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Disturbance profile—a measure of small-scale disturbance patterns in ponderosa pine stands

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Abstract

Disturbance profiles in single unharvested, selectively harvested, and thinned stands of *Pinus ponderosa* in the Black Hills of South Dakota were compared using spatial statistics. The unmanaged stand was more dominated by closed canopy, expressed less variation in canopy density and no differences in complexity of canopy gap shapes, and uneven spread of disturbance symptoms. The biological meaning of many indices remains undefined for small scale disturbance phenomena, but their disturbance profiles could eventually be used to assess current and desired forest conditions and suggest actions to meet specific management objectives.

Keywords: Disturbance; Canopy gaps; Multipest; Disturbance interactions

1. Introduction

Canopy gaps are discrete openings in the forest canopy caused by small scale disturbances (Watt, 1947). Several previous reports have noted gap-causing disturbance agents in the Black Hills (Von Schrenck, 1903; Hinds, 1968, 1971; Lundquist, 1991a,b,c, 1993; Eckberg et al., 1994), but their influence on productivity, biodiversity, land management options, and other commodity and non-commodity forest resources is poorly documented.

Impacts of small-scale disturbances on some forest resources are easily described and measured, but other impacts are not. What, for example, are the impacts of small-scale disturbances on old-growth, and how are they recognized? Do all disturbances reduce forest health, and how are they measured and monitored? How can a desired future condition of a scenic corridor be described if small scale disturbances are desirable? If some disturbances improve forest health, how are the good ones recognized, maintained, or promoted? Descriptions of stands based on basal area, stem density, and average diameter at breast height (dbh) are adequate for making timber production decisions, but may be insufficient to make decisions regarding non-timber resources.

In the future, managers may aim at conserving disturbance processes (Baker, 1992). They will need to understand what disturbances do, how they interact, and how they are measured. New approaches for measuring the impacts of gaps on ecosystem patterns and processes are needed, particularly those associated with evaluating non-timber resources.

The spatial arrangement of gaps in a forest community affects various resources. It can, for instance, influence wildlife distribution, management unit boundary designations, and pest spread patterns (Bradshaw, 1992). Gustafson and Parker (1992) have suggested

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that quantitative spatial indices can enhance our understanding of connections between ecological patterns and processes. Spatially defined data show where disturbances are absent as well as where they occur.

Several indices describe and measure spatial characteristics (Forman and Godron, 1986). These indices have mostly described landscape-scale phenomena. Spatial statistics have not been widely used at smaller scales. Only a modest amount of work has been done on the biological meaning of spatial statistics at small scales. Even less effort has been aimed at determining how management could make use of them.

The objective of this exploratory study was to examine the utility of spatial analysis on a small scale, and to propose a multivariate integrative measure called "disturbance profile". Various descriptive indices were used to contrast disturbance activity in one unharvested plot and two previously harvested plots.

2. Materials and methods

2.1. Study sites

This study was conducted on the Custer District of the Black Hills National Forest in South Dakota. Three stands of *Pinus ponderosa* Douglas ex P. Laws were chosen to represent some extremes in management activities found on this forest (Fig. 1).

(1) Upper Pine Creek Research Natural Area (UPC)—a 475 ha area located 8 km west of Mt. Rushmore National Monument (T2SR5E Sec 15) composed of unharvested stands on sites long protected from wildfires. Average stem = dbh 29.76 cm, stem density = 437 stems ha^{-1} (sph), basal area (BA) = 30 m^2 ha^{-1}.

(2) Palmer Creek (PC)—an 80 ha area within the Norbeck Wildlife Preserve, approximately 2 km west of the UPC (T2SR5E Sec 8) composed of stands selectively harvested before 1960. Average stem dbh = 37.21 cm, stem density = 190 sph, BA = 20 m^2 ha^{-1}.

(3) Fourcorners (FC)—an approximately 40 ha area, 15 km west of the UPC (T2SR3E Sec 7). Stands in FC were commercially thinned in 1991 as part of a two-step shelterwood with intermediate thinning (Black Hills National Forest Plan, in review). Average stem dbh = 36.88 cm, stem density = 131 sph, BA 15 = m^2 ha^{-1}.

