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Characterizing disturbance in managed ponderosa pine stands in the Black Hills

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Abstract

Spatial indices were used to characterize 12 stands representing the range of management activities found in the Black Hills of South Dakota. Canopy gaps within each stand were assessed for cause and for states of snag and log decomposition. Causes of gaps were characterized as pathways involving predisposing factors, killing agents, and tree responses. Management intensity was inversely correlated to number of pathways. Diversity of disturbance pathways within stands was positively correlated with several indices of canopy variability based on crown density. Cluster analysis using these indices grouped the 12 stands into six clusters based on disturbance profiles. Although the biological meaning of these clusters requires further research, this technique offers a way to summarize and compare disturbance complexes within stands.

Keywords: Geostatistics; Spatial analysis; Disturbance profile; Gap dynamics

1. Introduction

Diseases, insects, fire, storms, and other disturbance agents interact to alter the structure and function of forest ecosystems (Van der Kamp, 1991; Haack and Byler, 1993). Logging, cattle grazing, recreation, fire suppression and other management practices can contribute, even exacerbate, the activities and interactions of disturbance agents. Fire suppression in the Black Hills of South Dakota, for example, has markedly increased stand density throughout forest stands (Progulske, 1974) with a corresponding increase in susceptibility to mountain pine beetle infestation (Sartwell and Stevens, 1975; Schmid and Mata, 1992). Shelterwood silviculture with intermediate thinning, commonly practiced in the Black Hills since 1956 (Boldt et al., 1983) has likely enhanced the activity of Armillaria root disease (Lundquist, 1991), and correspondingly increased susceptibility to bark beetles (Filip, 1989; Stanosz and Patton, 1990; Gregory et al., 1991).

In a recent study in the Black Hills, Lundquist (1995) described the disturbance status of stands with three management histories using indices based on canopy structure, disturbance pathway composition, and the status of snags and logs. Observations from that study suggested that effects of various combinations of disturbance agents (including tree harvesting) on the forest ecosystem could be quantified using combinations of indicator indices, referred to as 'disturbance profiles'. Lundquist hypothesized that disturbance profiles might be useful to forest planners in measuring current stand conditions, describing desired conditions, and establishing ecosystem scale standards and guidelines. Although too few stands were studied in that descriptive study to draw firm conclusions, the results suggest the following alternative hypotheses:

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Table 1
Management history and other characteristics of study sites used in this study. Data obtained from National Forest System database in the Custer Ranger District files

Stand	Age (years)	Size (ha)	Management emphasis[a]
U818	86	34	Uncut, old growth; 4B
U1146	98	36	Uncut, uneven-aged; 5C
U908	100	91	Uncut, old growth; 4B
U184	90	15	Uncut, old growth; 4B
S129	64	50	Shelt seed cut 7/92; 5B
P312	56	32	Precom thin 9/92; Comm thin 6/89; 7A
P905	76	23	Precom thin 9/83; 4B
C315	62	35	Thinned 1992; 7A
S503	105	40	Seed cut 1992; 7A
S146	106	43	Shelt seed cut 9/92; 5B
S804	100	35	Seed cut 4/82; 7A
S1103	109	23	Shelt seed cut 12/81; 7A

[a] 4B, Norbeck Wildlife Preserve; 5B, Wildlife Winter Range; 5C, Wood Fiber Production; 7A, Wood Fiber Production with Grazing (Black Hills National Forest, 1994).

(1) the diversity of disturbance pathways influences structural heterogeneity of the forest vegetation;

(2) the diversity of disturbance pathways influences the abundance and composition of snags and downed logs;

(3) the intensity of management influences structural heterogeneity in the forest vegetation;

(4) the intensity of management influences the diversity of disturbance pathways in the forest vegetation;

(5) individual stands can be categorized and classified on the basis of their disturbance profile.

In the study described below, 12 stands with a range of management histories were used to test these five hypotheses.

2. Methods and materials

2.1. Study sites

This study was conducted on the Custer District of the Black Hills National Forest. Forest managers were asked to select a set of stands representative of the range of management activities practiced in that forest. *Pinus ponderosa* Douglas ex P. Laws stands representing each of the following treatment combinations were chosen: (1) no previous tree harvests (four stands); (2) thinned within last 2 years (two stands); (3) thinned more than 10 years ago (two stands); (4) seed tree harvested less than 2 years ago (two stands); (5) seed tree harvested more than 10 years ago (two stands) (Table 1). Descriptive statistics for these stands were obtained from the National Forest System database at the Custer District Office.

2.2. Field assessments of plots

To develop disturbance profiles, one 4-ha plot was placed in each stand. Each plot was composed of a 10 m × 10 m grid. At each grid intersection, an optical densiometer reading (0–100%) was taken (Grifting, 1985), for a total of 400 readings. Variograms for each plot were generated from these data using GS+ (Gama Design Software). A variogram is a model of spatial dependence of canopy density (Isaaks and Srivastava, 1992), which was used in this study for kriging (Myers, 1991) and composing patterned isopleths. A patterned isopleth is a checkerboard-like two-dimensional diagram composed of 400 cells, each representing an area of 100 m^2 (10 m × 10 m). Patterned isopleths represent a visualization of the spatial variation of canopy density over the plot (Lundquist et al., 1994).

