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Change in spatial characteristics of forest openings in the Klamath Mountains of northwestern California[1], USA

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Abstract

Change in the spatial characteristics of forest openings was investigated in three forested watersheds in northwestern Siskiyou County, California totalling approximately 24,600 hectares. Watersheds with minimal human disturbance were chosen for study. However, fire suppression has been pervasive throughout. Characteristics of forest openings (area, perimeter, distance between neighboring openings) were measured on aerial photographs taken 41 years apart. An index of regional form was determined for the landscape. Shape complexity for each opening was calculated using two indices based upon fractals. Significant differences were found using the Kolmogorov-Smirnov two-sample test between the perimeters, areas, distance from sample point to nearest opening, and distance between neighboring openings. The perimeters and areas became smaller, and the distances from the sample point to the nearest opening and between neighboring openings became greater over the 41 years between aerial photo sets. The estimated area occupied by openings decreased from 25.8% to 15.6% of the study area. No significant difference was found in the shape of the openings except as the shape indices were influenced by changes in size of the openings.

1. Introduction

Forest openings are an important component of landscape diversity. Patterns of openings contribute to variety for wildlife habitat through influencing vegetation diversity and edge (Franklin and Forman 1987). They can serve as microsites favorable for regeneration of shade intolerant species of vegetation. Openings can become places for the initiation of secondary succession. They contribute to variety through becoming patches of successive vegetation and age classes (Sousa 1984; White and Pickett 1985).

Openings that are the result of disturbance are usually short lived, the actual time for them to fade into the forest matrix depending on site conditions and vegetation response. Openings are occupied over time by various vegetation communities. Patterns may change considerably in space and time (Knight 1987; Baker 1989), making it difficult to determine a characteristic landscape mosaic (Christensen 1991).

The alteration of landscapes by human activities in forested areas has generated great interest in recent years. Most interest has focused on dramatic changes in forest landscape patterns brought about

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through lumbering activities (Edmonds 1979). Considerable research has been undertaken to describe the ecological effects of this activity and associated changes, especially as wildlife habitat may be affected (*e.g.* Franklin and Forman 1987; Harris 1984; Mladenoff *et al.* 1993, Swanson *et al.* 1990).

However, less attention has been paid to more subtle but no less significant changes in forested landscapes where little management activity, with the exception of fire suppression, has taken place. It has been well established that fire, as a prominent disturbance factor, played a major role in the patterning of vegetation stand structure and mosaics in the forest landscapes of western North America (*e.g.* Heinselman 1978; Kilgore 1981; Knight 1987).

Investigations of temporal changes in stand structure and patch dynamics have demonstrated considerable change in western forested landscapes within parks and wilderness as well as in other areas relatively free of human manipulation (Parker 1987; Parsons and DeBenedetti 1979; Savage 1991; Vale 1977). These studies have reported changes since the late 1800's in age class characteristics, stand density, species composition, and a significant reduction in fire occurrence. Few if any studies of this nature have been undertaken in the Klamath Mountains of northwestern California and southwestern Oregon.

Along with changes in stand structure and patch pattern one would expect changes in characteristics of forest openings (Parsons and DeBenedetti 1979). However, there have been few studies characterizing changes in canopy gaps or other types of openings within forested landscapes in California. Most of the existing studies have investigated the changes in meadows (*e.g.* Helms 1987; Taylor 1990; Vale 1981).

The few fire history studies undertaken in the Klamath region have reported that frequent fire appears to have played a major role in the past. Fire suppression activities begun in the early 1900's with the creation of the National Forest System appear to have reduced the frequency of fire analogous to that in other areas of the western United States (Agee 1991; Wills 1991).

The work reported here was undertaken as a first step in the study of temporal and spatial changes in stand structure and patch mosaics of forested landscapes in northern California. The objectives of this work were to answer the following questions: 1) what are the characteristic sizes and shapes of openings in these forests, 2) how have these characteristics changed over time, and 3) how have distances between openings changed?

This initial work focused on relatively unmanaged forested landscapes in order to provide a baseline of dynamics for comparing more manipulated landscapes. It is necessary to understand the dynamics of the less managed landscapes in order to appropriately assess changes in managed landscapes. Finding completely unmanaged landscapes is essentially impossible in California forests. Fire suppression has been ubiquitous, and there is very little forest that has not been affected.

