Edge Effects and the Effective Size of Old-Growth Coast Redwood Preserves

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Abstract—Data were collected to determine the depth of influence of conditions created by clear-cut timber harvest on adjacent old-growth stands of coast redwood. Fourteen variables related to stand structure and composition, wildlife habitat, and physical environment exhibited significant correlation to distance from the timber harvest boundary. Results were applied to the core area model (Laurence and Yensen 1991) to determine the effective size of forest preserves, and to make recommendations on the size and function of buffer zones. The core area model was used to determine the effective size of the five old-growth patches associated with the study sites. A significant loss in total preserve area due to the presence of induced edges occurred in all cases.

Timber harvesting can affect adjacent forest stands by altering microclimate along the edge of the disturbance and by exposing trees to the dangers of windthrow and crown die-back. These impacts may, in turn, affect vegetation composition and structure. The character of the remaining forest is altered along its edge, reducing the effective size of a preserve (Schonewald-Cox and Bayless 1986). 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 clear-cut timber harvesting has been so prevalent in the coast redwood forest type that very little of the original forest remains. Virtually all of the remaining old-growth forest is preserved on public lands. In most cases, these preserves are surrounded by managed land. 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.

Physical and biological factors that actively move material or energy across landscape boundaries have been referred to as vectors (Kelly and Rotenberry 1996). Kelly and Rotenberry describe a method for designing buffer zones that requires the identification and ranking of present vectors. Potential vectors can be inhibited by reducing boundary permeability. This can be accomplished through a variety of means, including increasing the size of buffer zones, or altering the type of activities permitted within buffer zones. Discussions about impacts of edge effects on the integrity of preserves can focus on the vectors themselves, or on the measurable impact of these vectors on biotic variables.

A discussion of effective old-growth size by Harris (1984) focused on a single vector. Heightened wind effects could be 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. He suggests that six tree heights would give a more accurate measure of the edge influence for preserves with irregular shapes. Harris also discusses the importance of the matrix in which an old-growth island exists. 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 discussed further in Janzen's (1983) inestigation of a forest preserve in Costa Rica. Janzen focused on a single biotic variable, species composition, for his analysis. 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 (Franklin and Foreman 1987). Franklin and Foreman 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

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factors such as species diversity. These factors were shown to be correlated to distance from the edge. For example, species diversity was shown to decrease in proximity to the edge.

A model for determining the core area, or the effective size, of a preserve was developed by Laurence and Yensen (1991). This model refines 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 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 meters. A multivariable approach could be applied to this method in a manner similar to the core area model.

In general, these models suggest that the greater the length of the perimeter, in relation to the area of the preserve, the smaller the core area will be. Therefore, in order to maximize the integrity of an old-growth stand, the perimeter/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/area ratio of preserves should be maximized (Brown 1985). This management option was supported by research that suggests that species richness and habitat diversity increase in proximity to the edge (Beedy 1981, Gates and Gysel 1978, 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 emigration 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. For example, a species such as the spotted owl requires a minimum area of old-growth forest to persist. Unfortunately, these characteristics have not been well defined in the literature. It is much more complex to manage for an entire community or forest type than it is to manage for a single species. However, if the management goal is to preserve the intrinsic characteristics of a stand, including its structure and composition, the best approach is to measure as many related variables as possible in order to determine the effect of edge on each.

The goal of this study was to determine the effects of clear-cut 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, to estimate the effective size of old-growth redwood preserves and to make recommendations in regard to buffer zones in this forest type.

Methods

Data were collected along 360 meter transectsrandomly located across the boundaries between clear-cut areas and adjacent old-growth stands on nine sites in the redwood forest region of northern California. A stepwise regression analysis of this data was used to identify the depth of influence of the clear-cut areas on the old-growth forests. Effective size of preserves was then predicted on the basis of the depth of influence of measured variables, with the core area model.

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 (defined as the point where no cut stumps were visible). Circular 20-meter diameter sample plots were set at 40-meter intervals along transects, with five plots on each transect located within the uncut forest and four plots located in the regenerating stands. The data collected on sample plots were used to quantify the following variables:

Table 1—Characteristics of study sites.

Name of study site	Year of harvest	Elevation (meters)	Average slope (%)	Aspect	Harvest area (he)	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

- Height of canopy layers (canopy, subcanopy, shrub, herb)
- Frequency of observed crown die-back
- Percent cover and cover class of canopy layers
- Density of size classes and density of size classes by species
- Dominance of major tree species
- 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 highest p-value was removed.