Canopy gaps were defined as cells within the isopleths or groups of cells with a standard normal variable less than -1.0 (Berry, 1987). Standard normal variable was calculated using

Table 2
Disturbance profiles of each stand assessed in this study. Individual indices are explained in text

Index	Stand no.											
	U184	U908	C315	U818	U1146	P905	P312	S129	S1103	S146	S804	S503
BAPREV	32	32	21	30	30	25	21	29	22	26	30	13
BACUR	32	28	21	25	25	21	19	19	13	16	16	7
BADIF	1	18	2	2	22	17	12	41	42	45	45	28
AVEDENS	77	76	75	67	66	65	62	43	41	37	32	31
GAPERC	7	0	13	3	3	5	7	43	49	63	69	75
GAPAREA	7	0	15	3	3	6	7	43	49	63	69	75
STUMP	1	2	12	0	66	97	391	128	280	310	280	279
TOTEDGE	83	90	112	95	91	100	108	113	95	103	117	100
GAPEDGE	11	0	40	10	10	15	16	77	73	88	100	85
GAPFREQ	6	4	5	5	5	9	7	2	1	2	1	1
VARANGE	14	2	1	5	92	61	72	69	84	26	41	5
SNAGFREQ	8	12	3	4	7	7	20	4	13	18	9	0
LOGFREQ	15	37	22	14	77	147	387	70	251	562	166	149
HDENSIO	1.1	0.8	1.2	1.0	1.0	1.1	1.2	1.5	1.1	1.2	1.4	1.3
HSNAG	1.1	1.1	0.7	1.2	0.4	0.3	0.2	0.1	0.2	0.2	0.2	0
HLOGS	1.1	0.1	1.1	1.2	0.8	1.3	0.9	0.8	0.8	0.8	0.4	1.0
FRACDM	1.4	1.3	1.2	1.2	1.3	1.2	1.3	1.3	1.4	1.4	1.3	1.4
VARSILL	267	39	682	74	71	116	166	498	107	151	237	122
DOMINAN	0.5	0.3	0.4	0.6	0.4	0.6	0.4	0.1	0.5	0.4	0.3	0.3
EDGETYPE	10	3	10	9	6	8	8	10	8	10	10	9
CONTAG	2.5	0.9	1.4	3.6	1.8	3.8	3.5	1.3	3.1	2.0	1.4	2.0
SKEWDENS	−1.8	−0.5	−0.9	−1.0	−0.4	−0.8	−0.4	0.2	1.0	0.8	0.7	1.1
KURTDENS	2.8	0.3	−0.3	1.8	−0.1	0.4	0.5	−0.8	1.2	0.6	−0.3	0.5
CVDEN	0.3	0.1	0.4	0.2	0.2	0.2	0.3	0.6	0.4	0.4	0.6	0.6

$$SNV = (X_{obs} - X_{mean}) / X_{sd}$$

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, and X_{sd} is the standard deviation of the mean densiometer reading for a plot.

For some of the analyses described below, data were pooled for stands with similar canopy density means. Welch's test for groups with heterogeneous variances (Milliken and Johnson, 1984) and Dunnett's T3 multiple comparison procedure (Dunnett, 1980) were used to discern stands with significantly ($P < 0.05$) different densiometer means.

Field assessments were conducted using methods developed by Lundquist (1995). Briefly, variable plots were established at 20 m intervals (every alternate grid intersection) using a basal area factor (BAF) of 2.5 $m^2 ha^{-1}$ to characterize current stand conditions within each 4 ha plot (described below). Species, diameter at breast height (dbh), and decomposition condition were noted for all trees, snags, and cut stumps within each plot. Basal area, stem density and quadratic mean diameter were calculated (Husch et al., 1972). To determine preharvest conditions, cut stumps were tallied and analyzed as if stems were still attached and stump surface diameter was used as an approximation of dbh.

Patterned isopleths were used in the field as maps to relocate individual gaps, which were then assessed, as described below, for: (1) cause, predisposing conditions, and associated tree responses, and (2) abundance and condition of standing snags and downed coarse woody debris.

2.3. Assessment of disturbance pathway diversity

A group of scientists conferred at each gap in the field to determine the most likely predisposing agents (non-genetic agents that enhance susceptibility to killing agents), killing agents (the agents that actually killed the trees), and gapmakers or the tree response that resulted in the canopy disturbance (e.g. death, windthrow). Preliminary studies identified the following predisposing factors: fire, cattle grazing, shallow soil, tree harvesting, destabilization caused by changes in stand structure, and suppression. The following killing agents were identified: lightning, fire, tree harvesting, mechanical damage, bark beetles, root rot, wind, neighboring tree fall, weak parasites and pathogens, and ice and snow build-up. The following gapmakers were identified: shattered stem, burned stem, tree removal, standing dead, broken stem, butt snap, uprooting, and tree push.

The relative activity of each pathway was the proportional area over which specific pathways occurred on the plot, using

$$\text{ACTIVITY}_{a,b,c} = \sum \text{AREA}_{a,b,c}/40\,000\ \text{m}^2$$

where $\text{AREA}_{a,b,c}$ is the area of all gaps with pathway a, b, c, $\text{ACTIVITY}_{a,b,c}$ is the activity of pathway a, b, c; a is predisposing factor a, b is killing agent b, and c is gapmaker c.

Diversity of disturbance pathways was based on frequency of different disturbance pathways within all gaps within each plot and summarized as number of causal pathways (CAUSNO) and as the Shannon–Weaver Index (HCAUSE) (Odum, 1971).

The relationship between harvest history (average densiometer reading, number of stumps, or change in basal area) and disturbance diversity (number of causal pathways) was examined with linear regression analysis.

