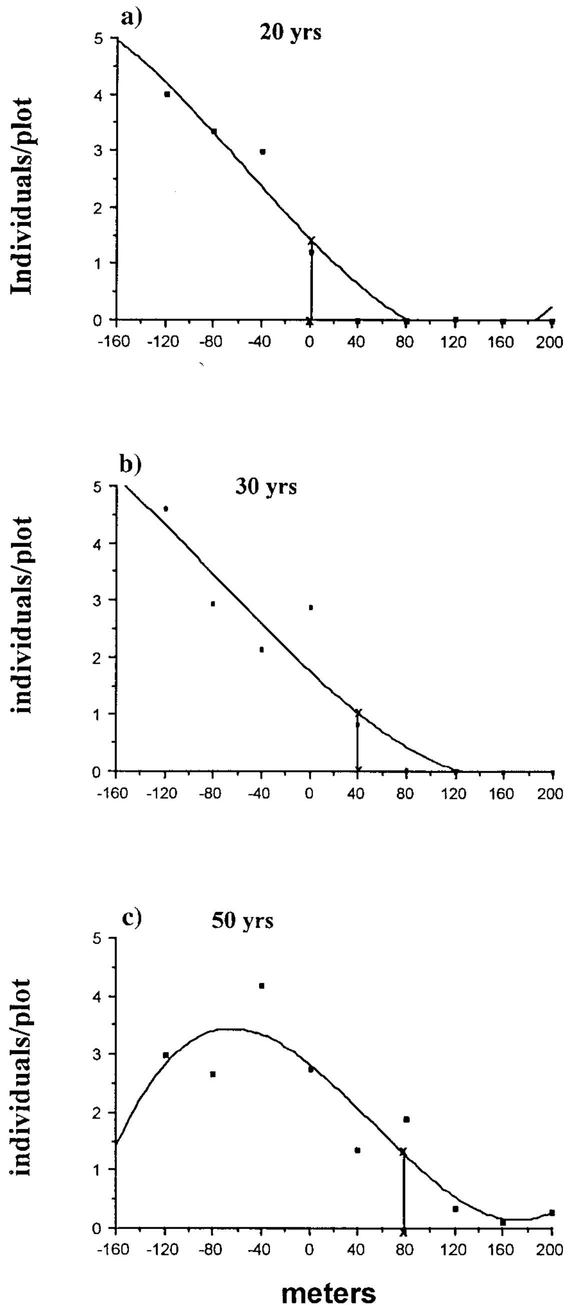

Figure 4. Density of alder poles for three post-harvest age groups measured across timber harvest boundaries in Redwood National and State Parks. a) $R^2 = 0.127$, $p < 0.0001$; b) $R^2 = 0.270$, $p < 0.0001$; c) $R^2 = 0.210$, $p < 0.0001$. Depth of influenced estimated using a procedure adapted from Oosting (1948). The scale on the x-axis refers to distance from the edge as positive in the direction of the old-growth forest and negative in the direction of the regenerating areas. The zero mark represents the timber harvest boundary.

Table 2. Depth of influence of variables correlated to distance from the timber harvest boundary.