2. Description of the study area

The study area encompassed portions of the Dillon, Clear and Swillup Creek watersheds (24,600 ha) near Happy Camp in the Klamath National Forest, California (approx. 41°42′N, 123°35′W). The geology of the area is complex, with four general lithologic types having been described: 1) metasedimentary, 2) granitic, 3) ultramafic and 4) quaternary landslide types. The general topography consists of steep slopes (45–85%) averaging approximately 60% (USDA Forest Service 1990). Elevations range from approximately 250 m to >2000 m.

The mixed evergreen forests characteristic of the area have been described by Bingham and Sawyer (1991) and Sawyer *et al.* (1977). Other important forests in the area are the mixed conifer forest found in middle-to-higher elevations and the more or less open mixed conifer with shrub or herebaceous understory found on the ultramafic sites. These later forests have been described by Sawyer and Thornburgh (1977), Sawyer *et al.* (1977), and Whittaker (1960).

The complex geology, topography and zonation of the vegetation contribute to variable landscape patterns.

The climate is modified Mediterranean characterized by warm, dry summers and cool, wet winters.

Approximately 90% of the precipitation falls from October through May with the remainder coming from occasional summer thunderstorms. Average annual precipitation ranges from 1120 mm to 2000 mm, generally increasing with elevation (USDA Forest Service 1990). The dry summers create severe fire weather in most years between July and September (Wills 1991).

There has been relatively little human disturbance other than fire suppression activities in the study area. A large portion of the study area is included in the Siskiyou Wilderness, and much of the remaining area was inventoried as Roadless Area until released for multiple-use management by the Congress in 1984 (USDA Forest Service 1990).

Fires were undoubtedly the most frequent and widespread disturbance factor affecting landscape dynamics before the creation of the National Forest System (Atzet and Martin 1992; Atzet and Wheeler 1982). Analysis of fire scars from a few widely scattered, individual trees in adjoining watersheds supports the scenario of frequent fire (mean 8–24 yr between fires) before 1900 (unpublished data on file). Fire suppression activities began in the first decade of this century but were not effective until the late 1940's (Wills 1991).

3. Methods

3.1. Data collection

Both ephemeral openings (gaps from various forms of disturbance) and more permanent openings (such as those edaphically or otherwise physically controlled) were included in this study. An opening was defined as an area of approximately 0.1 hectares or larger, occupied by vegetation made up of herbs, shrubs, or trees (conifers or hardwoods) no greater than 1/3 the height of the surrounding stands and/or occupied by rock, soil or water.

Fifty random sample points were selected on 1:24000 topographic maps. These sample points were located on each of two sets of approximately 1:16000 aerial photographs for the study area, one from 1944 and one from 1985. Data collected for each sample point were: 1) distance from sample point to the edge of the nearest opening (first opening), 2) distance from the edge of the first opening to the edge of its nearest neighbor (second opening), 3) perimeter of each opening (including the perimeter of any islands), 4) area of each opening (excluding the area of any islands), and 5) the non-opening area around each opening closer to it than any other opening. Where a sample point fell within an opening, that opening was treated as the first opening with a distance from the sample point of 0. No attempt was made to ensure that the openings sampled in the 1944 earial photos were those sampled in the 1985 photos. The locations of the 50 random sample points were the same in both periods.

3.2. Data analysis

Three shape and form indices were calculated to determine which may be more useful for describing changes in spatial characteristics.

A description of regional form as a fractal dimension for the landscape (*e.g.*, De Cola 1989) was derived for both the 1944 and 1985 data. The index was determined by regressing opening perimeter against opening area (cf. O'Neill *et al.* 1988). Difference between the regional forms of the two time periods was determined using a t test for differences in the slopes (1/2 the fractal dimension). This index will be referred to as the index of landscape form (I_{LF}).

Two additional indices were calculated for each opening from the perimeter and area measurements for each time period. These indices were shape (C) (Rex and Malanson 1990) and fractal dimension (D) (Krummel *et al.* 1987). The fractal dimension (D) as used here is considered an index of shape for individual openings with no assumption as to self-similarity over a variety of scales (Milne 1991). These indices were used to describe the complexity of the opening shapes by comparing perimeter to area for each opening. The indices of D and C are expected to increase as complexity of the shape increases.

Other popular shape indices, such as the patch shape index (Forman and Godron 1986) and com-

Table 1. Summary of opening characteristics measured in 1944 and 1985 aerial photographs.