Table 4
Results of Dunnett's T3 multiple comparison procedure for average densiometer readings of plots used in this study

Stand	Ave. densiometer (±SD)	Harvest intensity
U184	77 (±18)	None
U908	76 (±9)	None
C315	75 (±25)	Low
U818	67 (±12)	None
U1146	66 (±12)	None
P905	65 (±13)	Low
P312	62 (±14)	Low
S129	43 (±24)	High
S1103	41 (±13)	High
S146	37 (±15)	High
S804	32 (±19)	High
S503	31 (±19)	High

2.4. Assessment of snag and log decomposition

Each snag (over 12 cm dbh and more than 1 m in height) and downed log (over 12 cm at widest end and more than 2 m in length) within gaps was scored for decomposition class using diagrams developed originally for spruce/fir forests in the Pacific Northwest (Maser et al., 1979; Thomas et al., 1979), and modified by the author for ponderosa pine in the Black Hills (Lundquist, 1995). Snag classes were living (1), declining (2), new dead (3), old dead (4), loose bark (5), no bark (6), broken stem (7), butt snap (8), cut stump (9), and windthrow (10). Log classes were fresh (1), old (2), clean (3), half decomposed (4), and mostly decomposed (5). Distributions of snag and log decomposition classes were pooled for sites with statistically similar densiometer means. Decomposition class frequency distributions were contrasted

Table 3
Pearson product-moment correlations (r with P-values in parentheses) between various indices used in this study as measured of management intensity

	AVEDENS	BADIF	BANOW
BADIF	−0.87		
	(0.001)		
BANOW	0.85	−0.64	
	(0.001)	(0.026)	
STMPNO	−0.75	0.62	−0.77
	(0.005)	(0.031)	(0.003)

AVEDENS, average densiometer reading for the plot; BADIF, difference in basal area between eastimated preharvest state and current state; BANOW, current basal area; STMPNO, number of stumps.

Table 5
A list of the causal pathways identified in the stands examined in this study and the proportional area over the entire 4 ha plot on which each pathway occurred. Causal pathways are described in order as predisposing factor, killing agent and tree response

Causal pathway	Stand no.										
	184	908	818	1146	905	312	129	1103	146	804	503
Cattle Wind Uprooting	–	–	–	–	–	0.1	–	–	–	–	–
Cutting Beetles Stdgdead	–	–	–	–	0.7	–	–	–	–	–	–
Fire Barkbeetles Stdgdead	–	<0.1	–	0.1	0.1	–	–	–	–	–	–
Fire Firedamg Kiledregen	–	<0.1	–	–	–	–	–	–	–	–	–
Fire Firedamg Stdgdead	–	0.1	0.1	0.1	0.2	–	–	–	–	–	–
Fire Treefall Treepush	–	<0.1	–	0.1	–	0.3	–	–	–	–	–
Fire Wind Buttsnap	–	–	–	0.4	–	–	–	–	–	–	–
Fire Wind Stembreak	–	<0.1	0.1	–	–	–	–	–	–	–	–
Fire Wind Uprooting	–	–	1.0	0.5	0.5	–	–	–	–	–	–
Micsite Drain Regabsent	2.0	–	–	–	–	–	–	–	3.5	–	–
Micsite Harshsoil Regabsent	–	–	0.6	0.3	–	–	8.4	–	–	–	–
Micsite Thkundgrth Regabsent	–	–	–	0.3	–	–	2.1	–	–	–	–
None Bkbeetles Stdgdead	–	–	–	–	–	–	–	16.2	–	–	–
None Bkbeetles Stembreak	–	0.1	–	–	–	–	–	–	–	–	–
None Cutting Treeremoval	–	0.1	0.2	0.7	2.4	2.4	10.5	16.2	24.5	60.0	75.3
None Lightning Burn	0.8	0.1	0.3	0.3	0.2	0.4	–	16.2	3.5	–	–
None Mancleared Regenabsent	–	–	–	–	–	–	–	–	31.5	–	–
None Mancleared Treeremoval	1.2	<0.1	0.6	0.2	–	1.2	14.7	–	–	8.6	–
None Minigstart Treeremoval	–	<0.1	–	–	–	–	–	–	–	–	–
None Treefall Treepush	–	–	–	–	–	–	4.2	–	–	–	–
Overmature Bbeetles Stdgdead	–	0.1	–	–	–	–	–	–	–	–	–
Overtop Ice Stembreak	–	<0.1	–	–	–	–	–	–	–	–	–
Overtop Ice Treepush	2.0	<0.1	–	0.1	–	1.1	–	–	–	–	–
Overtop Treefall Treepush	–	–	–	–	–	–	2.1	–	–	–	–
Overtop Wkparasites Stdgdead	–	–	–	–	–	0.1	–	–	–	–	–
Rootrot Wind Buttsnap	–	<0.1	–	–	–	–	–	–	–	–	–
Rootort Wind Uprooting	–	0.1	–	–	–	–	–	–	–	–	–
Shalsoil Bkbeetles Stdgdead	–	<0.1	0.2	–	–	–	–	–	–	–	–
Shalsoil Unkwn Stdgdead	–	<0.1	0.1	0.2	–	–	–	–	–	–	–
Thickregen Shade Regenabsent	–	–	–	–	0.5	–	–	–	–	–	–
Unknown Bkbeetles Stdgdead	0.8	–	–	0.3	–	0.1	–	–	–	–	–
Unknown None Stdgdead	–	–	–	–	–	–	–	–	–	–	–
Unknown Unknown Stdgdead	–	–	–	–	0.2	0.4	2.1	–	–	–	–
Unknown Unknown Uprooting	0.4	–	–	–	–	–	–	–	–	–	–
Overall frequency	18	73	39	65	83	60	21	3	18	8	1
No. of pathways	6	17	9	13	8	9	7	3	4	2	1
Cause diversity (H')	1.3	2.2	1.9	2.1	1.6	1.8	1.6	1.1	1.0	0.4	0

among grouped stands using Pearson's χ^2 test of independence (Sokal and Rohlf, 1981).