Variable		Correlation coefficient	P-value	Depth of influence (m)
Sub-canopy height		0.341	<0.0001	200
	20 yr	0.559	<0.0001	200
	30 yr	0.497	<0.0001	200
	50 yr	−0.077	0.4014	n/a
Solar radiation		0.339	<0.0001	180
	20 yr	0.415	<0.0001	140
	30 yr	0.376	<0.0001	200
	50 yr	0.776	<0.0001	n/a
Sub-canopy cover		−0.314	<0.0001	160
	20 yr	−0.245	0.0068	200
	30 yr	−0.100	0.2767	120
	50 yr	−0.649	<0.0001	120
Pole density		−0.229	<0.0001	80
	20 yr	−0.422	<0.0001	120
	30 yr	−0.413	<0.0001	40
	50 yr	0.117	0.2053	0
Crown dieback		−0.217	<0.0001	120
	20 yr	0.249	0.0059	80
	30 yr	0.219	0.0159	120
	50 yr	0.242	0.0075	120
Richness of shrubs		0.213	<0.0001	40
	20 yr	0.133	0.1468	40
	30 yr	0.405	<0.0001	40
	50 yr	0.129	0.1590	n/a
Herbaceous cover		0.208	<0.0001	120
	20 yr	−0.319	0.0004	120
	30 yr	−0.353	<0.0001	120
	50 yr	−0.128	0.1646	160
Species richness		0.169	0.0013	180
	20 yr	0.106	0.249	160
	30 yr	0.193	<0.0001	160
	50 yr	0.400	<0.0001	200
Bear damage		−0.141	0.0075	40
	20 yr	0.153	0.0943	40
	30 yr	−0.199	0.0294	n/a
	50 yr	−0.397	<0.0001	n/a
Seedling density		0.139	0.0080	120
	20 yr	0.176	0.0549	120
	30 yr	0.157	0.0870	160
	50 yr	0.176	0.0545	n/a
Density of poles (Red Alder)		−0.134	0.0108	80
	20 yr	−0.235	0.0096	0
	30 yr	−0.188	0.0401	40
	50 yr	0.024	0.7918	80
Dominance (Douglas-fir)		−0.133	0.0116	40
	20 yr	−0.171	0.0622	40
	30 yr	−0.256	0.0046	40
	50 yr	0.063	0.4944	n/a
Richness of trees		−0.110	0.0377	40
	20 yr	−0.364	<0.0001	0
	30 yr	0.019	0.8364	40
	50 yr	0.025	0.7855	120

Table 3. Results of spatial analysis of edge effects on old-growth patches in Redwood National and State Parks.

Study site	Total area	Affected area	Fraction of total	Effective old-growth	Fraction of total
Total area (ha)	16701	8848	0.53	7853	0.47
Dedication Grove	59	59	1.00	0	0.00
Mill Creek	975	459	0.47	516	0.53
Jedidiah Smith	3410	798	0.23	2612	0.77
Redwood Creek	3724	1871	0.50	1853	0.50

Results

A total of 13 variables, out of 57 measured, had significant correlations with distance from the timber harvest boundary (Table 2). Variables that were not correlated to distance from the edge included the density and dominance of all species not listed as correlated, and those with a strong covariance with included variables. For example, Species richness and Shannon diversity were both highly correlated to distance from the edge. Species richness was used in the subsequent analysis because the correlation was marginally higher. Correlation coefficients and p-values were determined separately for each of the post-harvest age groups, in order to compare the effects of time on these variables. The sign of correlation coefficients describes the slope of the line from the timber harvest boundary into the uncut forest. A positive slope, therefore, indicates a negative impact on that variable in proximity to the edge.

The depth of influence was also calculated for each variable. A wide range of influence was exhibited by the sample variables (0 to 200 m). Solar radiation, for example, exhibited a positive correlation with distance from the edge out to approximately 180 m within the old-growth portion of the stands (Figure 2). Solar radiation levels were lower near the edge in the old-growth stands due to a high density of sapling and pole-sized trees recruited shortly after harvesting of the adjacent stands.

Species richness and solar radiation exhibited nearly identical curves (Figure 3). The depth of influence in this case was also approximated at 180 m. It is important to note that though the slope of the line is positive, the influence of the edge is negative. The similarity of these two variables was not coincidental. The decrease in species richness in proximity to the edge is likely the result of decreased solar radiation. This argument is supported by a significant correlation between the two variables ($p < 0.001$).

Time effects

The depth of influence of the timber harvest boundary was also related, in many cases, to time since harvest. Notable variation was apparent in the slope and depth of influence of many variables in relation to time since harvest. For example, the relationship between solar radiation and distance from the timber harvest boundary varied considerably between the three post-harvest age groups. The distribution for the 20-year-old age group was characterized by a relatively steep slope and a depth of influence of approximately 140 m. The slope for the 30-year-old age group was slightly less steep, but the depth of influence was in excess of 200 m. The 50-year-old age group was characterized by a zero slope, showing no depth of influence.