	Yr.	P[1]	Mean	SD	Minimum	Median	Maximum
Area (hectares)		0.002					
	1944		0.53(0.48)[2]	0.43(0.44)	0.09(0.08)	1.05(0.71)	297.8(297.8)
	1985		0.27(0.25)	0.31(0.29)	0.07(0.07)	0.33(0.29)	54.6(54.6)
Perimeter (kilometers)		0.017					
	1944		0.75(0.67)	0.85(0.89)	0.10(0.16)	0.99(0.81)	45.6(45.6)
	1985		0.39(0.37)	0.59(0.58)	0.14(0.14)	0.45(0.39)	16.8(16.8)
Distance 1 (meters)[3]		0.001					
	1944		[4]	[4]	0	12	232
	1985		[4]	[4]	0	26	202
Distance 2 (meters)[5]		0.004					
	1944		17.9	28.1	5	23	145
	1985		19.2	27.8	7	25	132
D (fractal dimension)		0.153					
	1944		1.50(1.50)	0.07(0.06)	1.32(1.32)	1.50(1.50)	1.66(1.66)
	1985		1.49(1.49)	0.04(0.05)	1.40(1.40)	1.49(1.50)	1.59(1.59)

[1] *P* is the probability of the characteristic being from the same population in the two time periods as determined using the Kolmogorov-Smirnov two-sample test.
[2] The value shown outside of the parentheses is for the 50 openings closest to the sample point. The value shown within the parentheses is for all 100 openings measured.
[3] Distance 1 is the distance from the randomly selected sample point to the nearest (1st) opening.
[4] Undefined because the procedure used to calculate the Mean and SD here requires division by 0.
[5] Distance 2 is the distance from the 1st opening to its nearest neighbour opening.

pactness index (Griffith *et al.* 1986), were considered. However, since patch shape and compactness indices are influenced by size, especially when the objects in question exhibit a wide range of sizes, they are questionable as shape indices (Austin 1984, Griffith *et al.* 1986). The interpretation of shape becomes difficult to separate from the influence of size. Because a large range of sizes of openings was expected in this study, these shape indices were considered not appropriate here. Once the influence of size is accounted for, these indices behave similarly to the fractal dimension D noted above.

Differences in indices and spatial characteristics between the two time periods were tested using the nonparametric Kolmogorov-Smirnov (KS) test (Davis 1986). To account for unequal probabilities of opening selection associated with the openings of different sizes, each was weighted prior to testing in the KS test by the following.

$$W_i = \frac{X_i}{\sum \frac{1}{P_j} * P_i}$$

Where:
W_i = weighted value *i* of variable of interest.
X_i = measured value *i* of variable of interest.
P_i = probability of selection of value *i* for variable of interest. P_i is determined as the proportion of the total study area represented by opening *i* and the area surrounding opening *i* closer to that opening than any other (the Theissen polygon of that opening) (Overton 1993).
P_j = probability of selection of value *j* for an observation of the variable of interest where $j = 1$ to n.

An estimate of the total area occupied by openings in each time period was made using the estimation procedure for variable probability sampling as described by Overton (1993). The average area of the openings for each time period was determined using procedures to describe the properties of mosaics as explained by Upton and Fingleton (1985).

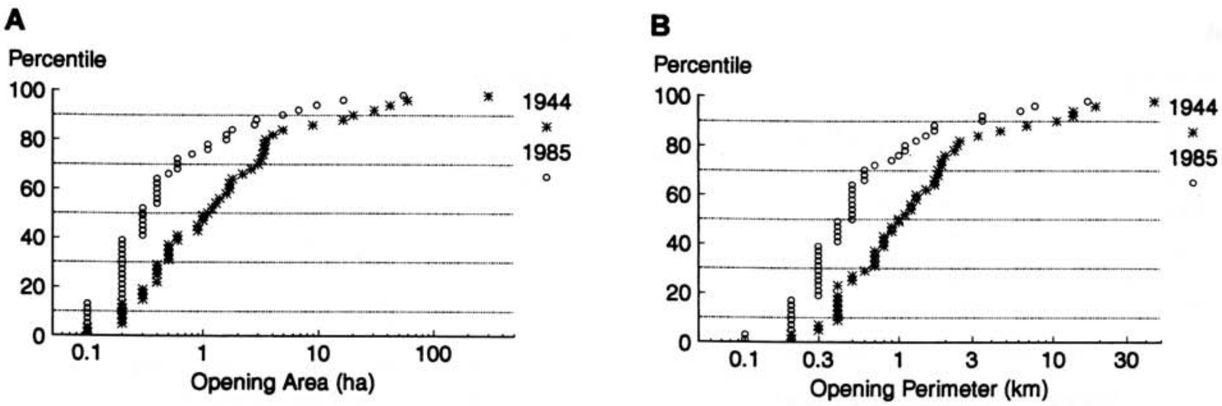

Fig. 1. Percentile plots of A) area and B) perimeter of openings illustrating how the openings on the 1944 aerial photographs tend to be larger than those found on the 1985 aerial photographs.