Determining the Depth of Influence

Variables that were determined to be 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). For this procedure, 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.

Application of the Core Area Model

Estimations of the depth of influence were applied to the core area model, as described by Laurence and Yensen (1991). This model uses two factors to predict core area of forest patches, assuming they are completely surrounded by harvested land. The edge function describes the distance of edge influence into a stand. The shape index describes the perimeter to size ratio of a site.

The shape index (SI) describes the deviation of the shape of a preserve from a circle. A circle that has the lowest possible area to perimeter ratio is given an SI of 1. The shape index was calculated using the total area (TA) and the perimeter length (P).

$$SI = \frac{P}{200\left[(\pi TA)^{0.5}\right]}$$

The shape index term was combined with an edge function (d) "depth of influence" to determine the affected area (AA).

$$AA = \{(3.55)(d)(SI)[(TA/10{,}000)^{0.5}]\}$$

The affected area was then subtracted from the total area TA to determine the core area.

Core Area = TA-AA.

Buffer Zones

The depth of influence calculated for the study sites was compared to the "three tree height rule" (Harris 1984). Appropriate buffer zone width was then estimated using both the "three tree height rule" and the depth of influence estimate from the data gathered in this study.

Results

A total of 13 variables were found to have significant correlation to distance from the timber harvest boundary (table 2). 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.

In addition to correlation factors, the depth of influence was calculated for each variable. A wide range of influence was exhibited by the sample variables (0 to >200 meters). Solar radiation, for example, exhibited a positive correlation with distance from the edge out to approximately 180 meters within the old-growth portion of the stands (fig. 1). The distribution of this variable is of particular significance because solar radiation is a vector of influence. Therefore, the distribution of other variables can be discussed in relation to this variable.

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

Variable		Correlation coefficient	P-value	Depth of influence (meters)
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

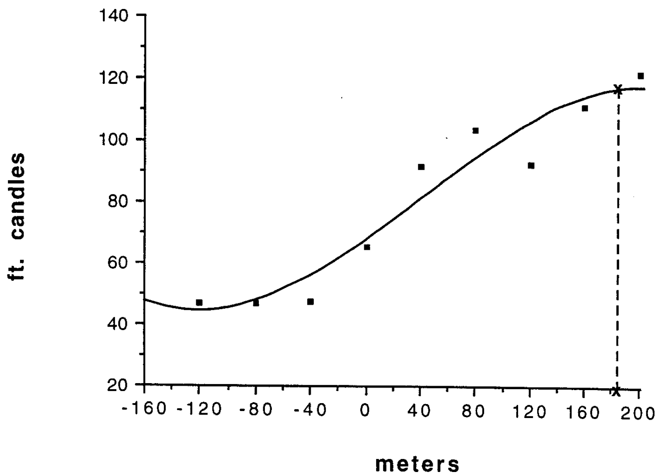

Figure 1—Solar radiation and distance from the edge. The scale on the x axis refers to distance from the edge as positive in the direction of the old-growth forest and negative in the direction of the regenerating areas. The zero mark represents the timber harvest boundary.

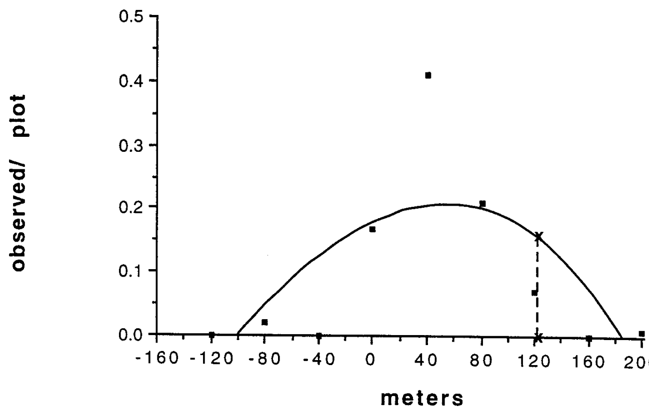

Figure 3—Crown dieback and distance from the edge.

Species richness and solar radiation exhibited nearly identical curves (fig. 2). The depth of influence in this case was also approximated at 180 meters. It is important to note that though the slope of the line is positive, the influence of the edge is negative. Species diversity is reduced in proximity to the timber harvest boundary. 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 ($p < 0.0001$).