A similar pattern was apparent for species richness. However, because variation in species richness was related to variation in solar radiation, the peak magnitude was delayed. The greatest slope was found for the 30-year-old age group, and by 50 years the slope began to erode. In addition, in a similar fashion to solar radiation, the depth of influence increased with time, from 160 to greater than 200 m. The clearest example of a time effect was observed for the pole density of alder (Figure 4). As a species that usually occupies open areas or riparian sites, alder is quite rare within undisturbed old-growth redwood forests. Consequently, virtually no alder was found within the old-growth areas sampled for the 20-year-age group. The 30 and 50-year age groups, however, exhibited an elevated density of this species to 40 m and 80 m respectively. A time effect is also apparent on the harvested side of the timber harvest boundary. While density of alder is elevated to -160 m within the regenerating stands for the 20- and 30-year-old age

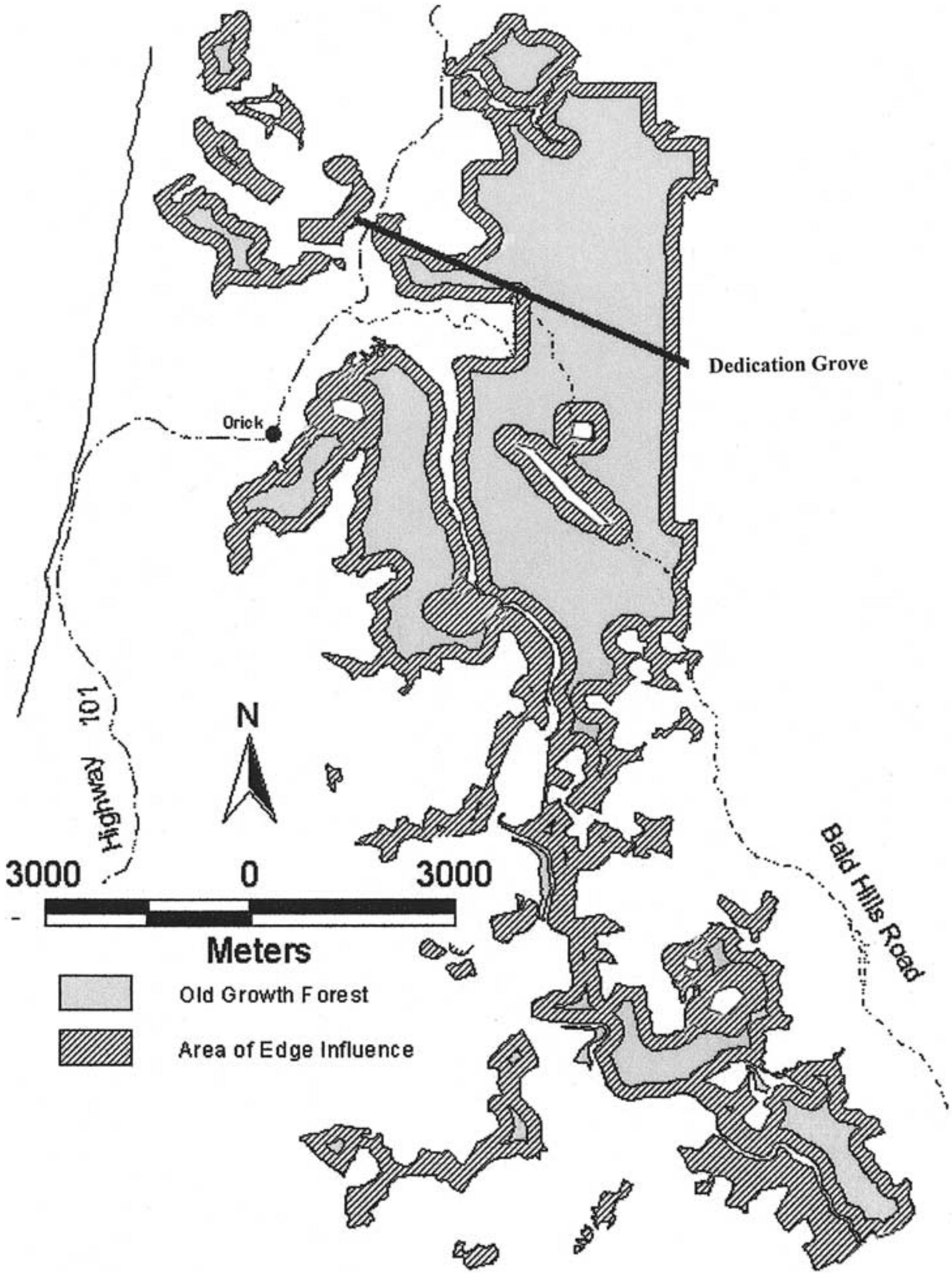

Figure 5. Effective old-growth and edge effects in Dedication Grove and Redwood Creek in Redwood National and State Parks.

groups, the density declines beginning at −80 m in the 50-year-old stands.

