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Forest roads and landscape structure in the southern Rocky Mountains

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Abstract

Roadless areas on public lands may serve as environmental baselines against which human-caused impacts on landscape structure can be measured. We examined landscape structure across a gradient of road densities, from no roads to heavily roaded, and across several spatial scales. Our study area was comprised of 46,000 ha on the Roosevelt National Forest in north-central Colorado. When forest stands were delineated on the basis of seral stage and covertype, no relationship was evident between average stand size and road density. Topography appeared to exert a greater influence on average stand size than did road density. There was a significant positive correlation between the fractal dimension of forest stands and road density across all scales. Early-seral stands existed in greater proportions adjacent to roads, suggesting that the effects of roads on landscape structure are somewhat localized. We also looked at changes in landscape structure when stand boundaries were delineated by roads in addition to covertype and seral stage. Overall, there was a large increase in small stands with simple shapes, concurrent with a decline in the number of stands > 100 ha. We conclude that attempts to quantify the departure from naturalness in roaded areas requires an understanding of the factors controlling the structure of unroaded landscapes, particularly where the influence of topography is great. Because roads in forested landscapes influence a variety of biotic and abiotic processes, we suggest that roads should be considered as an inherent component of landscape structure. Furthermore, plans involving both the routing of new roads and the closure of existing ones should be designed so as to optimize the structure of landscape mosaics, given a set of conservation goals.

Introduction

Landscape ecologists often use a comparative approach to characterize the effects of human-caused disturbance on landscape structure (Turner 1989). For instance, researchers have observed differences in landscape metrics such as patch size, shape, juxtaposition, and composition between lands with relatively few human impacts and lands that have experienced more substantial human-caused disturbance such as timber harvest (Ripple *et al.* 1991; Mladenoff *et al.* 1993; Spies *et al.* 1994), fire suppression (Baker 1992, 1993), alteration of flood regimes (Miller *et al.* 1995), agriculture (Krummel *et al.* 1987; Ales *et al.* 1992), urbanization (Lagro 1992; Luque *et al.* 1994), or a combination of these (Turner and Ruscher 1988; Foster 1992; Zipperer 1993). In the northwestern U.S., Williams and Marcot (1991) reported differences in average patch size between forest stands in roaded and unroaded areas on the Klamath National Forest. Mid-seral patches were found to be 30–50% smaller, late-seral patches 15–25% smaller, and early-seral patches 14–31% larger in actively managed areas. Williams and Marcot (1991) suggest that road density may be used as a landscape-level index for deviation from more natural conditions.

Certainly, roads facilitate the spread, frequency, and intensity of disturbances on the landscape, with important consequences for organisms living there (Bennett 1991; Schonewald-Cox and Buechner 1992). Through changes in slope stability, paved

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collecting surfaces, and alterations in drainage patterns, roads may increase soil erosion, sedimentation, and landslides (Norse *et al.* 1986). Roads may influence fire regimes through increased fire ignition (Franklin and Forman 1987) as a result of human activities that occur in the transportation corridor, reduced fire size as a result of physical barriers to fire movement (Norse *et al.* 1986; Covington and Moore 1992), and increased accessibility for fire suppression activities. Roads fragment the structure of continuous forests, creating high contrast edges (Harris 1984; Franklin 1993) accompanied by changes in microclimate (Ranney *et al.* 1981; Chen *et al.* 1992) and reductions in the amount of forest interior (Schonewald-Cox and Buechner 1992). Finally, roads allow access for resource extraction, such as timber or minerals.

Given the wide range of road effects, it is reasonable to think of roads as a source of human-caused disturbance, or as disturbance corridors (Forman and Godron 1986), and to expect that roaded areas deviate from a more natural condition (Noss 1992). With this expectation, it seems reasonable to think that road density may serve as an index for the level of disturbance on the landscape or deviation from natural conditions. Similarly, non-roaded areas or those with low road density might serve as environmental baselines against which the impact of human activities can be measured. Aside from the Williams and Marcot study (1991), we are unaware of landscape-level studies that focus on the relationship between roads and landscape structure, or that attempt to quantify the relationship between road characteristics and landscape metrics.

In this study, we examine the relationship between roads and the structure of a southern Rocky Mountain (SRM) landscape. First, we examine the correlation between roads and landscape structure across a gradient of road density. Using a gradient of road densities rather than a categorical road/no road approach may be useful in identifying critical thresholds (*e.g.*, Krummel *et al.* 1987), or changes in domains of scale (Wiens 1989) as one moves from unroaded to increasingly roaded areas. In this analysis, forest stands are defined as areas of homogeneous forest type and seral stage, where boundaries are defined by changes in type or seral stage, not by road boundaries. Second, we investigate whether the composition of forest patches adjacent to roads differs from the composition of forest patches away from roads. This would be the case, for instance, if fire regimes or the amount of timber harvest differed near roads. Third, we examine how forest fragmentation changes when different road types are considered to constitute forest patch boundaries. These characteristics of forest stand size and shape may be of particular importance to species associated with forest interior or forest edge.

Methods

Study area

The Roosevelt National Forest is located in the Front Range of north-central Colorado. The study area occupies approximately 46,000 ha in the Redfeather District and is bordered on the south by the Cache la Poudre River and Colorado State Highway 14, on the west by the Laramie River and the Rawah Wilderness Area, on the north by the Colorado-Wyoming stateline, and on the east by a mixture of National Forest and private land. Elevations extend from 2400 m to 3400 m with most of the area ranging from 2800 to 3200 m.