In contrast to the previously discussed variables, the correlation of crown die-back to distance from the edge was negative (fig. 3). The depth of influence was 120 meters, and the shape of the distribution curve was different from that of species richness. The reason for these differences is most likely related to vectors. In contrast to species richness, which was correlated to lower solar illumination, the frequency of crown die-back was most likely the result of higher wind velocity near the edge.

The correlation of the density of red alder (*Alnus rubra*) poles also exhibited a negative correlation to distance from the edge, indicating a higher density of poles in proximity to the timber harvest boundary (fig. 4). The depth of influence in this case was approximately 80 meters.

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 (fig. 5). The distribution for the 20-year-old age group was characterized by a relatively steep slope and a depth of influence of approximately 140 meters. The slope for the 30-year-old age group was slightly less steep, but the depth of influence was in excess of 200 meters. The 50-year-old age group was characterized by a zero slope, showing no depth of influence.

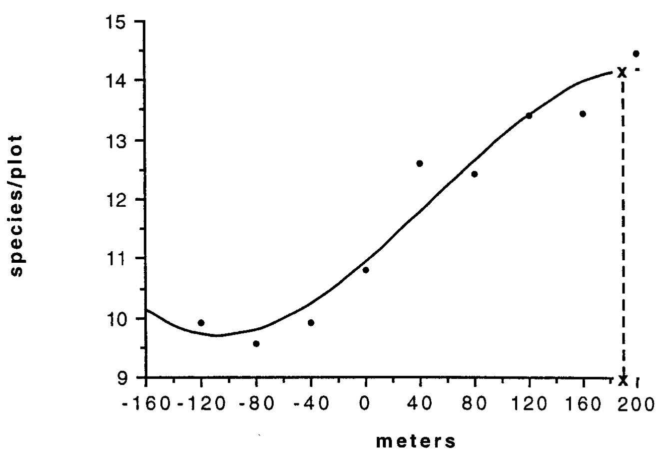

Figure 2—Species richness and distance from the edge.

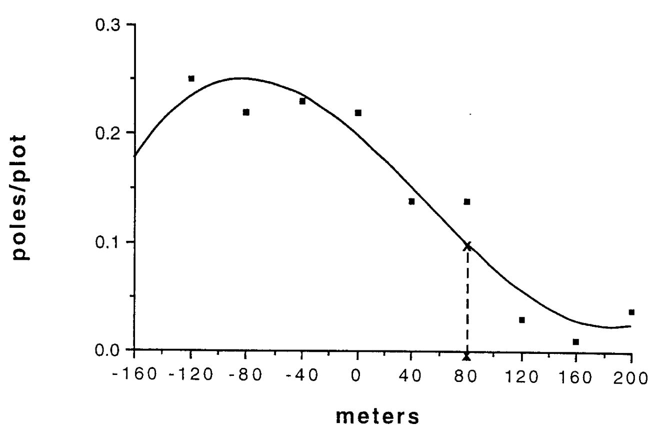

Figure 4—Density of alder poles and distance from the edge.