The results of this analysis indicate that the depth of edge influence is dependent on the variable in question and that time is a factor in the depth of edge influence. However, it is clear that the edge created by timber harvest significantly influenced the structure and composition of adjacent communities and that this influence, in many cases, was extensive.

Effective size of preserves

The influence of the induced edge created by timber harvest is dependent on the variable measured. A large number of variables were measured in this case in or-

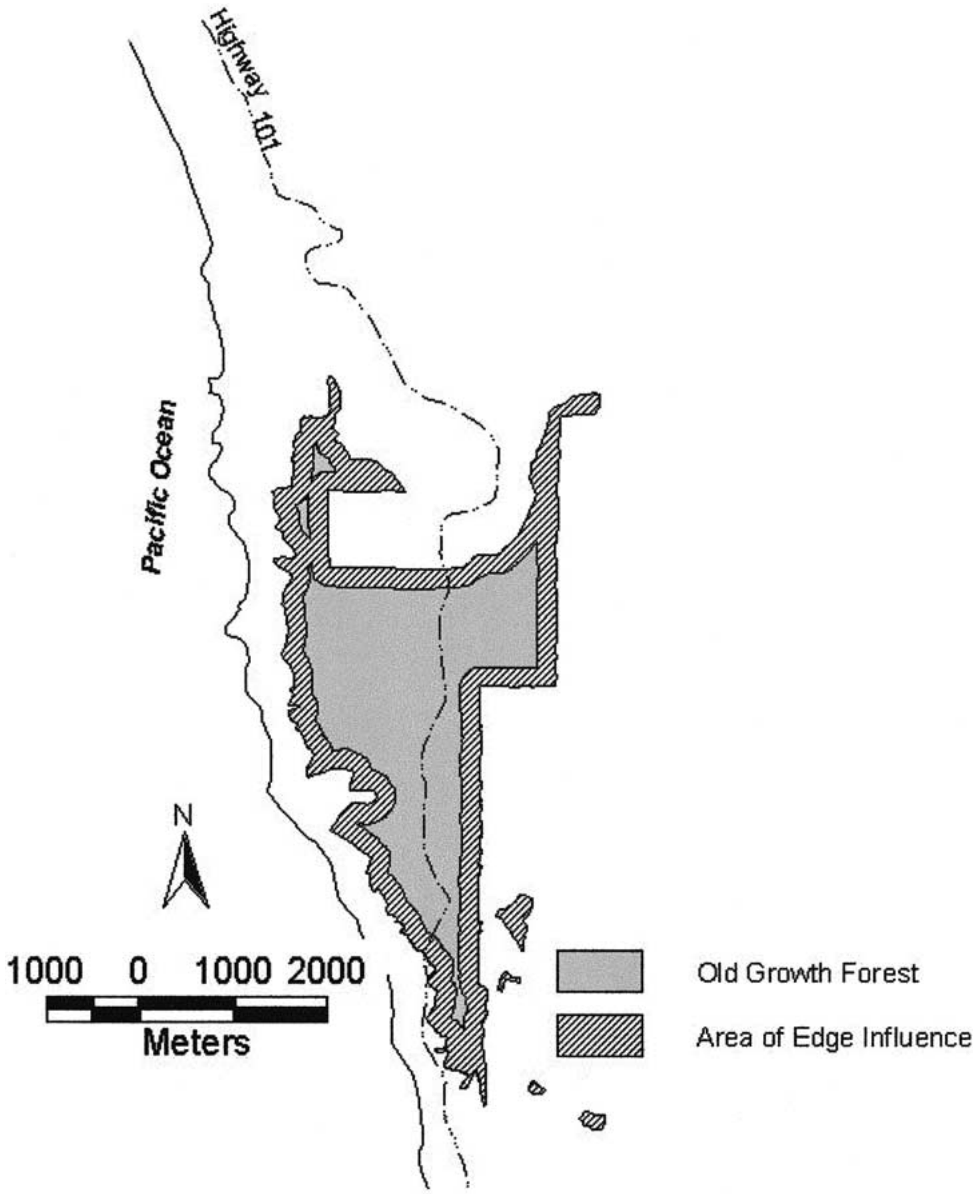

Figure 6. Effective old-growth and edge effects on the Mill Creek Unit in Redwood national and State Parks.