The vegetation in the area is typical of the upper montane (2400–2700 m) and subalpine (2700–3400 m) zones (Marr 1961). The former constitutes the elevational limits of *Pinus ponderosa* (ponderosa pine) and includes *Pseudotsuga menziesii* (Douglas-fir). The subalpine zone is dominated by *Picea engelmannii-Abies lasiocarpa* (Engelmann spruce-subalpine fir) forests. Two successional forest types, *Pinus contorta* (lodgepole pine) and *Populus tremuloides* (aspen), occur in both zones. Lodgepole pine occupies approximately 60% of the study area, nearly three times the percentage of the next most abundant forest type, spruce-fir. Mid-seral stands account for about 60% of the area, while early and late-seral stands occupy less than 10% and 30%, respectively.

We chose this area because, as the largest contiguous block of public land on the Roosevelt National Forest, the landscape analyses were not confounded by a lack of data for private inholdings. There were approximately 94 km of 2-lane gravel roads and 171 km of single-lane unimproved roads in the study area. Also, the area contained a mixture of heavily roaded sites and sites with low road densities, including most of an 18,000 ha roadless area (U.S. Forest Service 1979).

Forest stand boundary data were based on photo-interpretation of 1:24,000 color and color infra-red aerial photographs taken between 1977 and 1989. This data set was then manually delineated on 1:24,000 geo-rectified orthophotos, ground-truthed, converted to digital format, and imported into a workstation ARC/INFO GIS (ESRI 1991). Stands were subsequently delineated on the basis of forest type and seral stage (*sensu* Buttery and Gillam 1987), with stand sizes ranging from approximately 0.4 ha to > 500 ha. Stand attribute data were imported into ARC/INFO from the Resource Information System (RIS), a standardized database used in U.S. Forest Service Region 2. The road layer was based on 1989 1:24,000 base maps linked with attribute data from U.S. Forest Service Cartographic Feature Files, error-checked, and imported into ARC/INFO.

A 6 column by 9 row fixed grid with individual cells measuring 3 km per side was overlaid on the study area. Cells on the periphery of the grid that bordered on or contained private land were excluded from the analysis. The remaining 33 cells were used to define the spatial analysis units; any forest stand that was wholly contained in a cell was assigned to the corresponding unit (*e.g.*, cell 1: unit 1). In order to include all forest stands and to maintain stand integrity regarding size and shape, stands that fell on the border of more than one unit were assigned to the unit which contained the greatest portion of the stand. This decision rule resulted in the final analysis unit areas ranging from 692.5 to 1579.1 ha, as opposed to the original 3 × 3 grid cell areas of 900 ha (Fig. 1, 1*a vs.* 1*c*).

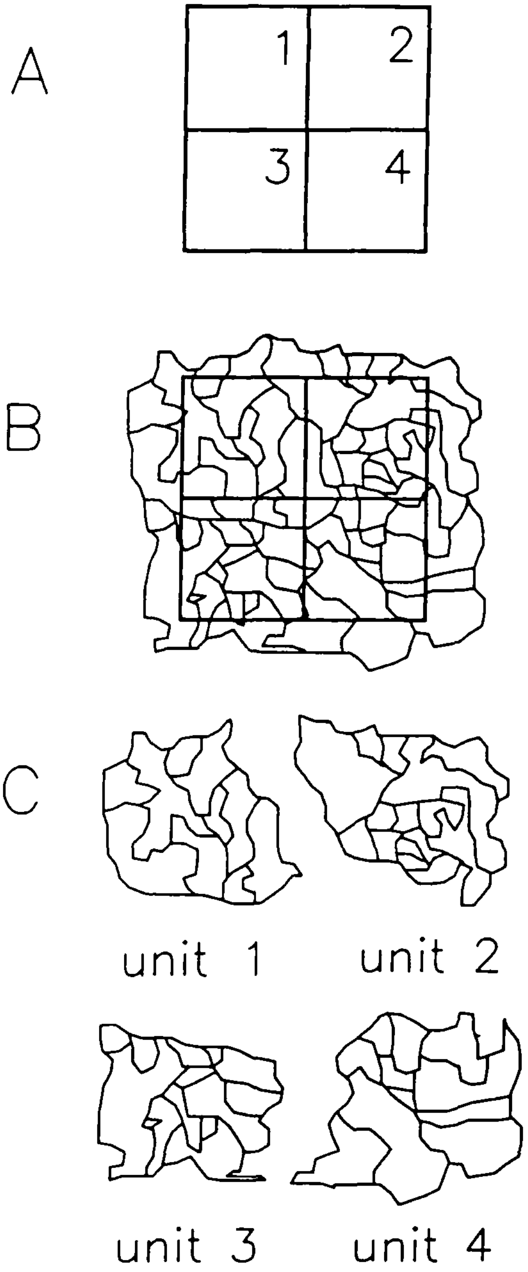

Fig. 1. A schematic diagram of the process used in assigning forest stands to analysis units. A sample grid with cells (1–4) of a given size (A) is overlaid on the study area (B). Stands within a given grid cell are assigned to the corresponding analysis unit (*e.g.*, cell 1:unit 1) and stands that fall on the border of more than one cell assigned to the unit that contains the greatest portion of the stand (C).