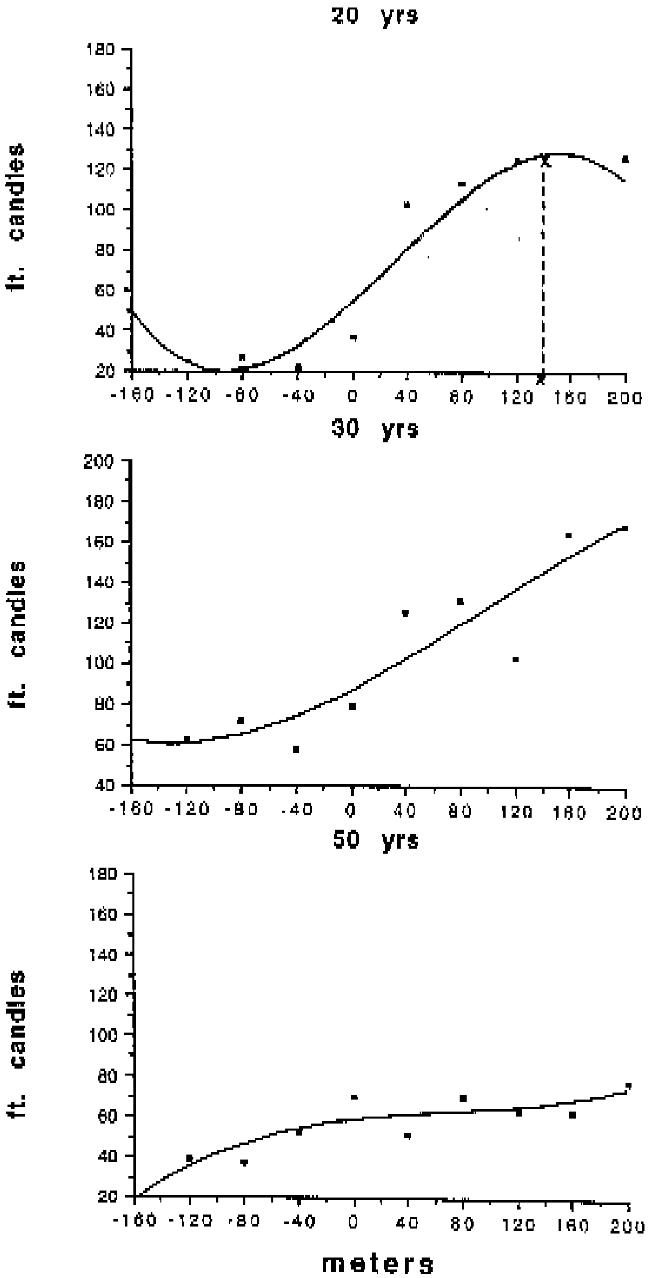

Figure 5—Solar radiation chronosequence.

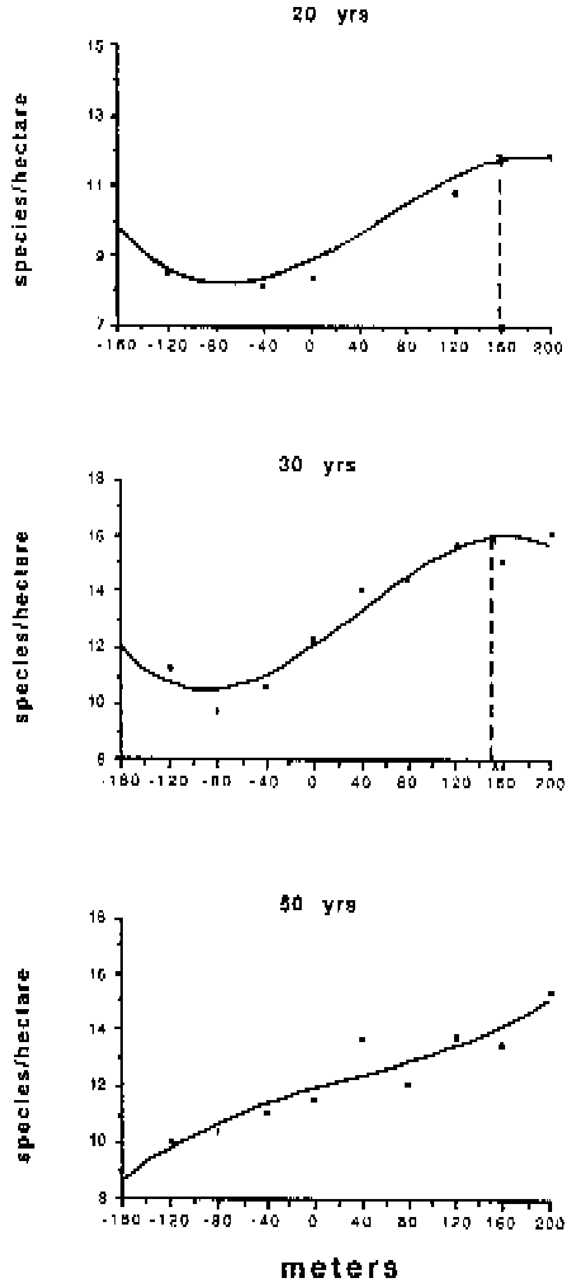

Figure 6—Species richness chronosequence.

An analysis of the three age groups together reveals a pattern of influence for this vector of influence that resembles a wave. Initially the crest is high, but the magnitude of the wave diminishes with time, until it virtually disappears.

A similar pattern was apparent for species richness (fig. 6). 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 meters.

The distribution of crown dieback frequency also suggested an increase in depth of influence with respect to time (fig. 7). However, because the visible effects of crown dieback persist, there was no leveling of the slope at 50 years.

