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Harvest block spatial configuration as a function of logging road density: Do larger more aggregated blocks create less road?

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Abstract

Logging roads are a large component of forest management and have been directly linked to a variety of negative ecological effects, including forest fragmentation. Much research exists that views logging roads as barriers to organism movement, and, from this standpoint, assumes roads are an element of fragmentation. However, little is known about the long-term relationship between logging-road densities and harvest patch spatial configuration—a major consideration for future trends in forest fragmentation. Using spatial landscape data from managed forest landscapes in southeast British Columbia, I tested a prediction that long-term logging road densities are correlated with harvest patch spatial configuration, which implies that logging road networks influence future forest spatial patterns. My study found that while road densities in 44 study landscapes were highly correlated with the total amount of harvesting, road densities were not correlated with spatial patch indices. I suggest that these findings are the result of road planning that is intended to access all available resources in a management area and is, therefore, independent of short-term harvest patch configuration. Furthermore, these results suggest that efforts spent on planning aggregates of larger harvest patches to achieve a goal of lower road densities may be ineffective in some cases.

KEYWORDS: *forest harvesting, landscape indices, logging roads, road density, spatial pattern*

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Introduction

Logging roads are a major component of current forest management practices and are a prominent landscape feature in managed forests worldwide. Recently, logging roads have attracted attention from the general public and within the conservation literature because of their perceived negative influences on visual quality (e.g., Sheppard *et al.* 2004) and wildlife (e.g., McLellan and Shackleton 1988), and other ecological effects. (Forman and Alexander 1998; Riitters and Wickham 2003). Logging road density is often suggested as an important index of forest management activity and its associated effects (e.g., D'Eon *et al.* 2004). In particular, logging roads in managed forests have been highly associated with forest fragmentation (Reed *et al.* 1996; Miller *et al.* 1996; Tinker *et al.* 1998; Heilman *et al.* 2002), which is arguably one of the largest forest conservation issues of recent decades (Haila 2002; Wade *et al.* 2003). Indeed, as an example, McGarigal *et al.* (2001) reported that logging roads in southwest Colorado had a greater impact on landscape structure than did the harvesting.

Forest management agencies often desire harvest blocks that are large and closely aggregated, since this spatial arrangement is usually more cost effective because of efficiencies gained in harvesting and transportation costs. An often-cited advantage of planning larger and more aggregated blocks is that this harvest pattern will, by reducing the amount of harvest dispersion and therefore reducing the required access, result in less road construction and, ultimately, less forest fragmentation. While intuitively appealing, this notion has not been tested to my knowledge in British Columbia, specifically in relation to long-term road networks and harvest-patch patterns. This, and other questions surrounding the issue of fragmentation effects from forest roads in British Columbia, remains unsubstantiated.

When treated as an element of forest fragmentation, logging roads are believed to exacerbate fragmentation effects by increasing forest patch density, decreasing forest patch size, and increasing amounts of forest edge (Reed *et al.* 1996; Tinker *et al.* 1998). However, these findings are based on the assumption that logging roads are a universal element of fragmentation that divide forests into distinct patches by creating uncrossable barriers to individual movement through forests. Therefore, by definition, logging roads fragment a forest by creating forest patches that organisms perceive to be smaller and farther apart (see D'Eon 2002a for review).

Using landscape-pattern data from managed forest landscapes in southeast British Columbia, I tested the hypothesis that road density influences harvest patch size, spacing, and other spatial configuration indices as harvest allocations are mostly based on road networks.

While the validity of this assumption may hold true for some species that perceive roads as barriers to movement, it may be untrue for larger vertebrates and vagile species that can move across logging roads or that actually use them for increased mobility (e.g., D'Eon *et al.* 2002). In this sense, the issue of logging roads as an element of fragmentation is species specific and not universally applicable. Further confounding the issue of logging roads is the wide variability in logging road construction, from small temporary access roads that resemble little more than vegetated trails, to large primary roads constructed for long life and heavy vehicle traffic. For these reasons I chose to instead investigate the influence of logging roads on spatial landscape patterns by focussing on the influence of road densities on harvest patch pattern.