Road density and landscape structure

We looked at how stand size and shape changed with road density across all forest types and seral stages. Because stand size and shape are influenced by landforms, we also explored how these metrics changed with topography. Roads were not considered to constitute stand boundaries for this set of analyses (*sensu* Williams and Marcot 1991; B. Williams, personal communication). In this way, stand boundaries were defined similarly across all road densities as areas of homogeneous forest type

Table 1. Cell sizes used to determine analysis units, number of units, and ranges in road densities and unit areas for each data set used to examine the relationship between road density and landscape structure.

Initial cell (km) size	Number of units	Road density (km/km^2)	Area of units (ha)
2 × 2	75	0.00–5.92	228.5–920.9
3 × 3	33	0.08–4.23	692.5–1579.1
4 × 4	17	0.29–2.76	1589.3–2773.9

and seral stage. All of these analyses were repeated with grid-cell sizes of 4 × 4 and 2 × 2 km, in addition to the 3 × 3 km grid, in order to investigate any scale-dependent trends in the results (Table 1).

Using linear regression, we examined the relationship between average stand size and road density. We also investigated the relationship between average stand size and an index of topography (T)

$$T_x = \sum_{i=1} \frac{S_{ix} A_{ix}}{A_x} * 100$$

where T_x is the index of topography for unit x, S_{ix} is the slope for stand i in unit x, A_{ix} is the area for stand i in unit x, and A_x is the total area for unit x. Higher values of T_x indicate more complex topography. Multiple linear regression was used to relate T_x to average stand size and road density.

Because roads may be associated with altered disturbance regimes (*e.g.*, fire ignition or suppression, timber harvest), we looked at the relationship between road density and the average stand size for early-seral (grass-forb and shrub-seedling stages), mid-seral (all sapling-pole and mature stages with < 30% canopy closure), and late-seral (mature stages with > 30% canopy closure and old growth) stands in each analysis unit (*sensu* Williams and Marcot 1991; B. Williams, personal communication). The average stand sizes for these seral stages were also regressed on the topographic index, T_x; and we looked at the relationship between road density and the percentage of a given analysis unit in early-seral, mid-seral, and late-seral stages using linear regression.

Two indices of the complexity of forest stand shapes on the landscape were regressed on both road density and the index of topography. The Patton index (*PI*) describes stand shape complexity by comparing the perimeter of a stand to the perimeter of a circle of the same area (Patton 1975), and is calculated using the formula:

$$PI = \frac{P}{2\sqrt{\Pi A}}$$

where P is the perimeter of a stand and A is the area. The *PI* has a lower limit of 1 for a circle, but may increase without limit. A *PI* of 2 indicates that a stand has twice as much perimeter as a circle of the same area, a *PI* of 3 for 3 times as much perimeter, etc. A *PI* was calculated for each forest stand in a unit and the average *PI* for each unit was used in the analysis.

The fractal dimension for an ensemble of patches is also an index of shape complexity (Mandelbrot 1977; Lovejoy 1982) and has been used to describe the degree of shape complexity of forest stands (Krummel *et al.* 1987; Turner and Ruscher 1988; O'Neill *et al.* 1988; Pastor and Broschart 1990; Mladenoff *et al.* 1993). It is estimated by regressing the log of patch perimeter (P) on the log of patch area (A) for each forest stand on the landscape. The fractal dimension (D) is related to the slope of the regression by the relationship (Krummel *et al.* 1987):

$$\log P = 1/2\,(D)\,(\log A)$$

The fractal dimension may range from 1 (least complex) to 2 (most complex). The fractal dimension was calculated for each analysis unit and then regressed on road density.

Roads and adjacent forest stand composition

We examined the extent to which the composition of forest stands adjacent to roads differed from that of stands away from roads. We compared the proportion of land in a given seral stage or forest type within a 20 m buffer of all roads with the proportion of that seral stage or forest type on the entire landscape using the formula:

$$F = \frac{A_b}{A_l}$$

where F is the factor relating the proportion of area occupied in the buffer (A_b) to the proportion of area occupied on the landscape (A_l) by a given forest

Table 2. The number of stands in various size categories when roads were not considered stand boundaries (NONE), only gravel roads were considered stand boundaries (GRAVEL), and all roads were considered stand boundaries (ALL). The percentage of the total study area is indicated in parentheses; for each column the percentages sum to 100.

Stand size (ha)	NONE	GRAVEL	ALL
0–5	912 (6.3)	1063 (6.7)	2349 (9.6)
> 5–10	479 (9.5)	490 (9.8)	604 (12.1)
> 10–20	355 (13.9)	365 (14.1)	423 (16.3)
> 20–30	166 (11.1)	172 (11.4)	178 (11.8)
> 30–40	73 (7.2)	74 (7.3)	82 (8.0)
> 40–50	55 (6.5)	54 (6.3)	57 (6.6)
> 50–100	82 (15.6)	89 (16.7)	82 (15.6)
> 100–200	49 (17.7)	44 (16.2)	38 (14.4)
> 200–300	5 (3.0)	5 (3.1)	4 (2.5)
> 300	7 (9.2)	7 (8.5)	3 (3.1)

type/seral stage x. An $F > 1$ indicates a greater proportion of the given forest type/seral stage in the buffer than its proportion on the landscape, while $F < 1$ indicates a smaller proportion of the given forest type/seral stage in the buffer.