The clearest example of a time effect was observed for the pole density of alder (fig. 8). 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 out to 40 meters and 80 meters, respectively. A time effect is also apparent on the harvested side of the timber harvest boundary. Where density of alder is elevated out to -160 meters within the cut-over areas for the 20- and

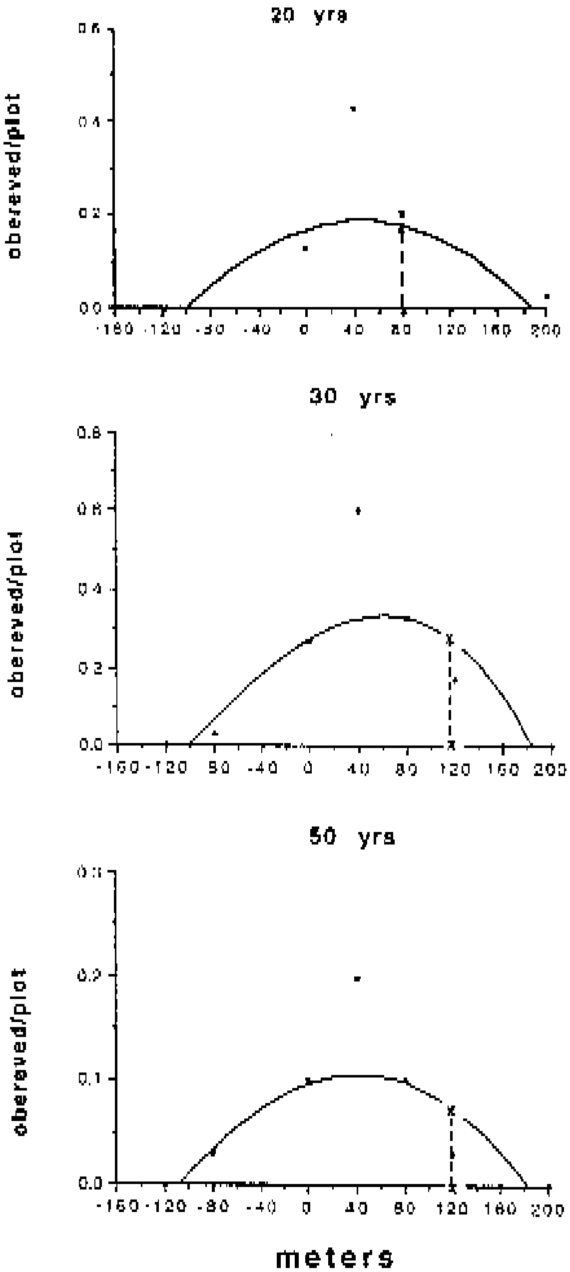

Figure 7—Crown dieback chronosequence.

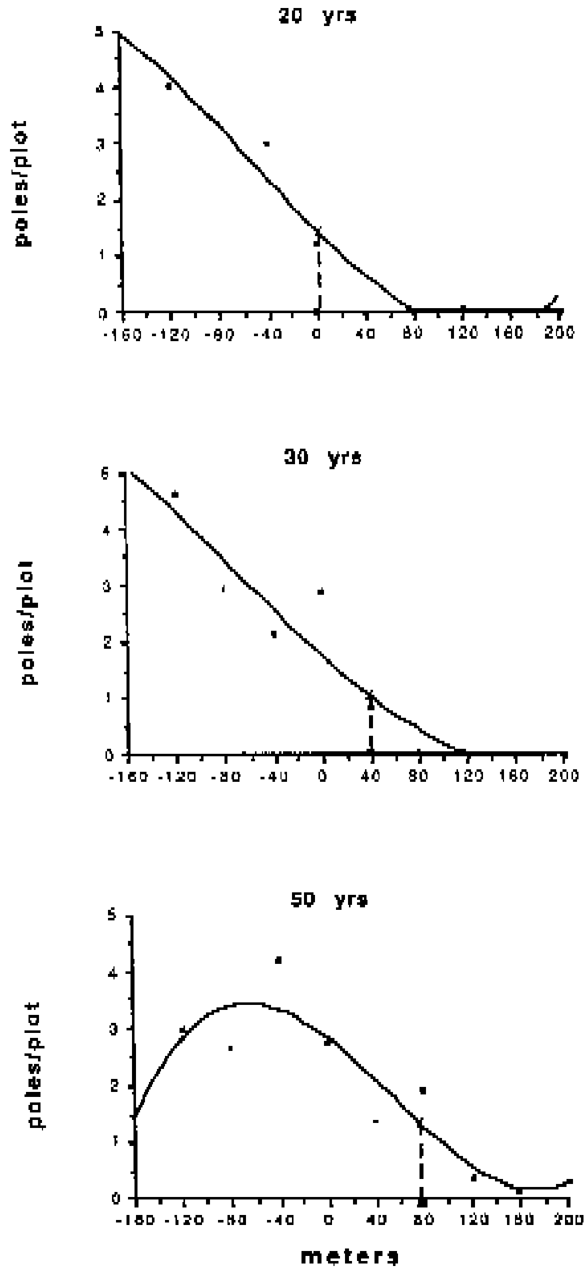

Figure 8—Density of alder pole chronosequence.