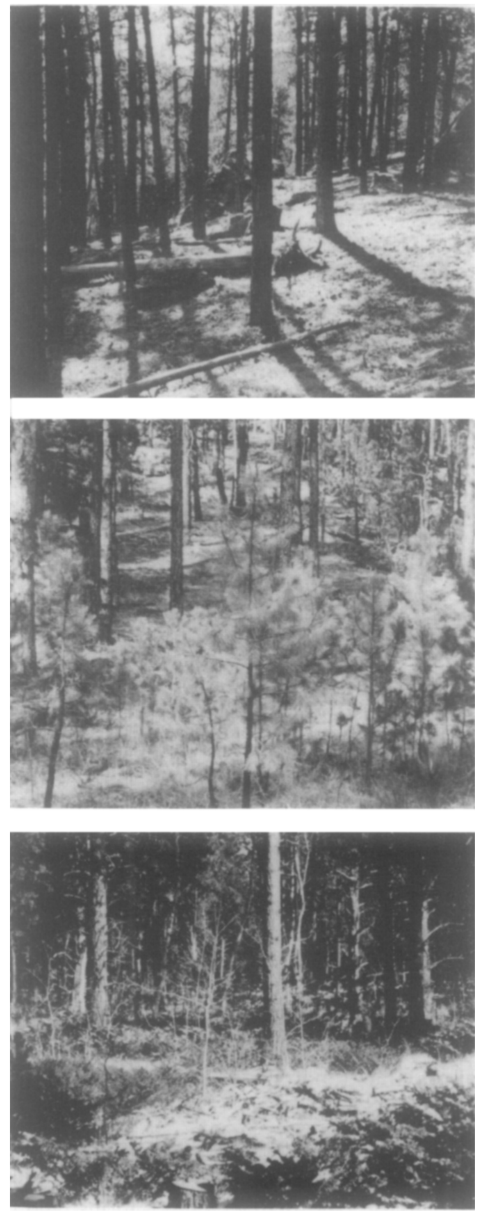

Fig. 1. Scenes representative of the three stands examined in this study. Top: the Upper Pine Creek Research Natural Area in which stands were not previously harvested. Middle: the Palmer Creek area in which stands had been selective harvested several years previously. Bottom: the Fourcorners area in which stands had been recently thinned.

In a companion study of these stands, Lundquist (1995) describes the interactions among disturbance

Table 1
Comparison of various measures of gap characteristics for Upper Pine Creek, Palmer Creek, and Fourcorners [a]

Index		UPC	Palmer	Fourcorners
Ave. stem diameter	(cm)	29.8	37.2	36.9
Stem density	(stems ha^{-1})	437	190	131
Basal area	(m^2 ha^{-1})	30	20	15
Gap frequency	(g ha^{-1})	26	57	36
Mean gap diameter	(m)	13.6	11.3	17.3
Skewness (gap dia. distr.)	(g_1)	0.6	1.1	1.2
Kurtosis (gap dia. distr.)	(g_2)	−0.7	−0.1	2.0
No. cause pathways		68	45	33
Shannon–Weaver (causes)	(H')	8.8	4.6	5.1
Snag frequency	(snags ha^{-1})	211	183	267
Log frequency	(logs ha^{-1})	214	211	194
Ave. densiometer	(%)	84	66	36
Skewness (densio. distr.)	(g_1)	−1.4	−1.3	0.8
Kurtosis (densio. distr.)	(g_2)	5.9	4.3	2.7
Shannon–Weaver (densio.)	(H')	0.7	1.3	1.4
Dominance	(c)	0.7	0.3	0.3
Contagion	(C)	2.0	1.9	1.7
Number of edges		218	327	139
Ave. gap area	(no. 100 m^2 cells)	3.2	12.6	2.0
Fractal dimension	(D)	1.3	1.4	1.3
Variogram sill	(semivariance)	133	177	444
Variogram range	(lag distance)	26	28	9

[a] Lundquist (1995).

agents, and their association with gaps, snags and other coarse woody debris. Table 1 lists several statistics calculated in that study, including average stem diameter, stem density, basal area, gap frequency, mean gap diameter, skewness of gap diameter distribution, kurtosis of gap diameter distribution, number of disturbance pathways, diversity of disturbance pathways, snag frequency, and log frequency.

2.2. Spatial profile

A 4 ha plot (200 m×200 m) overlaid with a 10 m×10 m grid was established within each stand. Plots were located at random, except that they were placed where no major rock outcrops, meadows, or other non-killing gap-causing agents might have prevented canopy development. At each grid coordinate, an optical densiometer reading representing canopy density was made using procedures described by Grifting (1985). A total of 400 readings was recorded in each 4 ha plot.

Variograms were generated from the spatial data for each site using GS+ (Gamma Design Software). Variograms are numerical models of spatial dependence (Isaaks and Srivastava, 1989) and are calculated using

$$V(h)=1/(2n(h))\sum[Z(x_i)-Z(x_i+h)]^2$$

where $V(h)$ is semivariance, h is distance between sample points (lag), n is the number of observations, $Z(x_i)$ is the value of the variable at x_i, and $Z(x_i+h)$ is the variable value at h distance from x_i. Variograms were subsequently used for kriging (Myers, 1991) and composing two-dimensional diagrams (patterned isopleths). Patterned isopleths were used to illustrate the two-dimensional spatial pattern of canopy density over the plots. In addition, response surface diagrams and contour maps were generated with SYSTAT (Systat Inc., Evanston, IL) and PSI PLOT (Poly Software International, Salt Lake, UT).