Roads and forest fragmentation

Because roads of different widths and intensities of use vary in their effects on organisms that occur near them (Bennett 1991; Schonewald-Cox and Buechner 1992), we investigated the way in which average stand size and shape change when various road-types were considered to constitute stand boundaries. Distributions of forest stand size and stand shape were compared when roads were not considered stand boundaries (hereafter NONE, n = 2183), only gravel roads were considered boundaries (GRAVEL, n = 2362), and both gravel and dirt roads were considered boundaries (ALL, n = 3803). There were no paved roads on the study site.

Comparisons were made between forest stand size distributions (Table 2) in a pairwise fashion (NONE *vs.* GRAVEL, GRAVEL *vs.* ALL, and ALL *vs.* NONE) using nonparametric multiple response permutation procedures (MRPP, Mielke 1991). The null hypothesis underlying MRPP is that the groups or sets of objects being compared are obtained from the pooled collection of the finite population (Mielke 1984, 1991). In order to achieve increased independence among patches, we divided them into two groups using the 33 analysis units created with the 3 × 3 grid and described in the preceding section. These units were divided between the two groups in a checkerboard fashion, such that common borders existed only between units of different groups, while units within a group touched only on the diagonal.

Distributions of forest stand shape, as described by the Patton index (Patton 1975), were compared using both a paired and unpaired design. The paired comparison was intended to track effects on individual patches and, therefore, determine how many stands were affected by a given road type. The unpaired comparison allowed us to evaluate changes at the level of the landscape. Again, stands were divided into two groups as described above. For the paired design, an average PI was taken for stands created by subdividing a stand with a given road type, maintaining a one-to-one spatial correspondence between PI's for the two sets being compared. The number of non-zero differences between, for instance, NONE and GRAVEL, indicates the number of stands in NONE that were subdivided when gravel roads were considered to constitute stand boundaries. For the paired design, distributions were compared using Multiple Response Blocking Procedures (Mielke 1984) as modified by Slausen *et al.* (1991).

For the unpaired design, there was no averaging among stands and thus, the distributions resulting from subdivision with a given road type necessarily had more stands than the original distribution. For the unpaired design, distributions were compared using MRPP (Mielke 1984, 1991) where possible. For larger sample sizes, however, computational constraints prevented the use of MRPP, and for these analyses we used the Mann-Whitney U Test (Daniel 1990). For smaller sample sizes, identical results were obtained using either MRPP or the Mann-Whitney U Test.

It may be useful to know how changes in stand size and shape were related. For instance, if a large number of small stands were created after subdividing with a given road layer, do these new stands tend to have simple or complex shapes? In order to assess how changes in stand size and shape were related, NONE and ALL were each subdivided into 4 size categories: stands less than 5 ha, stands from 0 to 50 ha, stands between 50 and 100 ha, and stands greater than 100 ha.

Results

Road density and landscape structure

There was little relationship between average stand size and road density for the 4 × 4 grid ($p = 0.528$, $r^2 = 0.027$; Fig. 2*a*), the 3 × 3 grid ($p = 0.217$, $r^2 = 0.049$; Fig. 2*c*), or the 2 × 2 grid ($p = 0.167$, $r^2 = 0.026$; Fig. 2*e*). In each of the three grid sizes, there were differences in average stand size for units with the highest and lowest road densities, but the trend in these differences was not consistent. Some units with the lowest road densities had larger average stand sizes than units with the highest road densities; in other cases this trend was reversed. Furthermore, the variability of average stand size in units with intermediate road densities accounts for the nonsignificant relationship (see Figs. 2*a*, 2*c*, 2*e*).

On our study area, topography appears to exert a greater influence on average stand size than does road density. There was a stronger correlation between average stand size and the index of topography for the 3 × 3 grid ($p = 0.001$, $r^2 = 0.289$; Fig. 2*d*) and the 2 × 2 grid ($p = 0.002$, $r^2 = 0.123$, Fig. 2*f*), but less so for the 4 × 4 grid ($p = 0.153$, $r^2 = 0.131$, Fig. 2*b*). Road density accounted for little additional variation in average stand size after first including the index of topography, T_x, in the model (all p-values > 0.80, all r^2-values < 0.002).

We found no evidence to suggest a relationship between road density and average stand size by seral stage. When the average stand sizes for early-, mid-, or late-seral stages were regressed on road density, no correlations were found (all p-values > 0.10, all r^2-values < 0.10). Similarly, no relationships were found when regressing the percentage of an analysis area in a given seral stage against road density (all p-values > 0.10, all r^2-values < 0.040).

The results regarding the relationship between stand shape and road density were dependent on which shape index was used. There were no correlations evident when the Patton index was regressed on road density (all p-values > 0.37, all r^2-values < 0.025) or on the index of topography (all p-values > 0.05, all r^2-values < 0.055). Somewhat stronger relationships were observed, however, between the fractal dimension and road density for all three grids (4 × 4 grid: $p = 0.067$, $r^2 = 0.207$, Fig. 3*a*; 3 × 3 grid: $p = 0.022$, $r^2 = 0.158$, Fig. 3*c*; 2 × 2 grid: $p = 0.010$, $r^2 = 0.087$, Fig. 3*e*). There was a weak correlation between the fractal dimension and the index of topography for the 2 × 2 grid ($p = 0.004$, $r^2 = 0.106$; Fig. 3*f*) and the 4 × 4 grid ($p = 0.123$, $r^2 = 0.151$; Fig. 3*b*), but no correlation for the 3 × 3 grid ($p = 0.358$, $r^2 = 0.027$, Fig. 3*d*).