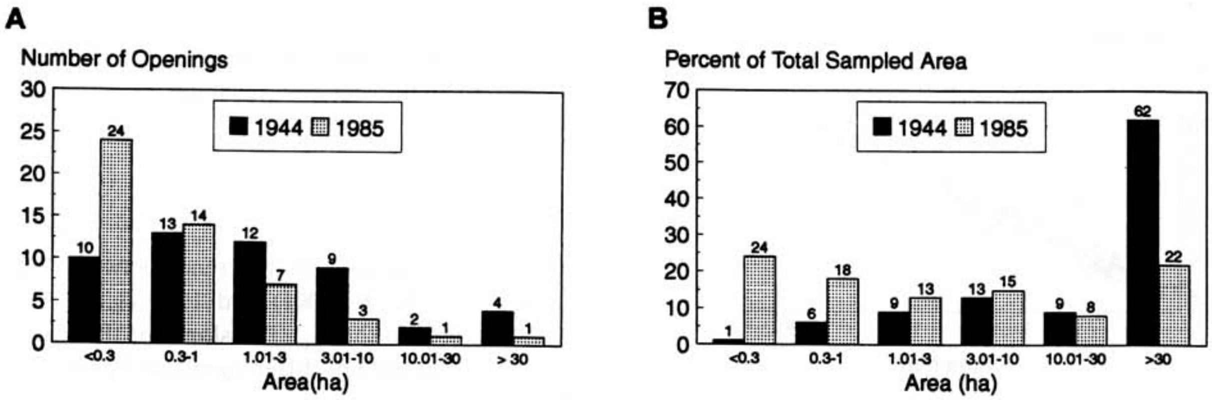

Fig. 2. Histograms of A) number of openings sampled in each size class and B) proportion of total sampled area represented in each opening size class.

4. Results

All results reported here are based upon analyzing the 50 openings nearest the randomly located sample points. Accounting for the variable probability of these 50 openings can be done without problem (Overton 1993). The characteristics of all 100 openings (the 50 nearest neighbor pairs) were also determined (Table 1). However, an appropriate way to account for variable probability of the nearest neighbor opening in this type of sampling scheme is not clear. Therefore, the 50 nearest neighbor openings were not used in the analyses reported below.

The data are highly skewed as is often the case with spatial data (Davis 1986). Therefore the data are displayed in quartiles and ranges (Table 1) in order to provide more information than would be the case if only means and standard deviations were used.

4.1. Sizes of openings

Openings decreased in area and perimeter between 1944 and 1985 (Fig. 1). The median area and perimeter of the openings in 1944 were more than twice those of 1985 (Table 1). The estimated proportion of the landscape occupied by openings in 1944 was 25.8% (6340 ha) and in 1985 was 15.6% (3845 ha). This latter difference is significant ($P < .001$) and amounts to approximately a 39% reduction in the area occupied by openings.

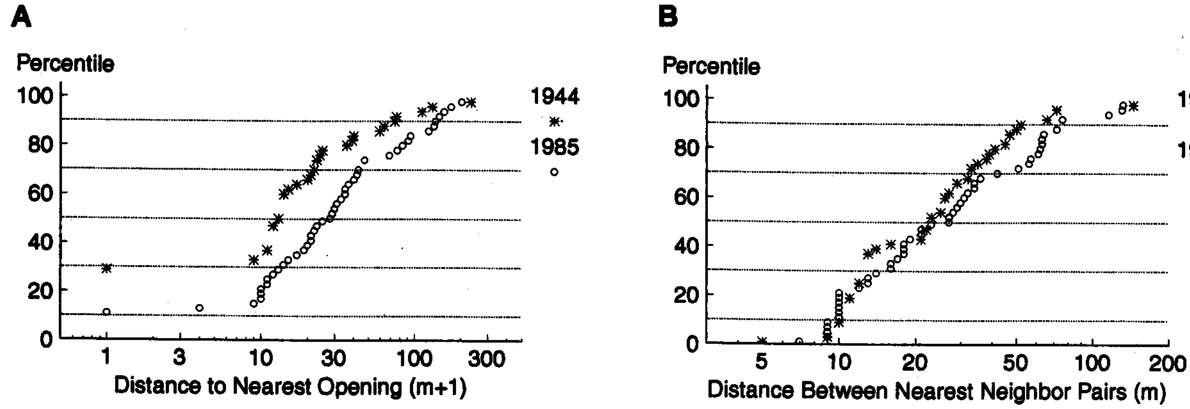

Fig. 3. Percentil plots illustrating increases between 1944 and 1985 in A) distance to nearest openings (m + 1 necessary because log of 0 is undefined) and B) distance between nearest neighbor pair for each sample point.