Data were summarized for the entire plot using the Rocky Mountain Spatial Analysis Program (Curtis Flather, Rocky Mt. Forest and Range Experiment Station, Fort Collins, unpublished). For this program, densiometer readings were converted to three classes of canopy density: open (0–60% canopy density), intermediate (61–75%), and closed (76–100%). The following spatial statistics were calculated.

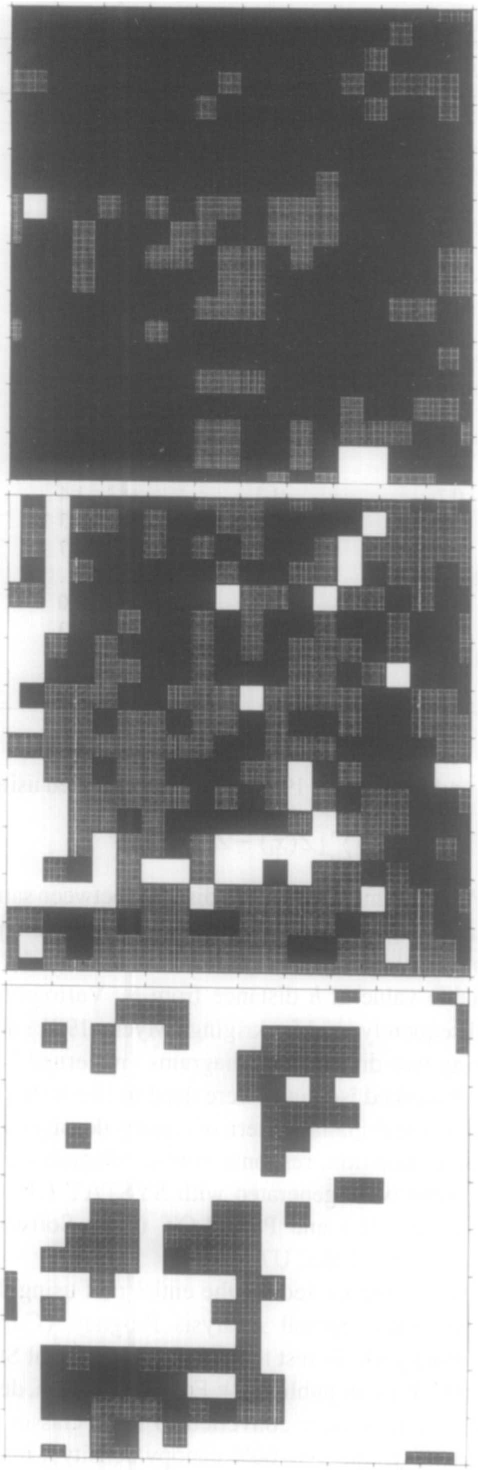

Fig. 2. Pattern isopleth based on canopy closure (densiometer readings) in plots at Upper Pine Creek RNA (top), Palmer Creek (middle) and Fourcorners (bottom). Relatively light squares correspond to relatively open sections of canopy.

(a) Fractal dimension (D) was calculated using the perimeter–area relationship

$$D = 2ln(0.25P)/lnA$$

where A is gap area, P is gap perimeter, and D is fractal dimension (McGarigal and Marks, 1993). Fractal dimension is a measure of gap shape complexity (Stewart, 1989). Values range from 1 to 2. Landscapes with higher numbers of gaps with complex shapes have correspondingly higher fractal dimension values. Patch shape influences various edge effects, such as animal movement, recolonization by vegetation, and possibly animal foraging (McGarigal and Marks, 1993).

(b) Dominance (c) was calculated using

$$c = \sum (n_i/N)^2$$

where n_i is the number of cells within the sample grid in canopy density class i and N is the total number of cells assessed. Dominance is a measure of the degree to which one or a few canopy density classes dominate the landscape (Simpson, 1949). At high c values, one or a few density classes dominate the landscape. At low values, canopy density is more evenly distributed among classes. Stands range along a continuum from closed to open. The greatest amount of edge occurs somewhere between.

(c) Contagion (C) was calculated using

$$C = [K_{\max} + \sum\sum q_{i,j} log(q_{i,j})]/K_{\max}$$

where $q_{i,j}$ is the number of cells of canopy density class i that are next to those with density class j. $K_{\max}$ is a constant, 2.77. Contagion is a measure of cell clustering (Gustafson and Parker, 1992). Values range from 0 (even distribution) to 1 (clumped distribution). Contagion indicates grouping of disturbance processes within a stand. This distribution may result from larger spatial scale phenomena such as landscape characteristics, locations of predisposing factors, spread in time of a disturbance, and others.