Roads and adjacent forest stand composition

While we found no relationships between road density and average stand sizes by seral stage, the proportion of area occupied by certain seral stages and forest types near roads differed from the composition of the entire landscape. Early-seral stages constituted a substantially higher proportion of the buffer than in the landscape (Table 3). Grasslands and spruce/fir stands also existed in higher proportions in the road buffer than on the landscape. Shrublands and stands dominated by Douglas-fir and ponderosa pine had smaller proportions in the buffer than on the entire landscape.

Roads and forest fragmentation

The stand size distributions for the study area showed substantial variation depending on which road types were considered to constitute stand boundaries. The MRPP analysis showed significant differences in the distributions of stand size between NONE (roads not boundaries) and ALL (all roads boundaries) regarding both number of stands (p-values for both groups < 0.001) and percent of total area (p-values for both groups < 0.001) represented in the various size categories. The trend for NONE *vs.* ALL was a general decrease in stands > 100 ha and increase in stands < 100 ha. The percentage of total area showed a similar trend.

Differences were also evident for GRAVEL (only gravel roads as boundaries) vs. ALL regarding number of stands (p-values for both groups < 0.001) and percent of total area (p-values for both groups < 0.001) in the different size categories. Here, the general trend was similar to that for NONE vs. ALL, and involved a decrease in the

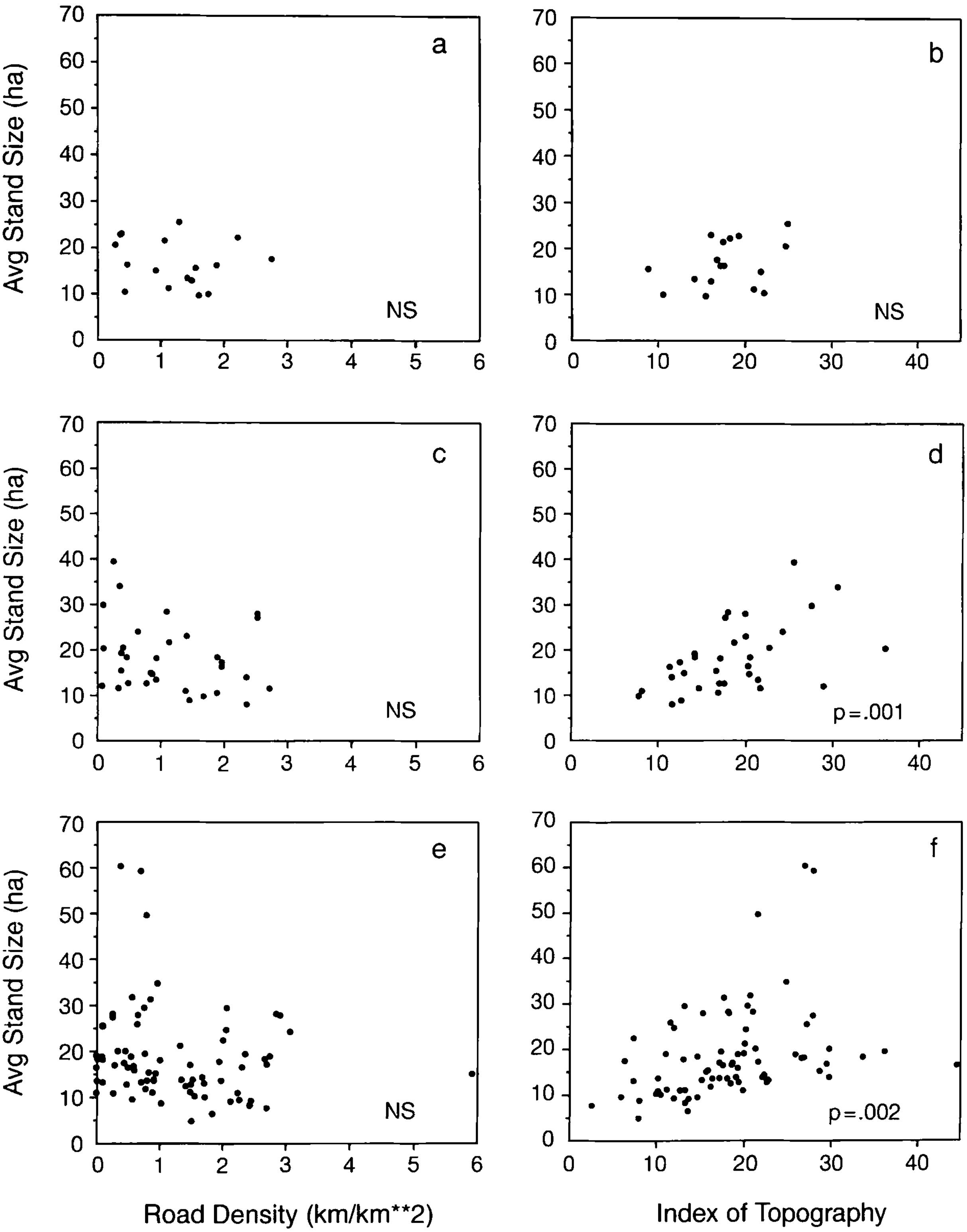

Fig. 2. Scatterplots of average stand size *vs.* road density and average stand size *vs.* the index of topography for the 4 × 4 grid (a and b), the 3 × 3 grid (c and d), and the 2 × 2 grid (e and f). P-values are given for significant correlations, while NS signifies non-significant correlations.