30-year-old age groups, the density began to decline beginning at -80 meters 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 (greater than 200 meters).

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 order to gain a broad understanding of edge influence on the intrinsic properties of old-growth redwood forests. A number of variables exhibited a depth of influence in excess of 200 meters suggesting that the intrinsic properties of the residual stands were influenced out to this point. Consequently, 200 meters was used as the standard for the following analysis. If a specific variable were being manage d for the depth of influence for that variable would be used.

Harris Model—The "three tree rule" is supported by the results of this study. The average canopy height at the furthest distance from the timber harvest boundary within the old-growth stands sampled was 60 meters. Using 60 meters as tree height, three times tree height equals

180 meters, which is similar to the 200 meter depth of influence determined by this study.

The Core Area Model—The model developed by Laurence and Yensen (1991), for determining the effective size of preserves, was applied to the old-growth stands associated with each study site, using the 200 meter depth of influence estimated with data from this study. Results from this analysis indicate that a substantial amount of the preserve areas were compromised adjacent to timber harvest operations (table 3).

The size and shape of each preserve were the determining factors in the estimation of the affected areas. Preserves with low shape indexes tended to be less affected, except when the total area was very small. For example, despite a low shape index, the calculated affected area for Dedication Grove 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. The northern and southern portions of the Redwood Creek drainage included core areas which composed 65% and 32% of their total areas, respectively. This dramatic difference is due primarily to the extremely irregular perimeter of the uncut portion of the southern part of the creek. An intermediate proportion of core area (61 %) was estimated for the Mill Creek, and the highest proportion of core area (68 %) was estimated for the Jedidiah Smith grove due to its nearly square shape.

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 core area 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. Application of the core area model (Laurence and Yensen 1991) further 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 were measured for this study in order to gain a general understanding of edge effects on stand structure and composition. The maximum depth of influence of 200 meters used in this analysis was based on the maximum depth of influence of a number of these variables. 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.

The validity of using a 200-meter depth of influence is supported by the "three tree height rule" (Harris 1984). With an average canopy height of between 46 and 76 meters at the furthest distance from the timber harvest boundary, the "three tree height rule" suggests a depth of influence of 138 to 228 meters. It is important to note that when applying this rule to preserves with irregular boundaries, Harris suggests the use of a "six tree height rule".

The core area model allows for a more systematic approach to the application of depth of influence estimates to preserves with irregular boundaries. The proportion each of the old-growth stands affected by boundary conditions varied widely and was dependent on the size and shape of preserves. In general, the results of this study suggest that, for stand characteristics such as the composition and structure of vegetation large preserves with a low perimeter to area ratio are the most resistant to edge influence.

Beyond the creation of preserves with appropriate shape and size, buffer zones are the best method for insulating a forest community from outside influences. A buffer zone has two properties, permeability and width. The permeability of a buffer zone is related to the ability of vectors to move through it. Solar radiation was measured as a vector in this study and showed a maximum depth of influence of more than 200 meters. Management activities such as selective harvesting within a buffer zone are likely to increase the permeability for this and other influence vectors. Measurements of the affect of permeability of buffer zones on the depth of edge influence were beyond the scope of this study, but offer excellent opportunity for further inquiry.

Assuming a buffer zone with no harvest activity and a preserve with a regular perimeter, a buffer zone that protects the integrity of the total area of the stand should be

Table 3—Core area model results.

Preserve	P	TA	SI	d	AA	CA
Dedication Grove	4634 m	58 he	1.72	200 m	93 he	0 he
Del Norte	26346 m	991 he	2.76	200 m	617 he	374 he
Jedidiah Smith	42327 m	2994 he	2.44	200 m	948 he	2046 he
Redwood Creek N	74085 m	5189 he	3.55	200 m	1816 he	3373 he
Redwood Creek S	54376 m	1785 he	4.06	200 m	1217 he	567 he

equal in width to the depth of edge influence. The results from this study indicate that for old-growth coast redwood stands this width would be a minimum of 200 meters, or approximately three times the average tree height.

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