(d) Variograms. Variogram values commonly increase with increasing distance between sample points (lag) from the y-intercept (nugget) to a plateau (sill). Curve shape and certain critical values of the variogram have been used to describe spatial properties of data (e.g. Cohen et al., 1990). Range is the lag distance coinciding with the sill, which defines the distance over which data are spatially correlated. Sill measures spatial heterogeneity and is approximately

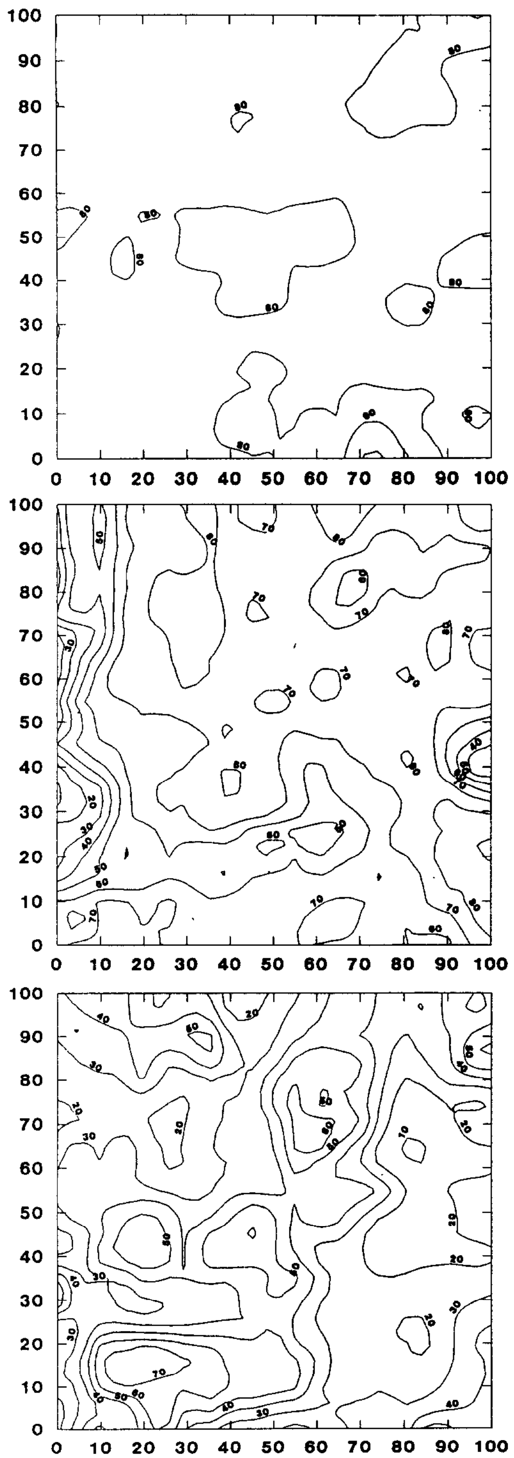

Fig. 3. Contour maps showing distribution of canopy openness at Upper Pine Creek RNA (top), Palmer Creek (middle) and Four-corners (bottom).

equivalent to sample variance. Nugget indicates the unexplained variance in the system. Isaaks and Srivastava (1989) describe variograms in more detail. In this study, variograms were calculated using GS+. To reveal differences in spatial continuity with direction, directional variograms were computed in 45° increments with $a = \pm 22.5°$ non-overlapping tolerance.

(e) Shannon–Weaver Index of General Diversity. An index of heterogeneity calculated using

$$H' = -\sum (n_i/N) log(n_i/N)$$

where n_i is the number of cells within the sample grid in canopy density class i and N is the total number of cells assessed (Shannon and Weaver, 1949). Of the many different indices of vegetation diversity, the Shannon–Weaver Index of General Diversity is perhaps the best-known and most commonly used (Odum, 1971).

(f) Number of edges. This index represents the number of edges between grid cells, where cells differ in canopy density class. Higher values correspond to greater structural diversity in the canopy. The amount of edge in a stand influences many ecological processes (Bradshaw, 1992). Many animals, for example, depend on the edge environment for feeding, reproduction, cover, and growth (Bradshaw, 1992).

(g) Gapped area. The total number of grid cells with canopy density values below 60%. This index is an indirect measure of the activity of disturbance processes within a stand. It shows the balance between disturbance processes that destroy canopy and recolonization processes that fill the gaps.