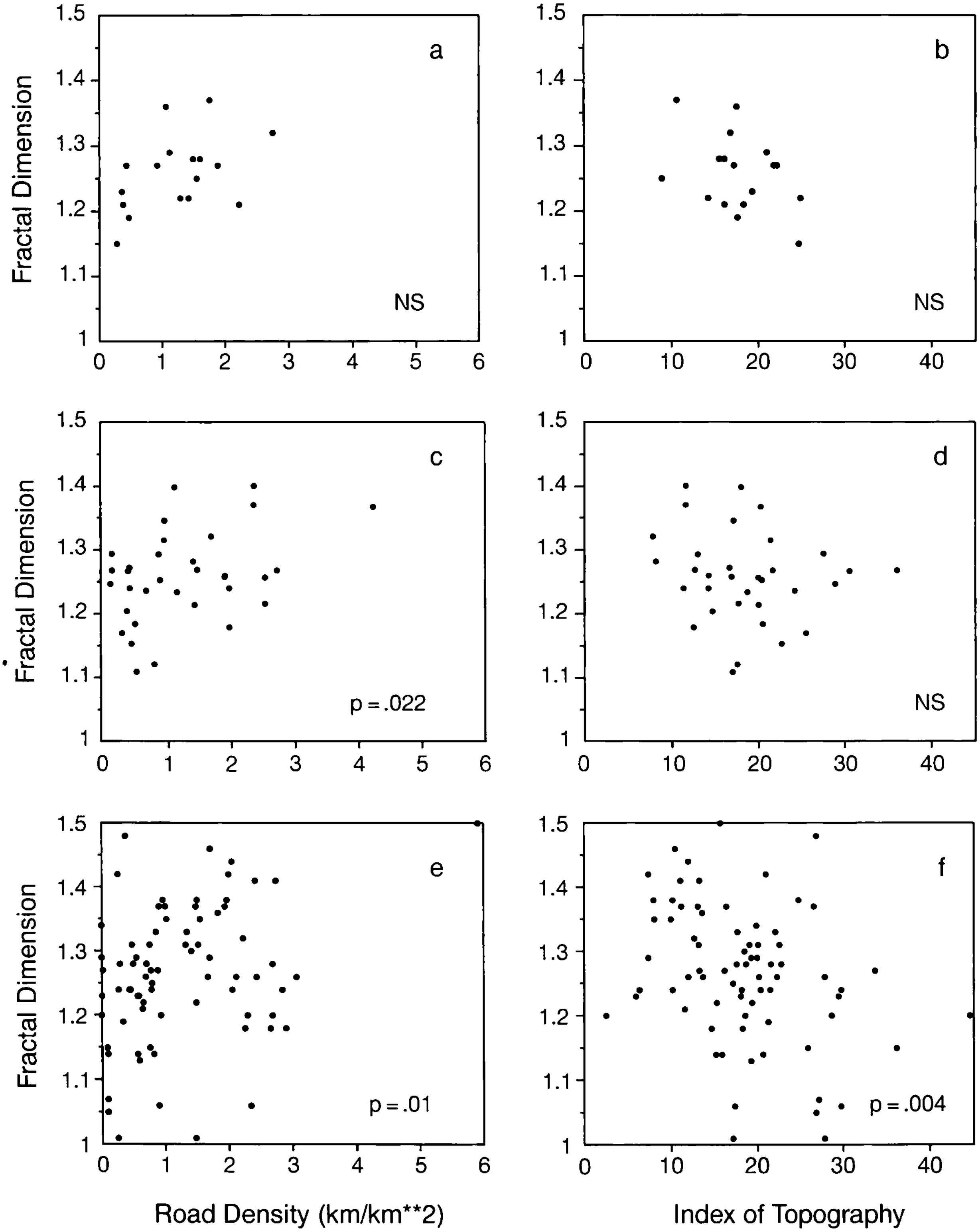

Fig. 3. Scatterplots of fractal dimension *vs.* road density and fractal dimension *vs.* the index of topography for the 4 × 4 grid (a and b), the 3 × 3 grid (c and d), and the 2 × 2 grid (e and f). P-values are given for significant correlations, while NS signifies non-significant correlations.

Table 3. A comparison of the proportion of area within a 20 m buffer of all roads (A_b) occupied by covertype/seral stage x with the proportion occupied on the entire landscape (A_l) by covertype/seral stage x using the formula: $F = A_{bx}/A_{lx}$. $F > 1$ indicates that a covertype/seral stage occupies a greater proportion of the buffer than its proportion on the landscape, while $F < 1$ indicates a smaller proportion in the buffer than on the landscape. The percentage of the landscape occupied by given covertype/seral stage is indicated in parentheses.

Covertype	F	Seral stage	F
Grassland (4.1)	1.59	Early (10.4)	1.43
Shrubland (4.2)	0.54	Mid (58.5)	1.08
Aspen (3.5)	0.74	Late (31.2)	0.70
Douglas-fir (1.2)	0.08		
Lodgepole pine (62.6)	0.90		
Ponderosa pine (2.5)	0.34		
Spruce/fir (21.6)	1.44		
Other vegetation (0.3)	1.91		

largest stands and an increase in smaller stands. The percentage of total area paralleled this trend.