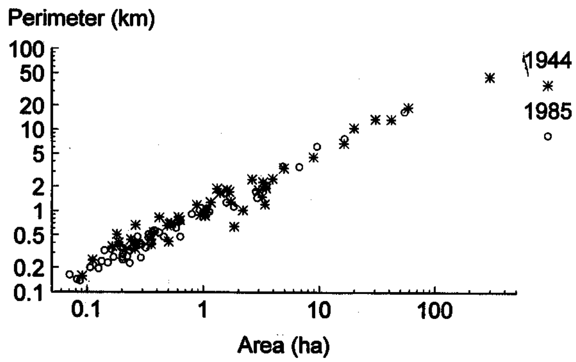

Fig. 4. Plot of perimeter against area for 1944 and 1985.

Smaller openings were more common than larger openings in both time periods (Fig. 2A). However, larger openings occupied a much larger portion of the total area of openings in 1944 than in 1985 (Fig. 2B). The proportion of area in the intermediate sizes does not appear to have changed as markedly.

4.2. Distances

Both the distances from the 50 randomly chosen sample points to the nearest opening and the distances between each nearest neighbor were greater in 1985 than in 1944 (Fig. 3). The median distance from sample points to the first openings had doubled between 1944 and 1985 (Table 1). The sample point location fell within 15 openings (30% of total) in 1944 and 5 openings (10% of total) in 1985.

The changes in sizes of openings and distances between them indicate that openings were filling in between 1944 and 1985.

4.3. Shape Indices

There was no significant difference between 1944 (1.35, $R^2 = .946$, $P < .001$) and 1985 (1.44, $R^2 = .970$, $P < .001$) in the I_{LF}. The slopes of the regression equations did not differ significantly ($P = .09$) (Fig. 4).

The index C appears to be related to size of the opening (Fig. 5B). Since the interpretation C could be confounded by the size of the openings, and since size has already been assessed, this index was dropped from further analysis.

No significant difference (Table 1) in the index D between 1944 and 1985 was found (Fig. 6). This indicates no significant change in the complexity of opening shapes between the two time periods even though there has been a change in size.

There is a larger range of values for D at smaller opening sizes. As the openings become larger the value of D approaches the mean (Fig. 5A). This pattern is similar in both 1944 and 1985.

5. Discussion

There have been significant changes in the spatial characteristics of the openings in the landscape studied between 1944 and 1985. The primary differ-

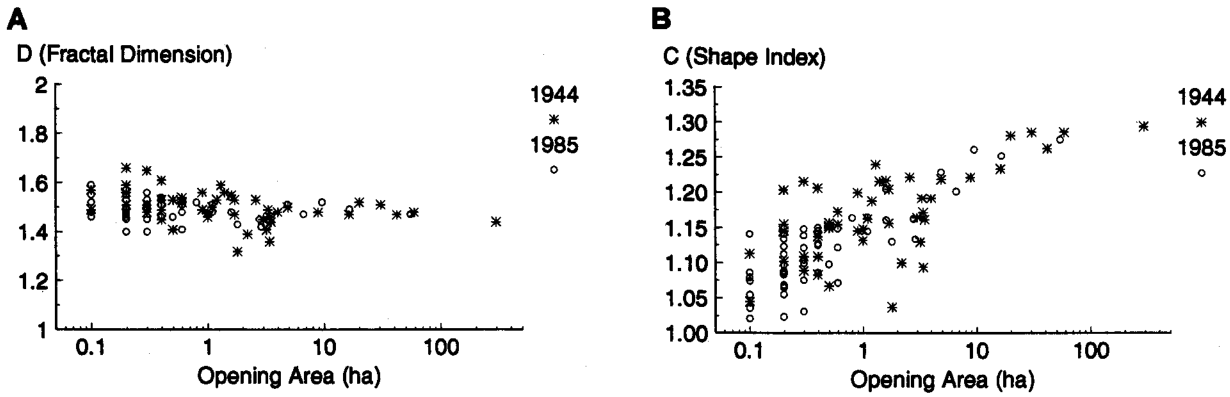

Fig. 5. Size of openings vs. A) index D and B) index C.