(h) Kurtosis of the densiometer distribution curve. This index indicates the relative representation of different crown classes. High values mean a balanced mix; low values mean that limited numbers of canopy classes dominate. Kurtosis is, in a sense, a measure of balance disturbance activities are within a stand.

(i) Skewness of the densiometer distribution curve. Positive values show that peaks of high frequency occur at low values within the densiometer distribution (i.e. an open stand). Negative values show that peaks occur at high values (i.e. a closed stand). Skewness is similar to dominance.

3. Results

Graphic indices varied among plots. Patterned isopleths showed spatial patterns that varied within and among plots (Fig. 2). UPC had mostly closed canopy with gaps composed of intermediate and low densities. Fourcorners showed a mostly open stand with islands of canopy. Palmer Creek showed a more equal distribution of the three canopy classes, but a more complex spatial pattern. Contour plots of UPC suggested much less relief than PC or FC (Fig. 3). Similarly, the surface diagram for UPC was relatively high and flat surfaced (Fig. 4). Fourcorners was low with a wavy surface.

Densiometer class distributions varied among sites (Fig. 5). Distribution curves for UPC and PC showed single peaks at 100% and 80%, respectively. The distribution curve for FC showed a bimodal distribution with peaks at 30% and 60%. These distributions mirrored average densiometer reading, skewness, and kurtosis values (Table 1). Furthermore, H' based on canopy density readings was less at UPC than the other stands.

Dominance varied from 0.26 to 0.66 at FC and UPC, respectively (Table 1). Closed canopy dominated at UPC. Contagion varied from 1.68 to 2.03 at FC and UPC, respectively. Canopy at FC was less clumpy than at other sites. Number of gap edges was greatest at PC and lowest at FC. Correspondingly, the average gap area was greatest at PC and lowest at FC. Fractal analysis suggests that these stands differed little in shape of gaps.

The omnidirectional variogram for UPC shows a spherical curve that rises from 69 (nugget) to a plateau of 133 (sill) at 26 m (range) (Fig. 6). For Palmer Creek, the variogram shows a linear curve rising from 177 (nugget) to 295 (sill) at 28 m (lag); the variogram seems to rise again beginning at 40 m, without reaching a plateau. This suggests a trend in mean and variance values across the plot larger than the maximum lag distance. The variogram for FC rises from 52 (nugget) to 444 (sill) at 28.5 m (lag).

Directional variograms show that spatial continuity varies with direction (Fig. 7). This directional dependence is most marked at FC. Zero and 45° variograms

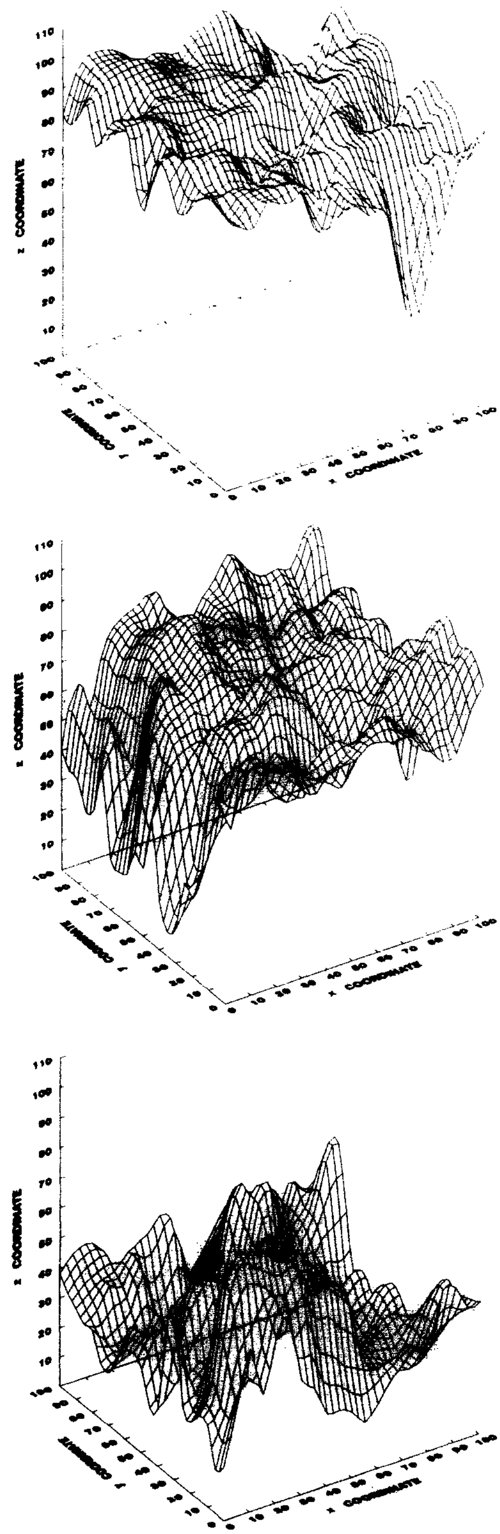

Fig. 4. Response surface diagrams showing canopy openness (z axis) and grid location (x,y coordinates) for Upper Pine Creek (top), Palmer Creek (middle) and Fourcorners (bottom).