der to gain a broad understanding of edge influence on old-growth redwood forests. A number of variables exhibited a depth of influence of 200 m suggesting that the structure and composition of the residual stands were influenced out to this point. Consequently, 200 m was used as the standard for the following analysis.

The size and shape of each preserve were the determining factors in the estimation of the affected areas. Preserves with low perimeter to area ratios tended to be less affected, except when the total area was very small. For example, despite a low perimeter to area ratios, the calculated affected area for Dedication Grove (Figure 5) was actually greater than its total area, indicating that the entire grove was influenced by the induced edge created by timber harvesting.

For larger preserves, the affect of shape was more apparent. For example, 50% of the old-growth in the Redwood Creek site was effected due to its highly irregular shape. In contrast only 47% and 23% of the Mill Creek and Jedidiah Smith sites were affected (Figures 6 and 7) due to their low perimeter to area ratios.

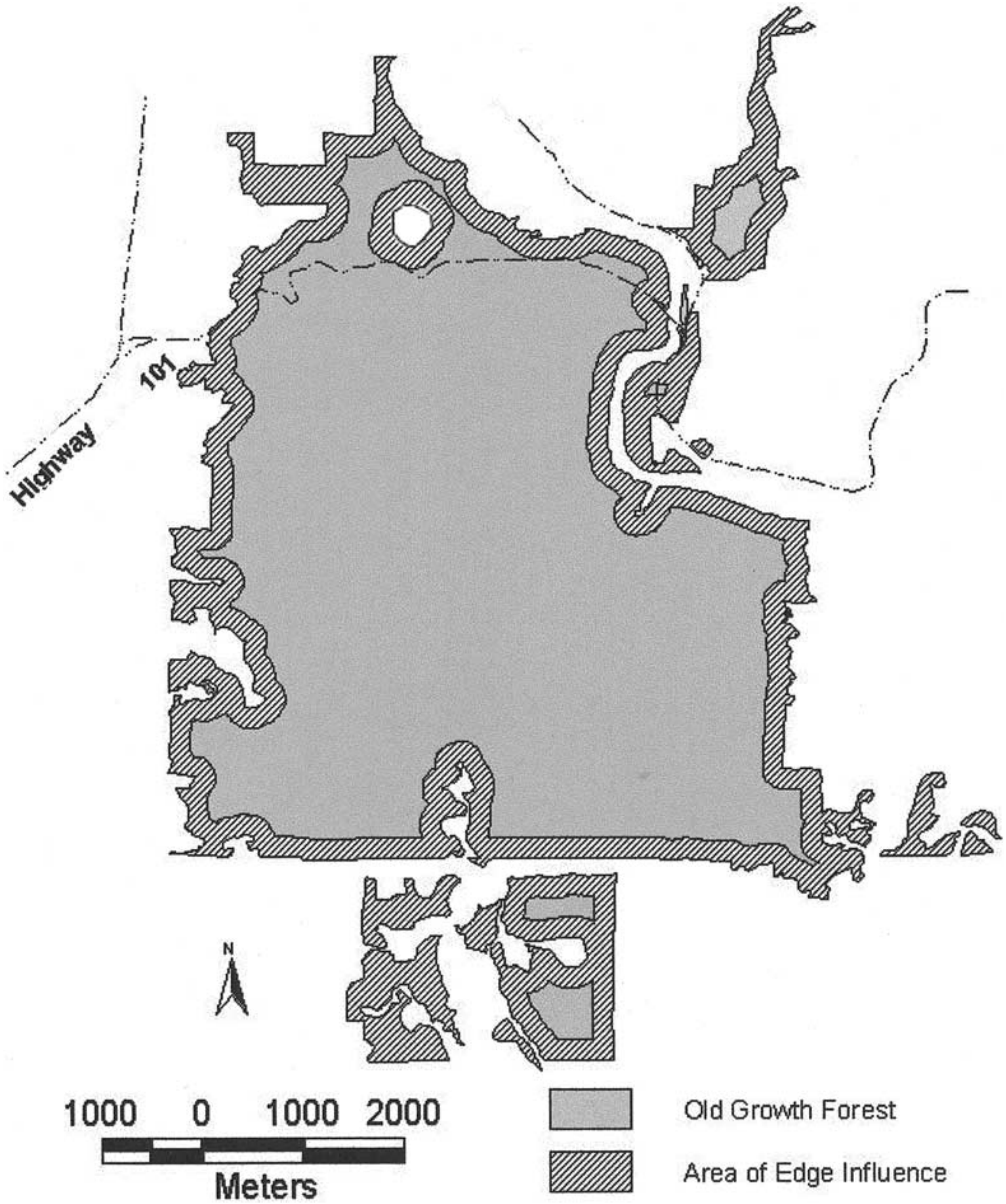

Figure 7. Effective old-growth and edge effects in Jedidiah Redwood State Park.

It is important to note that these estimates are based on the existence of a continuous boundary of harvested land surrounding each preserve. This contingency is presently the case for all of the sites. However, the imposition of Park jurisdiction over much of the previously harvested areas has resulted in a reduction of the disturbance in some cases. The old-growth forest stands along Redwood Creek, for example, are surrounded by lands protected by Redwood National Park. These lands are characterized by regenerating forests, which will mature over time and effectively increase the effective size of these preserves.

Conclusions

Results from data collected on nine sites within the Redwood National and State Park management area indicate that induced edges created by timber harvest have significant impacts on the structure and composition of adjacent old-growth coast redwood stands. Spatial analysis using ArcView suggests that this influence has reduced the effective size of the old-growth stands associated with these study sites. These results have important implications for the preservation of this forest type in regard to the design of preserves and the size of buffer zones. In order to apply these results, however, a clear understanding of management goals must be achieved.