Just as there were differences in stand size distributions, the distributions of stand shape, as represented by the Patton index, also varied dramatically depending on which road types were used as stand boundaries. Using the paired design, wherein we tracked changes in shape for individual stands, there were differences in the *PI* distributions for NONE vs. ALL when considering stands of all sizes ($p = 0.048$, Table 4). Highly significant differences were also observed between these two sets for all subdivisions based on stand size ($p < 0.001$, Table 4). Unimproved roads tended to bisect a substantially greater number of stands in all size categories than did gravel roads (Table 4). For example, gravel roads bisect 17 stands < 5 ha. Subtracting 17 from 187 shows that unimproved roads bisect 180 stands (see "Paired non-zero differences," Table 4). Unimproved roads had an especially profound impact on stands < 50 ha when one considers the relative proportions of gravel vs. unimproved roads on the landscape (94 km *vs.* 171 km).

With the unpaired design, there were highly significant differences in the *PI* distributions for NONE *vs.* ALL when considering stands of all sizes ($p < 0.001$, Table 4). Overall, stands with simple shapes showed the largest numerical increase (Table 5). There were more dramatic differences evident between these two sets when considering only stands less than 5 ha ($p < 0.001$, Table 4) or stands between 0 and 50 ha ($p < 0.001$, Table 4). For both size categories, large increases in simple stand shapes were evident (Table 5).

Discussion

Other workers have described differences in landscape structure between areas disturbed by humans and relatively undisturbed areas (Krummel *et al.* 1987; Turner and Ruscher 1988; Mladenoff *et al.* 1993). Similarly, Williams and Marcot (1991) found that average patch sizes differed when comparing stands in roaded areas *vs.* non-roaded reference areas on the Klamath National Forest in the PNW. Consequently, roadless areas are thought to represent baseline or more natural conditions on the Klamath (Williams and Marcot 1991). Why, then, does there appear to be no relationship between road density and average stand size in the SRM when roads are not considered to be stand boundaries?

In the PNW, the basis of comparison was roaded *vs.* non-roaded areas (Williams and Marcot 1991), while in the SRM, we examined average stand size across a gradient of road densities. There were, in fact, differences in average stand size between units with the highest and lowest road densities in the SRM. These differences were similar in magnitude to some of the differences observed in the PNW, but the trend in the differences that we observed was not consistent and was confounded by the variability of average stand size in units with intermediate road densities. Therefore, we assert that conclusions based on the extremes in road density (*i.e.*, roaded *vs.* non-roaded) could be misleading regarding the influence of roads on average stand size or the value of using road density as an index of departure from more natural conditions.

Given the methodological differences between the two studies, it was still somewhat surprising that there were no relationships between road density and either the average stand size for a given seral stage or the proportion of an analysis unit occupied by a given seral stage. While the harvest of trees, especially old growth, was probably more widespread in the Klamath region as a result of higher economic value (Pace 1991; Williams and

Table 4. Results of comparing distributions of the Patton index (PI) for forest stands when no roads were considered stand boundaries, only gravel roads were considered stand boundaries, and all roads were considered stand boundaries, using Multiple Response Blocking Procedures (MRBP, Slausen *et al.* 1991) for paired comparisons, and Multiple Response Permutation Procedures (MRPP, Mielke 1984) for unpaired comparisons. The null hypothesis is that the contrasted groups were obtained from the pooled collection of the finite population. For the paired comparison, the PI was averaged for the stands created by the subdivision of an original stand by a given road type. Non-zero differences indicate the number of original stands that were subdivided.

Forest stands	Contrast	Paired non-zero differences	p	Unpaired n after division	p*
all (n=2183)	none *vs.* gravel	107	0.244	2362	0.080
	gravel *vs.* all	600	0.144	–	< 0.001
	none *vs.* all	645	0.048	3803	< 0.001
< 5 ha (n=912)	none *vs.* gravel	17	0.003	1062	< 0.001
	gravel *vs.* all	174	< 0.001	–	< 0.001
	none *vs.* all	187	< 0.001	2332	< 0.001
< 50 ha (n=2040)	none *vs.* gravel	81	0.044	2217	0.040
	gravel *vs.* all	516	0.010	–	< 0.001
	none *vs.* all	556	< 0.001	3676	< 0.001
50–100 ha (n=82)	none *vs.* gravel	10	0.080	89	0.745
	gravel *vs.* all	36	< 0.001	–	0.920
	none *vs.* all	39	< 0.001	82	0.842
> 100 ha (n=61)	none *vs.* gravel	16	< 0.001	56	0.635
	gravel *vs.* all	48	< 0.001	–	0.353
	none *vs.* all	50	< 0.001	45	0.706

*indicates test results obtained using the Mann-Whitney U test.

Table 5. The number of stands in various categories based on the Patton Index (PI) when roads were not considered stand boundaries (NONE) and all roads were considered stand boundaries (ALL). In addition to considering the set of all stands, stands were also grouped in three size categories (stands < 5 ha, stands < 50 ha, stands 50–100 ha, and stands > 100 ha.