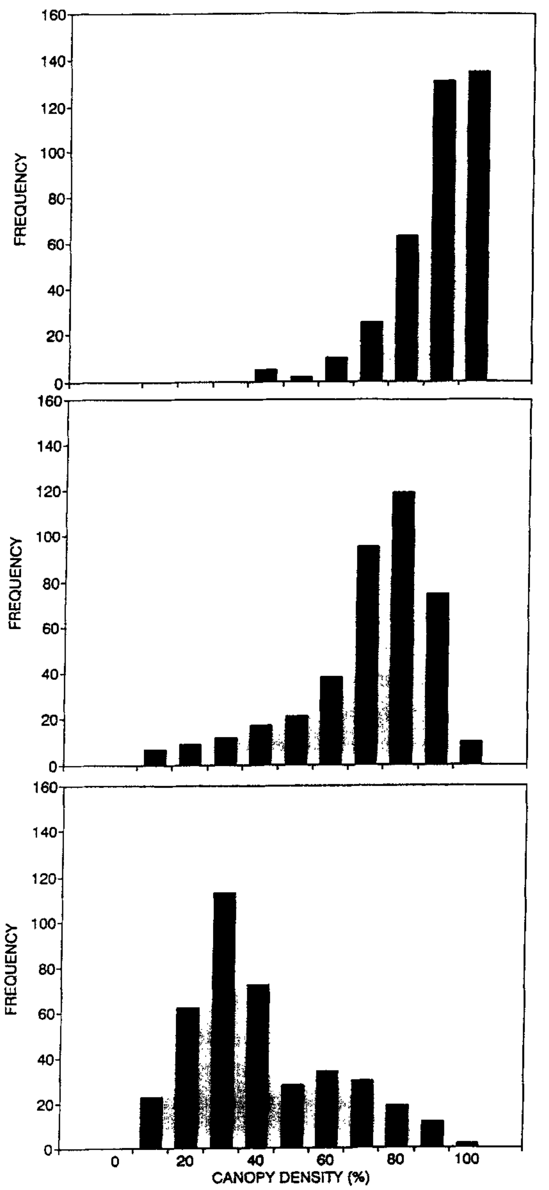

Fig. 5. Distribution of densiometer readings for grid plots at Upper Pine Creek (top), Palmer Creek (middle) and Fourcorners (bottom).

for FC show that multiscale spatial phenomena are present in those directions, and the 135° variogram shows increasing spatial dependency after reaching a low at around lag 26 m.

4. Discussion

Many definitions of canopy gap exist (Runkle, 1992), probably because gaps are surprisingly difficult to identify in the field. Spatially referenced data enable the application of landscape analysis tools such as GIS and geostatistics. These tools enable us to quantify characteristics of canopy gaps. Variography and other geostatistical techniques, for example, are useful for quantifying spatial correlation between points in space and for interpolating among sample points (Isaaks and Srivastava, 1989). In this study, variography was used to generate patterned isopleths. Forest managers could use these data to find the spatial scale appropriate for conserving disturbance processes, or to determine whether multiple scale phenomena are operating. Patterned isopleths would display the abundance and spatial distribution of canopy gaps across the site. Isopleths could be used as maps to locate gaps because they minimize subjective decisions in the field.

In this study, gaps were defined as 100 m^2 cells with 60% or less canopy density within the patterned isopleth. The choice of a threshold of 60% was subjective. Thresholds undoubtedly vary with stand type, harvest history, management objective, and other management considerations. More systematic methods of identifying unusual attribute values or grid cells exist. Berry (1987), for example, describes a standard normal variable, which is calculated using

$$SNV = [(X_{obs} - X_{mean}) / X_{sd}] \times 100$$

where SNV is the standard normal variable, X_{obs} is a single densiometer reading within the plot, X_{mean} is the average densiometer reading for all readings on a plot,

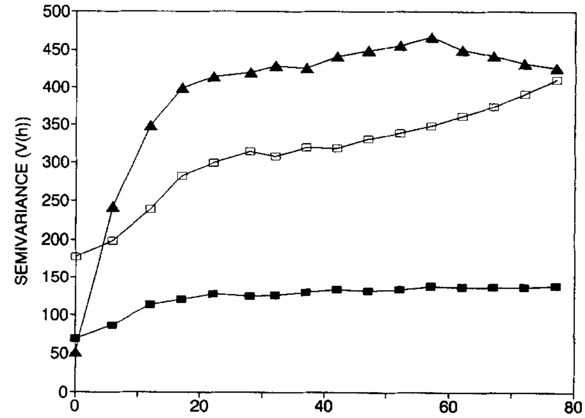

Fig. 6. Omnidirectional variograms (Isaaks and Srivastava, 1989) associated with densiometer readings at Upper Pine Creek (■), Palmer Creek (□) and Fourcorners (▲).