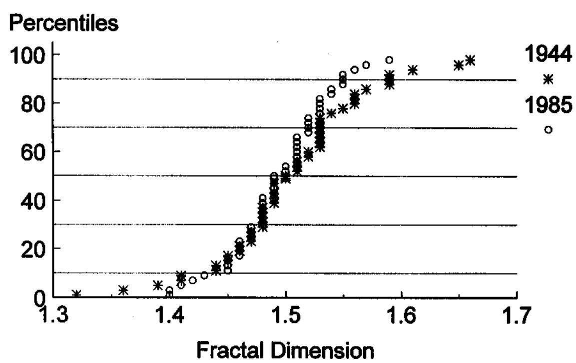

Fig. 6. Percentile plots of index D (fractal dimension) for 1994 and 1985.

ences between the characteristics in the 1944 and 1985 aerial photographs were that the openings in 1985 were smaller, with greater distance from the random sample points and between the pairs of nearest neighbors. These patterns of change are consistent with that expected under a fire suppression management regime (Kilgore 1981).

The openings did not become smaller simply by shrinking. They appear to have closed off at fingers and lobes, thus leading to fragmentation of the original openings (Fig. 7). Many of the larger openings had islands within them in 1944. By 1985 many of these islands had grown together and pinched off sections of the original opening. Thus what was a single opening in 1944, rather than just becoming a single smaller opening, often became a number of smaller openings by 1985 because of this pattern of fragmentation. As a result, both the first and second openings selected for a single point in 1985 may have been portions of a single opening in 1944. The pattern of fragmentation may account for the large increase in proportion of area in openings of the smaller sizes during the 41 yr.

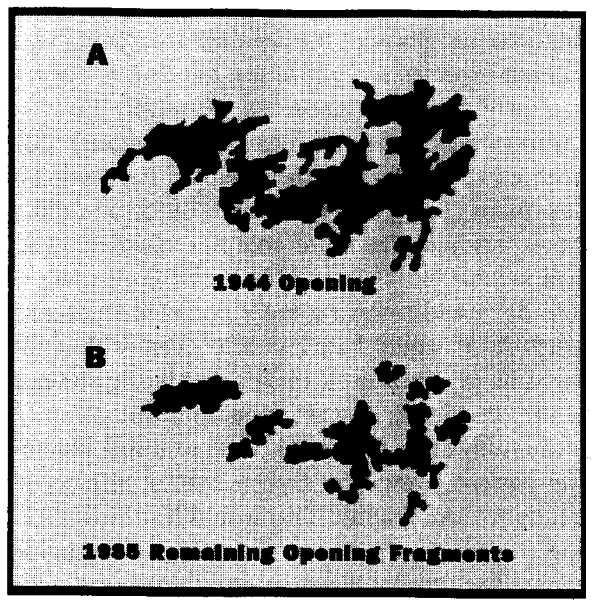

Fig. 7. Schematic representation of general pattern of fragmentation and shrinking of openings from A) 1944 to B) 1985.

Only three of the openings sampled in 1985 did not exist in 1944. One of these new openings was formed as a tree fall gap, while the other two were the result of landslides caused by the flood of 1964. All other openings measured in 1985 were remnants or fragments of those existing in 1944.

The distance from the randomly located sample points to the nearest opening and between openings increased significantly from 1944 to 1985. The increase in distance between openings along with the reduction in size and total area of openings could favor species that rely on interior habitat at the expense of those associated with edge, openings, or mosaics of habitat. The pattern of change suggests a more continuous cover of forest has developed with a finer grain and less variation in the pattern of forest and openings.

There has been little change in the complexity of the shape of the openings, at least for the openings closest to the sample points. The comparisons of I_{LF} as well as D indicate no significant change in characteristic shape of the openings measured. This was not expected in light of the removal of the influence of fire in this landscape. However, if all 100 openings are considered, there is a significant difference in I_{LF} ($P = .011$) between the two periods. The index for 1985 (1.41, $R^2 = .955$, $P < .001$) shows a somewhat more complex opening form than in 1944 (1.34, $R^2 = .938$, $P < .001$). If there is indeed a trend toward a more complex landscape structure, it would be more in concert with what might be expected in this landscape in the absence of fire. In a landscape as topographically complex as the study area, fire severity and resulting vegetation patterns would be expected to be influenced greatly by topography. This would lead to vegetation patterns more or less following topographic trends. The form of these patterns, at the scale considered in this study, would potentially be relatively simple. In the absence of fire, the vegetation patterns would be expected to be influenced more by local site conditions at a smaller scale than by the general topography.

A phenomenon observed but not measured was an apparent increase in the density of the forest canopy in stands adjacent to the openings. In the 1944 photographs it was not unusual to be able to see between the crowns of the trees to what appeared to be lower layers (shrub/herb/litter). For the same stands in the 1985 photographs it was uncommon to be able to see through the canopy to layers lower than what appeared to be an intermediate layer of hardwoods and/or young conifers. This observed change in stand density would be expected with the removal of the influence of fire (Parker 1987).