Harvest patches represent, in part, a component of future mature forest patterns by imposing a new pattern on the landscape, and are therefore of paramount importance to the issue of long-term landscape spatial patterns in managed forests (Nelson and Finn 1991). Therefore, if road networks govern spatial configuration of harvest patches, future forest patterns and fragmentation effects within harvested areas would be directly related to road densities—a critical consideration in the context of landscape pattern and forest fragmentation effects.

Using landscape-pattern data from managed forest landscapes in southeast British Columbia, I tested the hypothesis that road density influences harvest patch size, spacing, and other spatial configuration indices as harvest allocations are mostly based on road networks. I was particularly concerned with the question of whether larger, more aggregated blocks were associated with lower road density. This work builds on previous landscape-pattern research in this study area (D'Eon and Glenn 2005) and adds to the findings from that research.

If road density influences harvest patch spatial configuration, I predicted that spatial patterns of harvest patches would be highly correlated with road densities in managed forest landscapes, and display significant trends associated with increased road densities. As well, since total area (total amount of harvesting in this case) must be distinguished from spatial configuration (cut-block configuration in this case; Fahrig 1997; McGarigal and Cushman 2002; D'Eon 2002a) in landscape-pattern analyses, I tested the relationship between road density and harvest amounts separately from those of spatial configuration.

Study Area

Landscape pattern data were derived from managed forest landscapes totalling 352 253 ha (referred to as the "study area") within the Slocan Valley of the Selkirk Mountains in southeast British Columbia, Canada (49ºN, 117ºW; Figure 1; see D'Eon [2002b] and D'Eon and Glenn [2005] for more detailed study-area descriptions). Briefly, terrain within this mountainous area is generally steep and broken with slope gradients often exceeding 80%. Elevation ranges from 525 m along the main Slocan Valley bottom to 2800 m at mountain peaks (See Figure 1).

Forests made up 75% of the land cover within the entire study area; of this forest, approximately 57% was considered available for harvest (i.e., operationally feasible; British Columbia government timber supply review, 1998). Approximately 96% of forests in these landscapes were dominated by coniferous species (British Columbia Ministry of Forests data, 1998). Forests of this area are within the Interior Subalpine and Southern Columbia regions, as described by Rowe (1972), and are predominantly within three forest biogeoclimatic subzones, as described by Braumandl and Curran (1992), and natural disturbance regimes, as described by BC Ministry of Forests and Ministry of Environment, Lands and Parks (1995): Interior Cedar Hemlock Dry Warm (ICHdw) subzone at low elevations, Interior Cedar Hemlock Moist Warm (ICHmw) subzone at mid elevations, and Englemann Spruce Sub-alpine Fir (ESSF) subzone at higher elevations. Alpine parkland predominates above 2000-m elevations. Within one representative landscape (Lemon Creek), mid and mature forests (age > 80 years) made up 80.1% and early seral vegetation (< 40 yrs) including logged stands made up 16.2%. Logged stands made up 80.5% of the early seral vegetation in the Lemon Creek landscape.

Logging within the Slocan Valley began in the late 1800s but was primarily confined to selective harvesting. Broad-scale commercial logging and road building began around 1950. Since then, side drainages of the Slocan Valley have been managed for forest harvesting and road building to varying degrees. Many areas within the main valley corridor are privately owned and have been largely developed for agricultural and other human activities. As the focus of this study was on industrial forest land and also because no reliable forest and road inventory data exist (< 5 % of total study area), these areas were excluded from the analysis. Valhalla Provincial Park, situated along the west shore of Slocan Lake (Figure 1) and outside of commercially logged areas, was also excluded because it does not contain harvest blocks or logging roads.

The above events have created landscapes within the study area that can be generally characterized as dispersed clearcuts that are connected, to varying degrees, by logging road networks, and are within a predominantly mid to mature (~80 to 140 years) forest matrix.