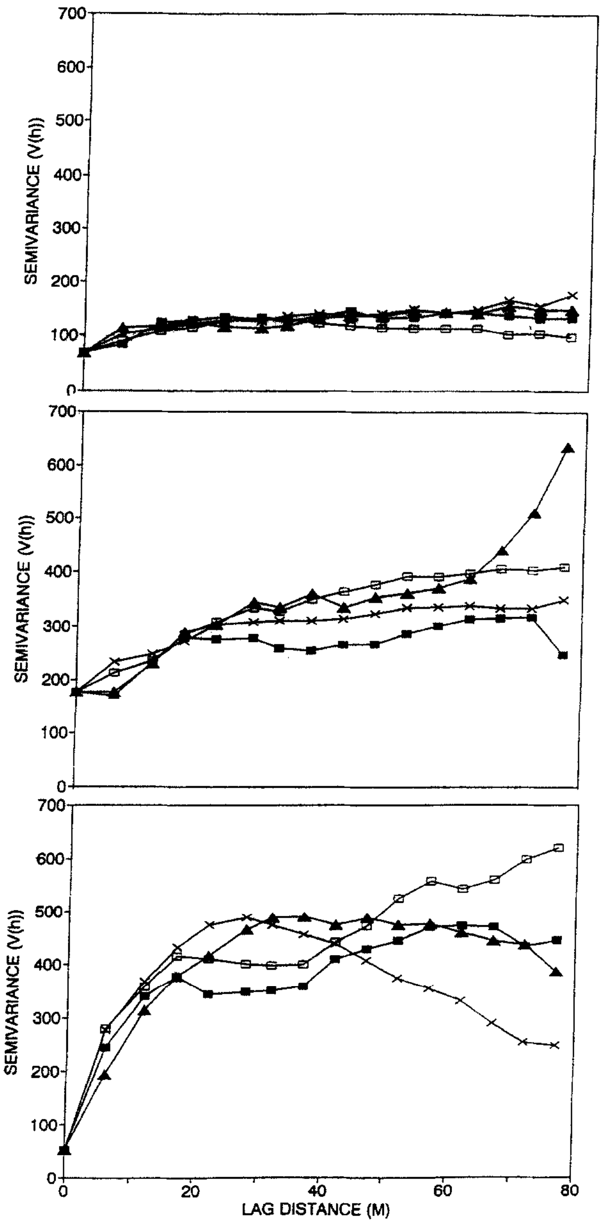

Fig. 7. Directional variograms (Isaaks and Srivastava, 1989) associated with densiometer readings at Upper Pine Creek (top), Palmer Creek (middle) and Fourcorners (bottom). ■, 0°; □, 45°; ▲, 90°; X, 135°.

and X_{sd} is the standard deviation of the mean densiometer reading for a plot. Standard normal variable values below -1.0 indicate subnormal conditions. Similarly, this variable might be used to formalize the definition of gap.

Results of this study indicate that various univariate, bivariate, and spatial statistics can systematically quantify many differences among variously disturbed stands. Specifically, the unmanaged stand examined in this study differed from the two previously harvested stands because it had the following characteristics.

(1) Less variation in canopy density (as measured by the Shannon–Weaver index for canopy density, variogram sill, patterned isopleths, contour maps, response surface diagrams).

(2) A more closed canopy (dominance, number of gap edges, number of gaps, average gap area, patterned isopleth, contour map, response surface diagram). A gap-dominated canopy structure characterized the moderately harvested stand, while tree-islands dominated the heavily managed stand.

(3) A more complex network of disturbance processes (number of disturbance pathways and Shannon–Weaver index based on disturbance pathways).

(4) A more complex collection of standing dead trees (Shannon–Weaver of snags).

(5) A more uneven spread (contagion, kurtosis) of disturbance symptoms across space. Furthermore, the unmanaged stand had a denser canopy (average densiometer readings, skewness) and larger gap size (average gap diameter, variogram range), but showed no differences in complexity of gap shape (fractal dimension).

(6) Less spatial dependency, as an artifact of harvesting (directional variograms). In other words, tree cutting not only reduced the number of trees, but gave their distribution a directional bias.