6. Conclusion

Spatial characteristics of this forested landscape have changed considerably from 1944 to 1985. Between 1944 and 1985 sizes of opening have decreased as distances between them have increased. Before the initiation of fire suppression activities, frequent fires were characteristic of landscapes in the vicinity of the study area. The changes observed are consistent with changes that would be expected when fire is removed from a landscape where frequent, low-moderate severity fire was a common ecological process. There was no detectable change in the characteristic form or shape of the openings over the 41 years. The ranges of values for all variables measured were greater in 1944 compared to 1985, suggesting a more diverse landscape mosaic in 1944 than in 1985.

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References

Agee, J.K. 1991. Fire history along an elevational gradient in the Siskiyou Mountains, Oregon. Northwest Science 65: 188–199.

Atzet, T. and Martin, R. 1992. Natural disturbance regimes in the Klamath Province. *In* Proceedings of the Symposium on

Biodiversity of Northwestern California. pp. 40–48. Edited by R.R. Harris, D.E. Erman, and H.M. Kerner. Univ. of California, Wildland Resources Center Report No. 29. Berkeley, CA.

Atzet, T. and Wheeler, D.L. 1982. Historical and ecological perspectives on fire activity in the Klamath geological province of the Rogue River and Siskiyou National Forests. USDA Forest Service, Pacific Northwest Region, Portland, OR. Pub. R-6-Range-102.

Austin, R.F. 1984. Measuring and comparing two-dimensional shapes. *In* Spatial Statistics and Models. pp. 293–312. Edited by G.L. Gaile and C.J. Willmott. D. Reidel Publishing Company, Dordrecht, The Netherlands.

Baker, W.L. 1989. Landscape ecology and nature reserve design in the Boundary Waters Canoe Area, Minnesota. Ecology 70: 23–25.

Bingham, B.B. and Sawyer, J.O., Jr. 1991. Distinctive features and definitions of young, mature and old-growth Douglas-fir/hardwood forests. *In* Wildlife and Vegetation of Unmanaged Douglas-fir Forests. pp. 362–377. Tech. Coords. L.F. Ruggiero, K.B. Aubry, A.B. Carey, and M.H. Huff. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. Gen. Tech. Rept. PNW-285.

Christensen, N.L., Jr. 1991. Variable fire regimes on complex landscapes: Ecological consequences, policy implications, and managements strategies. *In* Fire and the Environment: Ecological and Cultural Perspectives. pp. ix–xiv. Edited by S.C. Nodvin and T.A. Waldrop. USDA Forest Service, Southeastern Forest Experiment Station, Gen. Tech. Rept. SE-69.

Davis, J.C. 1986. Statistics and data analysis in geology. Second Edition. John Wiley & Sons, New York.

De Cola, L. 1989. Fractal analysis of a classified landsat scene. Photogrammetric Engineering and Remote Sensing 55: 601–610.

Edmonds, R.L. 1979. Western coniferous forests: how forest management has changed them. Biology Digest 5: 12–23.

Forman, R.T.T. and Godron, M. 1986. Landscape ecology. John Wiley and Sons, New York.

Franklin, J.F. and Forman, R.T.T. 1987. Creating landscape patterns by forest cutting: Ecological consequences and principles. Landscape Ecology 1: 5–18.

Griffith, D.A., O'Neill, M.P., O'Neill, W.A., Leifer, L.A. and Mooney, R.G. 1986. Shape indices: useful measures or red herrings? Professional Geographer 38: 263–270.

Harris, L.D. 1984. The fragmented forest: Island biogeography theory and the preservation of biotic diversity. University of Chicago Press, Chicago, Illinois.

Heinselman, M. 1978. Fire in wilderness ecosystems. *In* Wilderness Management. pp. 248–278. Edited by J.C. Hendee, G.H. Stankey and R.C. Lucas. USDA Forest Service, Miscellaneous Publication No. 1365.

Helms, J.A. 1987. Invasion of *Pinus contorta* var. *murrayana* (Pinaceae) into mountain meadows at Yosemite National Park, California. Madrono 34: 91–97.

Kilgore, B.M. 1981. Fire in ecosystem distribution and structure: western forests and scrublands. *In* Proceedings of the Conference Fire Regimes and Ecosystem Properties. pp. 58–89. Tech. Coords. H.A. Mooney, T.M. Bonnicksen, N.L. Christensen, J.E. Lotan, and W.A. Reiners. USDA Forest Service, Gen. Tech. Rept. WO-26.