Methods

Experimental Design

The study area was delineated into 44 distinct landscapes (mean area = 8 006 ha; range = 2 735–15 479 ha; SE = 442 ha, Figure 1; see D'Eon and Glenn [2005] for additional detail). Landscape boundaries were based on drainage patterns and were generally drawn along heights of land that distinguished between two adjacent drainages. Individual drainages usually form the basis of forest management planning units in this area, and were therefore useful land units for investigating the influence of forest management spatial patterns. Following terminology provided by Hurlbert (1984), landscapes were considered the experimental unit in a mensurative experiment with treatments based on past harvest levels and road densities. Harvest levels among landscapes ranged from 0 to 34.5% of the forest (harvested in past 40 years). Road densities ranged from 0 to 2.11 km of logging road per 100 ha (or km/km^2) of forested land.

Landscape Index Calculations

I defined harvest patches as clearcuts created between 1958 and 1998 (i.e., from recent to 40-year-old blocks). All source data were derived from 1998 British Columbia provincial forest cover-map information in digital format. Prior to 1998, virtually all harvest blocks in the

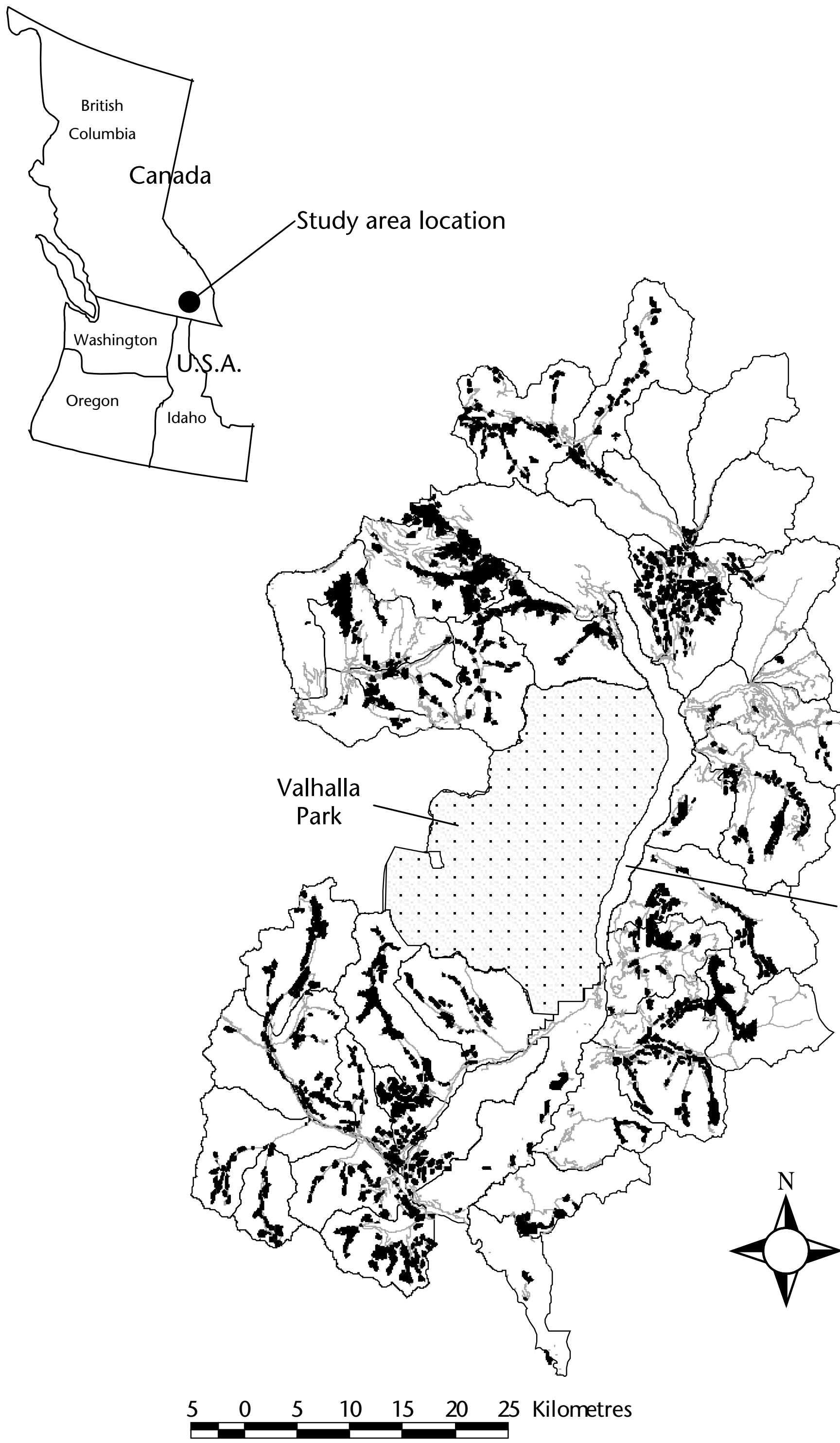

FIGURE 1. Landscapes, logging roads, and harvest patches used in a harvest pattern study within the Slocan Valley of southeast British Columbia, Canada (49°N, 117°W). Thin black lines are landscape boundaries for 44 landscapes used in the analysis; gray lines represent logging roads; solid black polygons are harvest patches (clearcut ≤ 40 years old). Source data is 1998 British Columbia Forest Service digital forest cover.

TABLE 1. Landscape indices used in pattern analyses for 44 landscapes within the Slocan Valley Basin in southeast British Columbia. In each case, variables were screened and transformed if closer to normal distributions could be obtained based on skewness and kurtosis indicators.

Index name	Description
PROP	Proportion of the forested land within a clearcut state.
PATDEN	Patch density expressed as number of patches per 100 ha of forest within a landscape.
COREDEN	Core density expressed as the amount of core area per 100 ha of forest within a landscape, assuming a 50-m edge effect from the patch perimeter.