(7) Smaller scale of spatial dependence (omnidirectional variogram, variogram range). Tree cutting increased the distance over which disturbance phenomena were related.

The indices used in this study represent only a small selection of the known spatial statistics (Geils, 1992; Reich and Geils, 1993). Cullinan and Thomas (1992), for instance, describe indices based on various tests for non-randomness. These tests include estimations based on transect intersections, variance vs. block size, Lefkovitch's index, spectral analysis, variance ratio plots, and others. Similarly, Gustafson and Parker (1992) use a patch elongation index based on percolation theory, a linearity index based on the medial axis transformation skeleton, and indices based on nearest neighbor analyses, patch size, and perimeter size. The

Table 2
Hypothetical spatial index values associated with stands managed for two different management objectives. Bird habitat: managed to maintain the habitat of a raptor that nests in parts of the forest with continuous canopy and feeds on small mammals that live at the edge of large gaps. Scenic corridor: managed to maintain visual diversity

Spatial indices	Bird habitat		Scenic corridor	
	Range of natural variability	Actual values	Range of natural variability	Actual values
Dominance	2–3	2.23	1–2	1.5
Fractal dimension	2.5–2.7	2.56	2.5–2.9	2.7
Contagion	2.5–3.0	2.0(low)	1–2	1.5
Ave. gap area	15–20	16	10–15	25(high)
Variogram range	400–500	450	400–500	300(low)
Number of edges	50–75	90(high)	150–250	300(high)
Number of gaps	10–15	11	20–30	25
Shannon–Weaver	1–2	1.12	3–4	2(low)
Variogram sill	15–25	16	15–25	16
Others				

work of many others has established a rich variety of spatial statistics (Turner and Gardner, 1990).

Single indices describe limited portions of the disturbance regime. Complete descriptions require multiple indices. Furthermore, a range of values, similar to range of natural variability suggested by Monnig and Byler (1992), probably defines optimum levels for individual indices. Baker (1992) suggests that probability density curves and standard summary statistics for a set of "essential" attributes (e.g. type, size, intensity, severity, timing, edge, and orientation) best characterize disturbance regimes.

In this study, a unique combination of index values (called disturbance profile) characterizes the disturbance regime of each stand. Disturbance profiles are multivariate parameters that integrate spatial and non-spatial statistics. Multivariate statistical methods could be used to define and quantify disturbance profiles for various management objectives and to establish desired conditions and monitoring criteria. Different stands could be compared using multivariate statistical techniques (Dillon and Goldstein, 1984).

Disturbance profiles could eventually provide a basis for forest planners to assess the current and desired condition of a forest. The combination of indices that defines a desired condition will undoubtedly vary with management objective, forest type, geographic location, management history, and other factors.

For example, a bird that nests in continuous canopy stands and feeds on small mammals at the edge of large gaps might require a stand with high dominance, fractal dimension, contagion, average gap area, variogram range, low number of edges and gaps, moderate Shannon–Weaver, and variogram sill. In contrast, a scenic corridor managed for visual diversity might require a stand with high Shannon–Weaver, fractal dimension, variogram sill, number of edges, number of gaps, and variogram range, relatively low dominance and contagion, and moderate gap area. The desired condition for maintaining these resources might require forest landscapes having a combination of index values (or disturbance profile) falling within the hypothetical ranges of natural variability shown in Table 2.

Ranges of natural variability and disturbance profiles would be developed by research and described in the Forest Plan. A forest manager would inventory the above stands to establish their current disturbance profiles. The current profile would be compared to the desired profile to decide whether adjustments were necessary or whether objectives should be changed. Adjustments would be made by modifying selected small scale disturbances (e.g. introducing or eliminating a disease or insect population, applying prescribed burns, harvesting trees) or adjusting predisposing factors.

A manager would evaluate the probable responses of various management alternatives using spatially referenced predictive models based on disturbance profiles (Lundquist et al., 1993). He might base a decision, in part, on the disturbance profiles of surrounding stands. Predictive models could be used to determine the long term dynamics of resource distribution and availability among these stands.

5. Conclusions

The assessment methods currently available to forest decision makers are inadequate to deal with the mix of resources they will manage in the future. Inventory and monitoring should describe current conditions and future trends based on ecosystem complexity. Non-spatial indices such as basal area, stem density, site quality, and average stem diameter provide information for timber production, and can describe only part of the complexity of forest ecosystems. Spatial indices complement non-spatial indices, and may be useful for managing stands to maintain ecosystem diversity (Mladenoff et al., 1993) or to establish management prescriptions aimed at non-timber resources. Spatial statistics will undoubtedly become more important as the use of GIS increases and as the software necessary for calculating these statistics becomes more accessible.

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