2.5. Assessment of disturbance profile

Twenty-five descriptive variables were calculated to characterize disturbances on each of the 12 stands. Spatial indices were calculated using GS+ and the Rocky Mountain Spatial Analysis Program (C. Flather, Rocky Mt. Forest and Range Experiment Station, Fort Collins, CO, unpublished). To use these programs, data were adjusted such that each cell of the grid was placed into one of five canopy density classes (0–19, 20–39, 40–59, 60–79, and 80–100%). The following spatial indices were calculated.

Table 6
Regression equations and correlation coefficients fit to plots of number of disturbance pathways per plot and corresponding disturbance profile indices

Index	Regression equation	r
Basal area change (BADIF)	$Y=-1.6.68+11211.31/x+-210603/x^2$	0.83
Disturbance diversity (HCAUSE)	$Y=8.23-0.05\times x-201.54/x$	0.88
Disturbance number (CAUSENO)	$Y=9.96\ \mathrm{e}^{(\ln(x)-4.14)^{(2/-0.24)}}$	0.87
Canopy diversity (HDENS)	$Y=0.004\ (x/-101)^{0.217^{(x/-101)}}$	0.79
Current basal area (BANOW)	$Y=0.055\ (x/-42.76)^{1.52}\ \mathrm{e}^{(x/-42.76)}$	0.58
Contagion (CONTAG)	$Y=-6.17+0.34\times x-0.003\times x^2$	0.34
CV densiometer (CVDEN)	$Y=-0.03+19.54/x$	0.67
Dominance (DOMIN)	$Y=0.55-7.82/x$	0.15
Edgetype (EDGETYPE)	$Y=11.61\times x^{(-0.002x)}$	0.17
Fractal dimension (FRACDM)	$Y=1.99-0.024x$	0.59
Gap area (GAPAREA)	$Y=228.23-6.215x+0.043x^2$	0.98
Gap edge length (EDGLNGTH)	$Y=251.36-5.99x+0.037x^2$	0.89
Proportion gapped area (GAPERCNT)	$Y=228.87-6.24\times x+0.043\times x^2$	0.98
Gap frequency (GAPFREQ)	$Y=5.65\times \mathrm{e}^{((x-69.58)/2)}$	0.85
Stump number (STMPNO)	$Y=0.004\times (x/-2.2)^{17.77}\ \mathrm{e}^{(x/-2.2)}$	0.79
Total edge number (TOTEDGE)	$Y=0.004\times (x/-98.28)^{0.375}\ \mathrm{e}^{(x/-98.28)}$	0.79
Variogram range (VARANGE)	$Y=0.004\times (x/-1.82)^{26.53}\ \mathrm{e}^{(x/-1.82)}$	0.79
Variogram sill (VARSILL)	$Y=1/(0.002\times x)$	0.10

(1) GAPFREQ (number of gaps per hectare): gap frequency is the total number of gaps, regardless of size, over the entire study plot. Higher values correspond to higher heterogeneity.

(2) GAPAREA (number of cells): gap area is the total gap area within the study site. It is measured as the total number of isopleth cells with SNA < -1.0. Maximum value is 400. Intermediate values represent higher heterogeneity.

(3) GAPERCNT (percent): proportion of cells (out of 400) with SNV < -1.0. Medium values represent higher heterogeneity.

(4) TOTEDGE (number of edges): an edge occurred where adjoining sides of grid cells had different canopy density class values. Higher TOTEDGE values correspond to higher heterogeneity.

(5) GAPEDGE (number of edges): edge length is the total length of gap edges. Higher values represent higher heterogeneity.

(6) EDGETYPE (number of edge types): edge type represents the number of unique combinations of juxtaposed cells with different canopy density classes. Higher values represent higher heterogeneity.

(7) DOMIN (unitless): dominance is a measure of how much one or a few canopy classes dominate the plot. High values indicate that one class of crown cover dominates. Lower values represent higher heterogeneity.

(8) CONTAG (unitless): contagion is a measure of clumpiness among cells with the same canopy density class. Contagion indicates whether large sections of the landscape differ in terms of the uniformity of canopy closure. Higher values correspond to higher heterogeneity.

(9) SKEWDEN (unitless): skewness characterizes the curve shape of the densiometer distribution (Sokal and Rohlf, 1981). Positive values indicate that peaks of high frequency occur at low values (e.g. a stand with relatively open canopy); negative values indicate that peaks occur at high values (i.e. a stand with relatively closed canopy). Medium values relate to higher heterogeneity.

(10) KURTDEN (unitless): kurtosis of the densiometer distribution characterizes the relative representation of different canopy density classes. High values mean uniform mix, low values mean few canopy classes dominate. High values in an old stand might indicate frequent small scale disturbances. Higher values represent higher heterogeneity.

(11) CVDEN (percent): coefficient of variation of the densiometer distribution indicates the amount of canopy density variation occurring across the plot.