EDGEDEN	Edge density expressed as the amount of edge area per 100 ha of forest within a landscape, assuming a 50-m edge effect on either side of a patch perimeter.
AVGPERM	Average patch perimeter length in metres within a landscape.
AVGAREA	Average patch area in hectares within a landscape.
AVGCORE	Average patch core area in hectares within a landscape, assuming a 50-m edge effect from a patch perimeter.
AVGEDGE	Average patch edge area in hectares within a landscape, assuming a 50-m edge effect on either side of a patch perimeter.
MEDAREA	Median patch area in hectares within a landscape.
NN	Average distance between patches and the nearest patch within a landscape based on closest straight-line perimeter to perimeter distance.
DISPER	Dispersion pattern index indicating spatial arrangement of patches (Clark and Evans 1954), ranging from 0 to 2.1491. Values close to 0 indicate aggregated spatial pattern, values close to 1 indicate a random distribution, and values approaching 2.1491 indicate even spacing among patches, or maximum dispersion.
EDGERAT	Ratio calculated as the amount of edge area divided by the amount of patch area for a given patch type in a landscape.
CORERAT	Ratio calculated as the amount of core area divided by the amount of patch area for a given patch type in a landscape.
SHAPE	An area to perimeter ratio from Paton (1975). A value of 1.0 indicates a perfect circle. The index increases from 1.0 with shape complexity and departure from a perfect circle.
FRACTAL	Variation of an area to perimeter ratio using an estimator of the fractal dimension of a line where the fractal dimension = 2logP/logA; where P = patch perimeter and A = patch area (Krummel *et al.* 1987; Ripple *et al.* 1991). A value of 1.0 indicates a straight line and increases with shape complexity to a theoretical maximum of 2.0 where a line becomes plane filling.

study area were clearcuts (as opposed to partial harvesting or other silvicultural treatments).

Within each landscape, a suite of 15 landscape indices (Gustafson 1998) was calculated, as listed in Table 1. For indices involving edge habitat, an assumed edge effect of 50 m from the patch perimeter was used. Previous research of this nature has suggested 50 m to be a good approximation of edge effects in western North American forests (McGargial and McComb 1995; Kremsater and Bunnell 1999).