Knight, D.H. 1987. Parasites, lightning, and the vegetation mosaic in wilderness landscapes. *In* Landscape Heterogeneity and Disturbance. pp. 59–83. Edited by M.G. Turner. Springer-Verlag, New York.

Krummel, J.R., Gardner, R.H., Sugihara, G., O'Neill R.V. and Coleman, P.R. 1987. Landscape patterns in a disturbed environment. Oikos 48: 321–324.

Mladenoff, D.J., White, M.A., Pastor, J. and Crow, T.R. 1993. Comparing spatial pattern in unaltered old-growth and disturbed forest landscapes. Ecological Applications 3: 294–306.

Milne, B.T. 1991. Lessons from applying fractal models to landscape patterns. *In* Quantitative Methods in Landscape Ecology. pp. 199–235. Edited by M.G. Turner and R.H. Gardner. Springer-Verlag, New York.

O'Neill, R.V., Krummel, J.R., Gardner, R.H., Sugihara, G., Jackson, B., DeAngelis, D.L., Milne, B.T., Turner, M.G., Zugmunt, B., Christensen, S.W., Dale, V.H. and Graham, R.L. 1988. Indices of landscape pattern. Landscape Ecology 1: 153–162.

Overton, W.S. 1993. Probability sampling and population inference in monitoring programs. *In* Environmental Monitoring with GIS. pp. 470–480. Edited by M.F. Goodchild, B.O. Parks, and L.T. Steyaert. Oxford University Press, New York.

Parker, A.J. 1987. Morphological divergence between conifer forests of Yosemite and Glacier National Parks, U.S.A. Arctic and Alpine Research 19: 252–260.

Parsons, D.J. and DeBenedetti, S.H. 1979. Impact of fire suppression on a mixed-conifer forest. Forest Ecology and Management 2: 21–33.

Rex, K.D. and Malanson, G.P. 1990. The fractal shape of riparian forest patches. Landscape Ecology 4: 249–258.

Savage, M. 1991. Structural dynamics of a southwestern pine forest under chronic human influence. Annals of the Association of American Geographers 81: 271–289.

Sawyer, J.O. and Thornburgh, D.A. 1977. Montane and subalpine vegetation of the Klamath Mountains. *In* Terrestrial Vegetation of California. pp. 699–732. Edited by M.G. Barbour and J. Major. John Wiley & Sons, New York.

Sawyer, J.O., Thornburgh, D.A., and Griffin, J.R. 1977. Mixed evergreen forest. *In* Terrestrial Vegetation of California. pp. 359–381. Edited by M.G. Barbour and J. Major. John Wiley & Sons, New York.

Sousa, W.P. 1984. The role of disturbance in natural communities. Annual Review of Ecology & Systematics 15: 353–391.

Swanson, F.J., Franklin, J.F. and Sedell, J.R. 1990. Landscape patterns, disturbance, and management in the Pacific Northwest, USA. *In* Changing Landscapes: An Ecological Perspective. pp. 191–213. Edited by I.S. Zonneveld and R.T.T. Forman. Springer-Verlag, New York.

Taylor, A.H. 1990. Tree invasion in meadows of Lassen Volcanic National Park. Professional Geographer 53: 457–470.

Upton, G. and Fingleton, B. 1985. Spatial Data Analysis by Example, Vol. 1: Point Pattern and Quantitative Data. John Wiley & Sons, Inc., Chichester, Great Britain.

USDA Forest Service. 1990. Baldy Fire Recovery Project: Final Environmental Impact Statement. Pacific Southwest Region, Klamath National Forest, Yreka, CA.

Vale, T.R. 1977. Forest changes in the Warner Mountains, California. Annals of the Association of American Geographers 67: 28–45.

Vale, T.R. 1981. Ages of invasive trees in Dana Meadows, Yosemite National Park, California. Madrono 28: 45–47.

White, P.S. and Pickett, S.T.A. 1985. Natural disturbance and patch dynamics: an introduction. *In* The Ecology of Natural Disturbance and Patch Dynamics. pp. 3–13. Edited by S.T.A. Pickett and P.S. White. Academic Press, Inc., San Diego.

Whittaker, R.H. 1960. Vegetation of the Siskiyou Mountains, Oregon and California. Ecological Monographs 30: 279–338.

Wills, R.D. 1991. Fire history and stand development of Douglas-fir/hardwood forests in northern California. Unpublished M.S. Thesis, Humboldt State University, Arcata, CA.