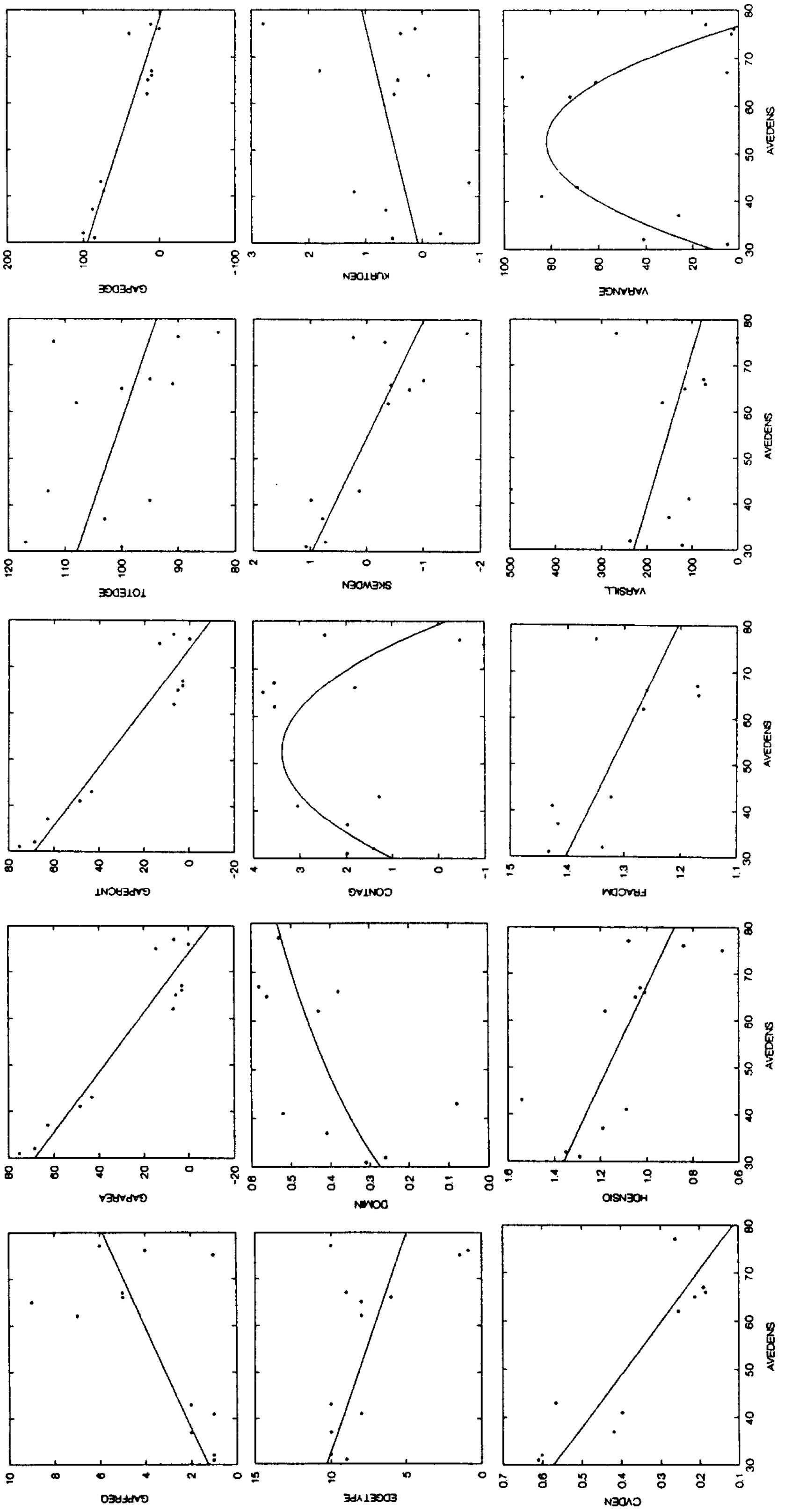

Fig. 1. Relationship between average densiometer reading per plot and various indices for structural diversity

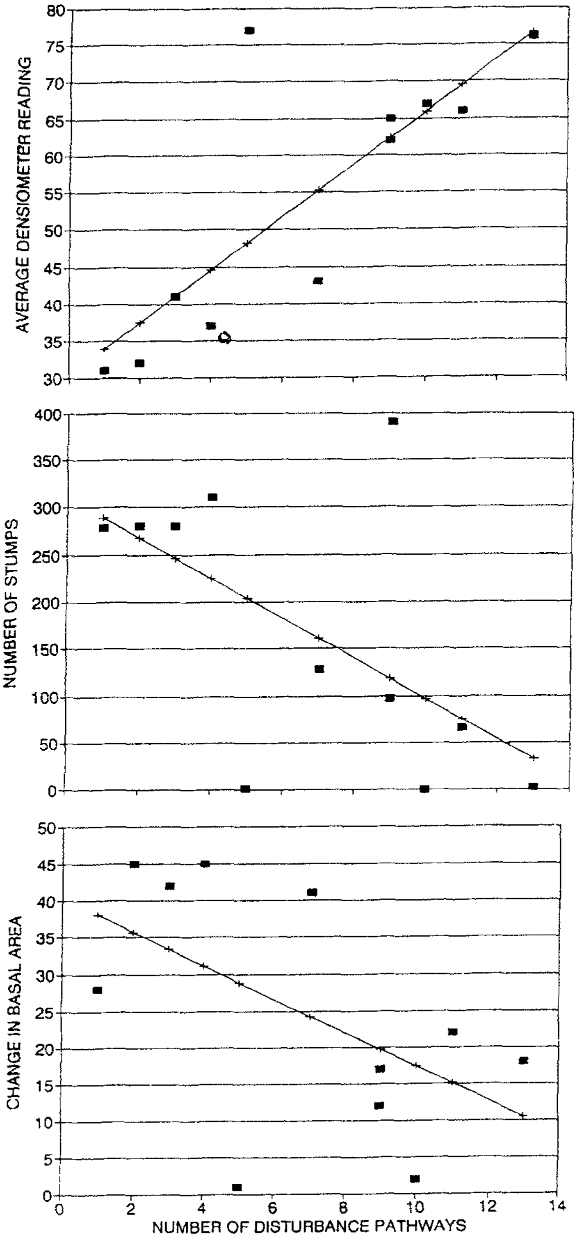

Fig. 2. The relationship between cause number (CAUSENO) and average densiometer reading (AVEDENS), number of stumps (STUMP), and difference in basal area between preharvest and current states (BADIF).