Road density was calculated as the total linear distance of logging roads divided by the forested land base within each landscape, and expressed as kilometres per 100 ha of forest. Logging roads are derived in the provincial database used in this study from aerial photography and mapped at 1:20 000 resolution. While logging road quality may have varied somewhat, I chose to assume that logging roads were of similar quality—an assumption I considered valid for the analytical purposes of this study. Logging roads in this study were typically one-lane gravel (i.e., unpaved) roads intended for four-wheel drive vehicles and logging trucks. These roads are extremely visible, easily discernible on aerial photographs, and therefore accurately delineated and updated regularly within the database. Trails (short temporary access routes within cutblocks and coded separately in the data, also referred to as skid trails) were not included in the analyses.

The suite of indices in Table 1 was chosen to specifically deal with a vector database (standard format within the British Columbia provincial forest-cover database). They were chosen based on their direct association with testable predictions, for their familiarity within the literature, and to ease comparisons with other work. While some overlap and redundancy may occur among indices, it is widely recognized that, currently, there is no single and universally applicable measure of landscape spatial pattern that can provide all the relevant information, and that most phenomena are best described using a suite of indices (Hulshoff 1995; Riitters *et al.* 1995; Garrabou *et al.* 1998).

Patch indices (as described previously in Table 1) were calculated within an ArcInfo geographic information system platform using uniquely programmed algorithms. Patches were defined using pre-existing stand boundaries in vector format in the forest cover database. The minimum stand resolution in the data was 2 ha (i.e., all polygons were $\geq$ 2 ha).

Data Analysis

All data analyses were performed using SYSTAT 8.0 (SPSS 1998) statistical software. Tests were considered significant at $\alpha = 0.05$. Non-normal data distributions were assessed using skewness and kurtosis indicators and transformed using logarithm, square root, and arcsine transformations to produce more normal distributions. Skewness or kurtosis were considered extreme if $\pm$ 2 times their standard error did not include zero (SPSS 1998).

To reduce the number of variables and provide a more meaningful representation of overall spatial configuration effects, I used principal components analyses (PCA) to test relationships between harvest patch spatial configuration and road density. I distinguished between indices that reflect information on habitat amount (e.g., proportion of forest in patch type) and those that reflect information on spatial configuration (e.g., nearest neighbour), since this distinction is critical in the investigation of landscape pattern (Farhig 1997; D'Eon 2002a). Highly correlated variables (Pearson $r > 0.9$) were first excluded to avoid multi-collinearity among variables (Tabachnick and Fidell 1996). PCA factor scores were retained and used in further analyses when eigenvalues were > 1.0. Component loadings matrices were rotated and sorted using a varimax orthogonal rotation (Tabachnick and Fidell 1996). We then used simple linear regression analyses between PCA factors and road densities among landscapes to test our predictions.

Results

Road densities in this study area varied among landscapes from 0 to 2.11 km per 100 ha of forested land ($n = 44$, $\bar{x} = 0.62$, SE = 0.075; Figure 1). Summary statistics for harvest patch indices used in this study (Table 1) are detailed in D'Eon and Glenn (2005).

Eleven indices (AVGPERM, AVGAREA, AVGCORE, AVGEDGE, MEDAREA, NN, DISPER, EDGERAT, CORERAT, SHAPE, and FRACTAL) related to spatial pattern (as opposed to directly representing habitat amount) were considered for principal component analyses (PCA) to derive new variables representing spatial patterns of harvest patches. While many patch indices are correlated with patch amount to some degree (D'Eon and Glenn 2005), these 11 indices do not directly represent habitat amount and do not provide information about habitat amount. On this basis, they were distinguished from other indices that directly provide information about habitat amount (as described below). To avoid multi-collinearity among variables, 4 patch indices were eliminated prior to PCAs due to high correlations with other indices (Pearson correlation $r > 0.9$). In this way, 7 indices were used in the PCA of harvest patch indices (Table 2), resulting in 3 new principal component indices (SPATIAL1, 2, and 3) from the original suite of 11 patch indices related to spatial configuration. Indices related to habitat amount (PROP, PATDEN, COREDEN, and EDGEDEN) were not included in PCA to distinguish between habitat amount and spatial configuration of habitat elements. Rather, these indices were sufficiently represented by PROP due to high correlation between PROP and each of PATDEN, COREDEN, and EDGEDEN within all patch types (all Pearson correlation $r > 0.815$).