			< 5 ha		< 50 ha		50–100 ha		> 100 ha	
PI	None	All	None	All	None	All	None	All	None	All
1-1.5	1119	1747	652	1215	1108	1736	10	9	1	2
> 1.5–2	681	1181	224	646	645	1149	28	28	8	4
> 2–2.5	220	483	30	237	182	445	27	32	11	6
> 2.5–3	78	202	6	121	59	183	6	7	13	12
> 3–3.5	33	101	0	68	22	90	5	2	6	9
> 3.5–4	23	58	0	35	11	48	1	0	11	10
> 4–4.5	12	22	0	12	6	18	3	4	3	0
> 4.5	17	26	0	15	7	24	2	0	8	2

Marcot 1991), it is likely that most of the gravel and dirt roads on SRM forests were originally associated with timber harvest. Hence, one would expect a greater proportion of early seral stages in units with higher concentrations of gravel and dirt roads. The average size of these SRM stands may be constrained by topography regardless of stand origin.

Both the SRM and the Klamath study areas are characterized by great topographic variation and steep relief (Whittaker 1960; Erickson and Smith 1985; Mutel and Emerick 1985; Pace 1991). Thus, landforms in both regions would be expected to result in a diversity of patch sizes and types in the absence of either human or natural disturbance (Swanson *et al.* 1988). In the current study, there was a stronger relationship between average stand size and topographic complexity than between average stand size and road density. Road density accounted for virtually no additional variation in average stand size when the index of topography was included in the model. It follows that some of the differences in stand characteristics attributed to road density in the PNW, as well as differences between the PNW and SRM, could also be related to topography.

Although there was not a consistent correlation between road density and average stand size in the SRM, differences in stand shape complexity with changes in road density were more apparent. This relationship was not addressed in the PNW study. Here, the positive correlation between the fractal dimension and road density was unexpected, as other investigators (Krummel *et al.* 1987; Turner and Ruscher 1988, O'Neill *et al.* 1988; Mladenoff *et al.* 1991) have attributed simpler patch shapes to human disturbance. These studies were conducted in the eastern and midwestern U.S., however, and the relationship between simpler shapes and human disturbance may not hold in areas where the topography is more variable. The shape of patches associated with human disturbance in the SRM, especially clearcuts, may be determined more by substantial topographic relief, resulting in more complex patches. Further support for this hypothesis is provided by Ripple *et al.* (1991), who found that areas with more extensive timber harvest were associated with more irregular patches in the Cascade Mountains of Oregon. From the results of the current study and those mentioned above, it becomes clear that landscape patterns in human-modified landscapes can only be interpreted by considering both the context and nature of the modification.

Any effort to quantify the influence of human disturbance on landscape structure must also include consideration of scale (Wiens 1989). We anticipated that the effects of roads would be most pronounced in areas adjacent to them and would thus be most apparent at the finest resolution. In the buffer analysis, differences were apparent between the composition of the buffer and that of the rest of the landscape for both covertype and seral stage. Such differences could be indicative of disturbances associated with roads, such as altered fire regimes or timber harvest, as evidenced by the greater representation of early-seral stands and underrepresentation of late-seral stands in the buffer. This result supports the observation that the effects of roads on landscape patterns are localized along the roads themselves.

Although there were differences between the area immediately adjacent to roads and the landscape as a whole, we found no general trends in the structure of landscape mosaics as road density increased. When road density is used as an index for naturalness, the underlying assumption is that disturbance could propagate anywhere along the road. This may be true for some types of disturbance, but is unlikely for other types. For instance, the ignition and spread of fire is less likely in drainage bottoms than on surrounding slopes and ridgetops (Romme and Knight 1981; Knight 1987). The heterogeneity of forest types along roads as well as the topographic context would be expected to result in differential responses to road-associated disturbance (Swanson *et al.* 1988; Knight 1987). Thus, the same disturbance type, initiated near or on roads, in areas of equal road density, may result in very different landscape mosaics.

When considered as stand boundaries, the impact of roads on the shape, size, and number of stands was pervasive. In the unpaired analysis, roads did not significantly alter the shape of stands greater than 50 ha because the fragmenting of large stands resulted in an increase in smaller stands with similar shapes. In the paired analysis, the shape of the initial stands changed significantly as roads fragmented them. Roads act as a localized effect to modify the shape of stands within an area by juxtaposing smaller, simpler-shaped stands with larger stands.

In summary, the relationship between road density and landscape structure is not easily quantified. Roads may alter the spread, frequency, and intensity of disturbances on the landscape, but their effects on landscape structure in the SRM are modified by the influence of topography and probably a variety of other factors that affect stand size and shape. Quantifying the departure from naturalness in roaded areas requires an understanding of the factors controlling the structure of unroaded landscapes, particularly in areas of great topographic relief.

When we considered roads to be stand boundaries, our analyses showed a large increase in the number of small stands with simple shapes, which tend to fragment the landscape, concurrent with a reduction in large and already rare matrix-forming patches which tend to connect the landscape

(Mladenoff *et al.* 1993). Roads in forested landscapes create high contrast ecotones (Harris 1984; Franklin 1993) associated with edge effects (Small and Hunter 1988), and consequently influence animal movement (Bider 1968; Oxley *et al.* 1974; Bakowski and Kozakiewicz 1988; Burnett 1992) as well as patch choice (Ferris 1979; Morgantini and Hudson 1980; Adams and Geis 1983; Thiel 1985; McLellan and Shackleton 1988). We therefore suggest that roads should be considered as an inherent component of landscape structure, rather than just a manifestation of human disturbance. Furthermore, plans involving both the routing of new roads and the closure of existing ones should be designed so as to optimize the structure of landscape mosaics, given a set of conservation goals.

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