Higher values correspond to greater heterogeneity.

(12) HDENSIO (unitless): Shannon–Weaver Index (H') based on densiometer classes is a non-spatial measure of the diversity in canopy density across the study site. Higher values correspond to higher diversity.

(13) FRACDM (unitless): fractal dimension is a measure of the complexity of gap shapes. Values for the variable vary from 1.0 (a perfect circle or square) to 2.0 (a very contorted circle or square). Higher values correspond to higher heterogeneity.

(14) VARSILL (semivariance): variogram sill is a measure of heterogeneity in crown density based on the semivariance level in non-spatially dependent parts of the variogram. Higher values correspond to higher heterogeneity.

(15) VARANGE (m): variogram range is the distance over which data are spatially dependent. Lower values, but not 0, correspond to higher heterogeneity.

(16) HSNAG (unitless): Shannon–Weaver Index (H') for snags is a measure of decomposition diversity of snags. Higher values represent greater diversity.

(17) HLOGS (unitless): Shannon–Weaver Index (H') for logs is a measure of decomposition diversity of logs. Higher values represent greater diversity.

(18) SNAGFREQ (number of snags ha^{-1}): snag frequency within gaps represents the number of snags ha^{-1} regardless of decomposition condition.

(19) LOGFREQ (number of logs ha^{-1}): log frequency within gaps represents the number of logs ha^{-1} regardless of decomposition condition.

The relationship between each of the above variables and management intensity (average densiometer reading) or disturbance diversity (number of disturbance pathways per plot) was examined using CURVEFIT (T.S. Cox, unpublished data, 1984) and regression analysis.

Together, these variables constituted the disturbance profile of each stand. The variables were analyzed with various multivariate analyses using SYSTAT (Systat Inc., Evanston, IL). Data were subjected to a principal components analysis to reduce their dimensionality, to discern qualitative and quantitative distinctions, and to

Table 7
Correlation coefficients and probability between number of disturbance pathways per plot and corresponding indices for snags and downed logs

Index	r	P
H' logs	0.06	0.85
H' snags	0.62	0.03
Log frequency	0.44	0.15
Snag frequency	0.01	0.99

Table 8
Factor loadings and percents of variance for principal factors extraction based on variables describing 12 stands of *Pinus ponderosa* with varying management histories. Loadings below 0.40 were replaced with zeros

Index	Principal component				
	1	2	3	4	5
AVEDEN	0.93	0	0	0	0
BACUR	0.83	0	0	−0.42	0
BADIF	−0.73	0	0	0	0
CAUSENU	0.92	0	0	0	0
CONTAG	0	−0.92	0	0	0
CVDEN	−0.76	0	0	0	0
DOMIN	0	−0.80	0	0	0
EDGETYP	0	0	−0.81	0	0
FRACTD	−0.80	0	0	0	0
GAPAREA	−0.96	0	0	0	0
GAPEDG	−0.88	0	0	0	0
GAPFREQ	0.81	−0.48	0	0	0
GAPPERC	−0.96	0	0	0	0
HCAUSE	0.93	0	0	0	0
HDENSIO	−0.49	0	−0.73	0.40	0
HLOG	0	−0.88	0	0	0
HSNAG	0.64	0	0	−0.66	0
KURTDEN	0	−0.53	0	−0.79	0
LOGFREQ	−0.41	0	0	0	0.81
SKEWDEN	−0.86	0	0	0	0
SNAGFRQ	0	0	0	0	0.97
STUMPNO	−0.65	0	0	0	0.59
TOTEDG	0	0	−0.58	0.65	0
VARANGE	0	0	0	0.71	0.45
VARSILL	0	0	−0.89	0	0
Percent variance	42	14	13	13	10

observe correlated variables. Because scale varied among variables, all variables were standardized before further analysis. Principal components analysis was conducted using the correlation matrix with varimax rotation and an eigenvalue of 1. Variables were ordered and grouped by size of factor loading to facilitate interpretation. Principal component scores were used in a cluster analysis based on Euclidean distances and average linkage methods.

3. Results

3.1. Assessment of management intensity

Stand age varied from 56 at P312 to 109 at S1103 (Table 1). Current basal area within plots ranged from 7 m^2 ha^{-1} for stand S503 to 32 m^2 ha^{-1} for stand U184 (Table 2). Preharvest basal area varied from 13 m^2 ha^{-1} for stand S503 to 32 m^2 ha^{-1} for stands U184 and U908. Number of stumps ha^{-1} varied from 0 for stand U818 to 391 for stand P312.