Based on factor loadings (Table 2) the principal component SPATIAL 1 primarily represented information associated with core ratio (factor loading = 0.930) and average patch area (0.758); SPATIAL 2 with patch shape (−0.837) and the fractal dimension (−0.948); and SPATIAL 3 with median patch area (0.836), edge ratio (0.836), and dispersion (−0.735).

Linear regression analyses between amount of harvesting in landscapes (PROP) and logging road densities were highly significant ($r^2 = 0.795$, $p < 0.001$; Figure 2).

TABLE 2. Component factor loadings for principal components analyses of harvest patch indices for 44 landscapes within the Slocan Valley Basin of southeast British Columbia.

	Principal components[a]		
Index[b]	**Spatial 1**	**Spatial 2**	**Spatial 3**
AVGAREA	0.758	-0.528	0.287
MEDAREA	0.202	0.258	0.836
DISPER	-0.078	0.375	-0.735
CORERAT	0.930	0.097	0.081
SHAPE	0.357	-0.837	0.210
FRACTAL	-0.094	-0.948	-0.137
EDGERAT	0.202	0.258	0.836
EIGENVALUE	3.263	1.708	1.031
EXPLAINED VARIANCE[c]	35.36%	30.22%	20.17%

[a] Only principal components with eigenvalues ≥ 1 retained and reported. Varimax orthogonal matrix rotation used to obtain factor loadings.
[b] Highly correlated (Pearson correlation $r > 0.9$) indices deleted from an original suite of 11 spatial pattern indices.
[c] Proportion of variance explained by each principal component.

In contrast, logging road density versus the spatial principal component indices for harvesting (SPATIAL 1, 2, and 3) were not significantly associated (all $r^2 \leq 0.100$, all $p > 0.056$; Figure 2), although relationships with SPATIAL 1 and 2 were marginally so ($p = 0.056$ and $p = 0.090$, respectively; Figure 2).

Discussion

Logging road densities had no significant association with past harvest spatial patterns in this study, thus falsifying a prediction that harvest patch spatial patterns are a consequence of road patterns, or vice versa. While regressions were only marginally insignificant for two of the spatial principal components (SPATIAL 1 and 2), which perhaps suggests a weak relationship, explained variability (r^2) and, therefore, predictive power was very low for all three spatial principal components. The amount of harvesting, however, was highly associated with road densities and had relatively high predictive power. The combination of these results implies that while the inherently obvious statement that, "more logging results in more roads" is true, it rejects the notion that harvest-patch attributes that are important to the issue of fragmentation, such as patch size and spacing, are related to road density.

The situation in this case is likely explained by road-building constraints experienced in rugged mountainous terrain where topography largely governs where roads are built. Indeed, typical efforts to design forest road networks occur not with thought to harvest patches, but to where the optimal locations are for roads based on terrain and long-term wood flow (Murray 1998; Clark *et al.* 2000; Anderson and Nelson 2004). Consistent with this, while Miller *et al.* (1996) found road density correlated with forest-stand shape, they failed to find a relationship between average forest-stand size and logging-road density in Colorado and concluded that topography exerted the greatest influence on stand size.

Current forest-management planning in this study area typically begins by planning road networks that will eventually access all potential long-term harvest areas in a planning unit, regardless of the short-term objectives. As a result, road networks tend to be constructed for maximum access to timber within a planning cell, given a set of terrain constraints. Therefore, road networks are largely independent of patch configuration in the decision-making and planning process and this largely explains the phenomena observed in my study. This result implies that long-term forest-patch patterns are not related to logging-road densities and vice versa (given similar relationships through time that were present during this study). Indeed, Nelson and Finn (1991) found exclusion-period length (length of time between harvest entries) had a greater effect on road networks than did block size.

A caveat of this work surrounds the issue of boundary delineation and the calculation of road densities. Since logging roads are typically not uniformly dispersed, one could imagine areas in a given landscape that are roadless and, therefore, could be omitted from a calculation of road density, producing different results. However, doing so in this study would have inserted unknown biases; boundary delineation would have had to been based on somewhat arbitrary decisions about where roadless areas start and end. Instead, landscapes in this study were chosen based on geographical criteria (chosen a-priori) and therefore represent an unbiased design.