A great deal of variability was found in the depth of influence of induced edges on the measured variables. The importance of the variables chosen for analysis of effective preserve size cannot be understated. A wide range of factors was measured for this study in order to gain a general understanding of edge effects on stand structure and composition. If a specific factor is being managed for, rather than general stand integrity, the depth of influence of that factor should be used rather than a generalized measure. In addition, if the management goal is protection of other resources, such as riparian systems, other variables would need to be included.

In general, these results suggest that the greater the length of the perimeter, in relation to the area, the smaller the effective size of the preserve will be. Therefore, in order to maximize the integrity of an old-growth stand, the perimeter to area ratio should be as small as possible. Application of the theory of island biogeography (MacArthur and Wilson 1967) on isolated preserves suggested a circular shaped preserve with the largest possible area offered the best chance of preserving biodiversity (Diamond 1975).

A contrary management strategy advises that the perimeter to area ratio of preserves should be maximized (Marcot and Meretsky 1983). This management option was supported by research that suggests that species richness and habitat diversity increase in proximity to the edge (Gates and Gysel 1978; Beedy 1981; Hanley 1983). In addition, the validity of applying the theory of island biogeography to ecological rather than oceanic islands has been questioned, particularly in regard to the immigration of species (Janzen 1983). It is significant that the research cited to support this management option is generally related to wildlife diversity (Harris 1988). Also, the research, which shows that species diversity has been elevated in proximity to community boundaries, has often been conducted on natural, or long-term induced, edges. Results for the diversity of plant species on temporary induced edges has generally yielded inverse results (Burgess and Sharpe 1981).

The question of minimizing versus maximizing edge is really a question of what variables are measured and what factors are being managed for. There is strong evidence that management for increased edge does allow the proliferation of certain wildlife species, especially game species (Brown 1985). In contrast, management for decreased edge helps preserve the intrinsic characteristics of residual stands, including vegetation composition and structure, and the complement of wildlife species dependent on the conditions of the forest interior.

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