Average densiometer (AVEDENS) reading was highly significantly correlated with differences in basal area between estimated preharvest state and current state (BADIF), number of cut stumps (STMPNO), and current basal area (BANOW) (Table 3). To simplify analysis, AVEDENS was subsequently used as a measure of harvest intensity. Mean densiometer readings significantly differed among plots ($F = 343$, $P < 0.001$). Dunnett's T3 multiple comparison procedure defined six groups: (1) U184, U908, C315; (2) U818, U1146, P905; (3) P905, P312; (4) S129, S1103; (5) S146; (6) S804, S503 (Table 4). With

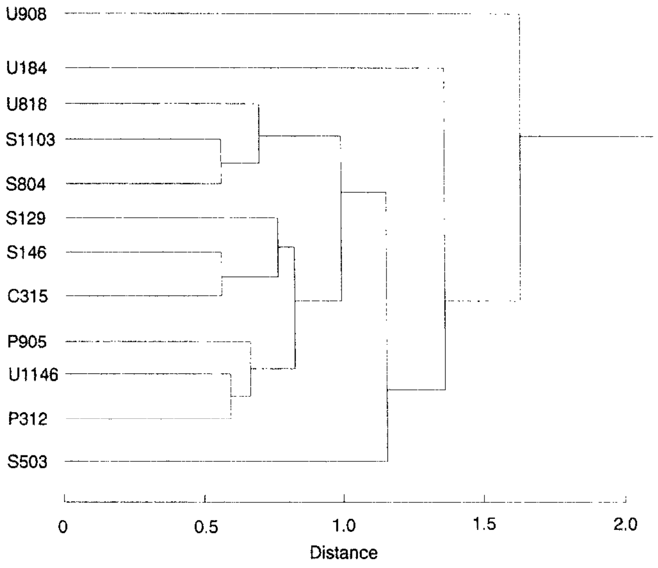

Fig. 3. Dendrogram showing the relationship of various stands measured in this study based on Euclidean distance and average linkage methods.

reference to previous harvest intensity, these groups are referred to as (1) none, (2) low, (3) moderate, (4) high, and (5) very high.

3.2. Characterization of disturbance pathways within plots

Thirty-four disturbance pathways were identified (Table 5), each of which was composed of various combinations of nine predisposing factors, 14 killing agents, and nine tree responses. The number and types of pathways varied among stands. Activity values for individual pathways varied from less than 0.1 for several pathways in several stands to 0.75 for tree harvest and removal in S503 (Table 5). Pathway frequency varied from 1 to 83 per plot. Pathway diversity (HCAUSE) varied from $H'=0$ to $H'=2.2$. The greatest number and variety of disturbance pathways occurred in unharvested stands.

3.3. Relationship between disturbance pathways and individual indices of the disturbance profile

Curves with various shapes were fit to scatter plots of disturbance diversity and individual indices (Table 6). Of the variables with $r > 0.60$, a parabola was fit to GAPAREA, EDGLNGTH and GAPERCNT; a log normal curve to HDENSIO, STMPNO, TOTEDGE, and VARANGE; a hyperbola to CVDEN; a mod Hoerl to HCAUSE; a normal curve to GAPFREQ; a log normal curve to CAUSNO. No correlation was found between disturbance diversity and BANOW, CONTAG, DOMIN, EDGETYPE, FRACDM, and VARSILL.

3.4. Relationships between management intensity and individual indices of the disturbance profile

Curves with various shapes were fit to scatter plots of management intensity and individual indices (Fig. 1). VARANGE, and CONTAG showed maximum values near the mid-range of average densiometer, indicating that heterogeneity was least at moderate management levels. GAPFREQ, DOMIN, and KURTDENS showed positive linear correlations with average densiometer values, indicating that greater management intensity decreased heterogeneity. Other indices showed negative linear relationships with average densiometer values, indicating that greater management intensity increased heterogeneity.

3.5. Relationship between management intensity and disturbance diversity

Disturbance pathway number (CAUSNO) and average densiometer reading (AVEDENS) had a significant positive correlation ($r=0.80$), indicating that diversity of disturbance agents decreased with increasing harvest intensity (Fig. 2). Furthermore, stump number ($r=-0.50$) and basal area reduction ($r=-0.55$) had significant inverse correlations with number of disturbance pathways (Fig. 2).

3.6. Relationship between disturbance diversity versus snag and downed log decomposition distribution

Disturbance pathway number was significantly correlated to snag diversity, but not log frequency, snag frequency, or log diversity (Table 7). Significant differences occurred in log distribution ($\chi^2=2694$, d.f. $=16$, $P<0.001$) and snag distribution ($\chi^2=1103$, d.f. $=24$, $P<0.001$) among stand groups according to previous management intensity.

3.7. Assessment of disturbance profile

Principal component analysis extracted five principal components (Table 8). All 25 variables loaded on one or more principal components; nine loaded on two or more variables. Principal component 1 was composed of 16 variables and accounted for 42% of the variance. Principal components 2, 3, 4, and 5 had 5, 4, 6, and 4 variables, respectively, and accounted for 14%, 13%, 13%, and 10% of the variance. The meaning of these principal components is not obvious. Cluster analysis based on the five principal components extracted by principal component analysis indicated six clusters: (1) U908; (2) U184; (3) U818, S1103, C315; (4) S129, S146, S804; (5) P905, U1146, P312; (6) S503 (Fig. 3).