Another important consideration in the investigation of logging road networks in an ecological context is the distinction between active and inactive roads (active

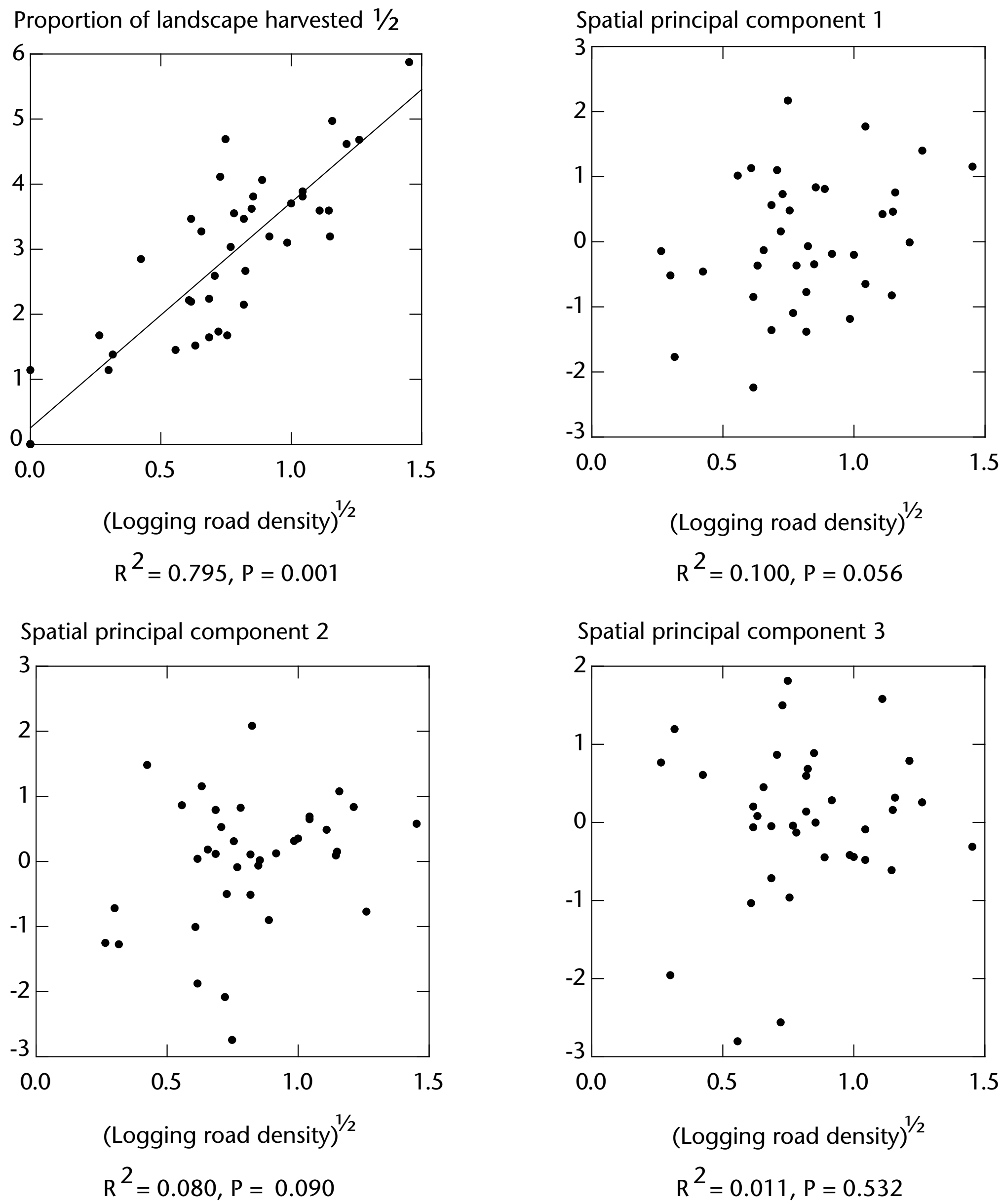

FIGURE 2. Regression analyses between logging road density, and proportion of landscapes harvested (square root transformed) and 3 spatial principal components of harvest patch indices in the Slocan Valley of southeast British Columbia. Logging road density (square root transformed) is in km per 100 ha of forest.

means actively maintained and used on a regular basis; inactive means not in regular use either due to deactivation or weathering). Nelson (unpublished data), again using simulation modelling, predicted that one of the biggest gains in planning larger harvest-block sizes would be a reduction in active road length. In our study, I did not make this distinction since the focus was on landscape patterns, which stay the same regardless of vehicle activity and maintenance. However, this distinction could be relevant depending on the ecological phenomenon or process under study, and is an avenue for future work. For example, issues such as traffic disturbance effects on wildlife or edge effects from regrowth would be different between actively maintained roads and those that are either inactive or deactivated. Future work of this nature could therefore focus on the stratification of road types in the context of varying ecological and fragmentation effects.

A final caveat of this work is the fact that my analyses investigated spatial patterns of past harvest operations. These past harvest operations may, or may not, have been planned with any a-priori road network objectives concerning their influence on harvest spatial patterns. My study therefore leaves open the possibility that one *could* manage road density through spatial arrangement of harvest patches, if that is an a-priori objective. The results reported here represent the status quo of forest management within my study area over the past 40 years—which is that road density and harvest spatial patterns were not correlated. However, the question of whether or not long-term road density and harvest spatial patterns can be correlated by design and integrated in management planning is a topic for further study.

Management Implications and Recommendations for Further Study

In this study, road densities were not correlated with indices of harvest patch configuration. Therefore, management effort spent on harvest block spatial allocation in an attempt to reduce road densities, a common goal in contemporary forest management, may not achieve this objective, or in a worst-case scenario, be wasted effort. For example, while perhaps some short-term reductions in road densities may occur by planning aggregated groups of larger harvest blocks rather than widely dispersed smaller blocks, long-term access to all harvestable areas in a landscape may result in a road network that is identical (or very similar) regardless of the spatial configuration of harvest blocks. This scenario has been demonstrated in simulation modelling in British Columbia where short-term gains in lower road densities were the result of small harvest-block size rules (J. Nelson, University of British Columbia, unpublished data). However, road length per unit volume of harvested wood did converge over long time periods regardless of size constraints on harvest blocks, which is consistent with my hypothesis.

A major consideration concerning the results of this study is the mountainous terrain where the data was collected. Since terrain can be a driving factor governing road construction, differences in terrain could produce differing results among different areas. Therefore, I recommend repeating this study, or investigating similar relationships between road networks and harvest patches, particularly in more gentle terrain where terrain restrictions are less and, therefore, may have less influence on road networks. These investigations should occur to establish the validity of many strongly held assumptions about the benefits of large aggregated patches in relation to associated road networks.

In summary, in mountainous terrain I suggest that a management argument for larger and more aggregated patches, based on the perceived outcome of lower short-term road densities, must be considered in light of long-term road construction plans that may result in similar long-term road densities, regardless of harvest patch configuration. This, and other road density relationships, should be investigated and tested in other jurisdictions under a variety of terrain types and under a variety of management objectives—particularly those that directly concern road density objectives.

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Test Your Knowledge . . .

Harvest block spatial configuration as a function of logging road density: Do larger more aggregated blocks create less road?

How well can you recall some of the main messages in the preceding Research Report? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. In this study, road densities were not associated with:
   - A) spatial patterns of harvest patches
   - B) road width
   - C) the amount of harvesting

2. A possible explanation for the above, is:
   - A) there is little planning in forest management
   - B) road networks are typically planned in their entirety prior to harvesting
   - C) forest harvesting often does not require new roads

3. Considerations for further study are:
   - A) the effects of harvest patterns on inactive versus active roads
   - B) the effects of terrain on road network and harvest pattern relationships
   - C) all of the above

Answers

1. A 2. B 3. C