4. Discussion

4.1. Hypothesis 1: Diversity of disturbance pathways influences structural heterogeneity in the Black Hills ponderosa pine forest type

Heterogeneity is a common denominator that influences many different forest resource values. Canopy gaps and the agents that cause gaps are major contributors to structural heterogeneity in the forest (White et al., 1985). Various indices can be used to measure structural heterogeneity (O'Neill et al., 1988; Mladenoff et al., 1993). The Shannon–Weaver Index of General Diversity is perhaps the most well-known (Christensen and Peet, 1982). In this study, heterogeneity of canopy density across the plot (HDENSIO) showed a significant negative correlation with number of disturbance pathways (CAUSNO) and causal diversity (HCAUSE). On the basis of HDENSIO, it is concluded that hypothesis 1 is true.

However, various indices in addition to HDENSIO can be used to measure structural heterogeneity (Turner, 1989; Whittaker, 1977; Scheiner, 1992). In this study, 15 of 21 indices were correlated with disturbance diversity, but trend patterns varied among these from negative to positive correlations. The relationship of disturbance with structural heterogeneity depends on the index used to characterize the latter.

4.2. Hypothesis 2: Diversity of disturbance pathways influences the abundance and diversity of snags and downed logs in the Black Hills ponderosa pine forest type

The snags and downed logs that disturbance pathways produce offer a major interface between disturbance processes and various non-timber resources (Harmon et al., 1986). Lundquist (1995) suggests that different disturbance causes influence the pattern of tree decomposition. Trees killed by bark beetles, for example, seem to have a tendency to break along the stem, whereas those killed by root diseases snap at the butt. In this study, number of disturbance pathways (CAUSNO) was positively correlated ($r = 0.62$, $P < 0.05$) with snag diversity (HSNAG), suggesting that hypothesis 2 is true. In contrast, however, disturbance diversity was not significantly correlated with log diversity and frequency and snag frequency, suggesting that hypothesis 2 is false for these characterizations.

In comparison with snag diversity, snag and log frequency are probably more dependent on disturbance frequency and intensity. Log diversity probably depends more on time. Degradation following a tree's response to disturbance is a little understood long term phase of the disturbance network. Snag and log composition documents and preserves the disturbance history of the stand.

Relationships depend on the tools and procedures used to assess snag and logs. The snag and log classification diagrams used here were developed originally for the Pacific Northwest. New diagrams may be necessary for the ponderosa pine forests of the Black Hills. More research is needed to describe the various stages of snag and log decomposition with time.

4.3. Hypothesis 3: Intensity of management influences structural heterogeneity in the Black Hills ponderosa forest type

The relationship between management intensity and structural heterogeneity is not straightforward. Seven of the 15 indices studied here were significantly correlated to management intensity. Dominance, variogram range and contagion showed curvilinear relationships and reach maximum values at mid-intensity levels. Other indices showed linear relationships.

The results indicate that for some measures of heterogeneity, a moderate level of management is necessary to obtain the greatest levels of structural heterogeneity. Hypothesis 3 is accepted. Management intensity does influence structural heterogeneity in the Black Hills ponderosa pine forest type. Management intensity can both increase and decrease heterogeneity, depending on which index is used to measure the latter.

Assessments of harvesting on disturbance regimes requires a quantitative indicator of management intensity. Management records for most stands, however, are not complete and dates of harvest or descriptions of preharvest conditions are either lacking or based on approximate measures. Preharvest stand conditions were estimated in this study using cut stumps, and harvest intensity was based on a comparison of this and the current conditions. In this study, several indirect indices of management were significantly correlated with direct measures of management. Average densiometer reading, for example, decreased as harvest intensity increased. Densiometer readings are based on current stand conditions, which are operationally measurable and easily assessed. However, use of optical densiometers at the intensities used here can be fatiguing to field crews and the reliability of densiometer readings has been questioned (Ganey and Block, 1994), primarily because of inter observer variation. A more suitable tool would certainly be useful, and more research should be done on examining alternatives to the optical densiometer.

4.4. Hypothesis 4: Intensity of management influences the diversity of disturbance pathways in the Black Hills ponderosa pine forest type

Lundquist (1995) described probable interactions of disturbance causes using relational diagrams. This study indicated that under endemic conditions, gap formation involves predisposing agents, killing agents and tree responses that are usually coupled in time and space. Results of the present study indicate that management reduced the disturbance diversity of the stand by lowering the number of disturbance pathways and focusing on the use of a relatively few pathways (primarily tree removal by cutting). This agrees with hypothesis 4.

4.5. Hypothesis 5: Individual stands can be categorized and classified on the basis of disturbance profile

Results show that impact of disturbance depends on the variable measured. Single indices can characterize limited structural and functional elements of ecosystems. Elements interact and single indices are probably inadequate to characterize ecosystem complexity (Karr, 1987). Munn (1988) suggests that integrated monitoring systems using several indices simultaneously would provide more useful early indicators of environmental changes than single indices.

5. Conclusion

Each one of the 12 plots in this study had a unique combination of index values that described its disturbance profile. 'Disturbance profile' represents a fingerprint unique to that stand. Various multivariate techniques can be used to compare and contrast disturbance profiles (Austin, 1985; Clarke, 1993). In this study, cluster analysis defined six groups. Harvest history is a major determinant of these groupings, but clustering also depends on other disturbance variables. Individual stands can be numerically categorized and classified, but full understanding of the multivariate relationships is difficult to achieve. The ecological meaning of these groups is vague (Austin, 1985). Each group has statistically similar combinations of disturbance index values, each of which relate in one way or another to the health of a forest ecosystem. Forest health is difficult to define because a forest is composed of a complex network of interacting structure and function that changes in time (Knauer et al., 1989; Shaw, 1992). Multivariate analyses of disturbance profiles may offer a way to quantify this complexity and thus measure forest health.

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