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Forest fragmentation in the Pacific Northwest: quantification and correlations

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Abstract

A forest fragmentation index was produced for western Oregon and western Washington that combined measures of forested area, percentage edge, and interspersion. While natural, human land-cover, and human land-use processes contribute to forest fragmentation in the region, the drivers of these processes are categorically different. Here we examine forest fragmentation caused by human land-use decisions, which accounts for 20% of the total forest edge in the region. Using multiple linear regression, we developed a model with socio-economic and environmental predictor variables that explains 80% of the variance of the forest fragmentation index across the region. Population density, income, and percentage agriculture were all significant and positively correlated with the fragmentation index. Significantly negative correlations were found between the forest fragmentation index and distance to highway, percentage federal land, slope, and a dummy variable indicating land in Oregon. The three components of the fragmentation index were used as predictor variables in separate regression models and yielded results similar to the composite index. Models run separately for western Oregon and western Washington were similar to the regional model except that distance to highway was only significant in the western Oregon model and income was only significant in the western Washington model.
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Keywords: Fragmentation; Land-use; Land-rent; Spatial patterns

1. Introduction

In numerous studies (see Saunders et al., 1991; Debinski and Holt, 2000), forest fragmentation has been shown to adversely affect ecosystem processes and patterns such as the distribution of breeding birds (McGarigal and McComb, 1995; Trzcinski et al., 1999). Concerns also have been raised about the impact of fragmented forests on designing conservation plans (Schwartz, 1997) and the ability of fragmented forests to function as working forests (Sampson and DeCoster, 2000). Although numerous studies have examined the effects of forest fragmentation on ecological processes, few studies have investigated the relationships between people and fragmentation (Wickham et al., 2000). The most similar research has been the investigation of the interactions between people and land-use and/or land-cover patterns (e.g., Bockstael, 1996; Turner et al., 1996), but these studies have not explicitly examined fragmentation.

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One reason for this dearth of human-fragmentation studies is the lack of a commonly accepted method for quantifying fragmentation. Li and Reynolds (1993) define forest fragmentation as "the processes of increasing the number of landscape pieces, decreasing interior habitat area, increasing the extent of forest-opening edges, or increasing isolation of residual forest patches". Forest fragmentation has been quantified using many different metrics of landscape structure (e.g., O'neill et al., 1988; Turner, 1989; Ripple et al., 1991), including patch area, patch density, patch size, patch variability, amount of edge, shape complexity, core area, nearest-neighbor, diversity, and contagion and interspersion among patches (McGarigal and Marks, 1994). Although a single metric is not capable of capturing the entire complex of landscape characteristics that influence forest fragmentation (Cain et al., 1997; Betts, 2000), some underlying trends indicate what components of fragmentation are most important to capture. A review of more than 100 articles by Betts (2000) showed that metrics related to percentage habitat cover, distribution of patch sizes, edge effects, and landscape configuration were the most commonly measured.

Although forest fragmentation occurs by both natural and human processes (Rochelle et al., 1999), we limited our study to fragmentation caused directly by human land-uses. This restriction removes both natural fragmentation and fragmentation that results from temporary land-cover changes caused by human actions, such as timber harvesting. The limitation of fragmentation to land-use changes allows the well-developed body of knowledge related to land-use change dynamics to be used as a foundation for exploring the relationship between people and forest fragmentation.

In this study, we combined multiple forest fragmentation metrics into a single index to quantify fragmentation across the Pacific Northwest (Fig. 1). By focusing our analysis on fragmentation caused by human land-use decisions, we found that edges between forests and human land-uses accounted for 20% of the total amount of forest edge across the study area (Fig. 2). The correlation between the forest fragmentation index and a set of socio-economic and physical variables were modeled using multiple linear regression. Results from this study provide insights into human forces that shape forested landscapes so that the human actions can be better assessed and addressed.

2. Study area

Models of forest fragmentation were developed for the Pacific Northwest—specifically Oregon and Washington west of the crest of the Cascade Range (Fig. 1). The forests of the Pacific Northwest are important from economic, ecological, and social perspectives. Habitat for wildlife, timber and nontimber forest products, and recreational retreats are just a few of the myriad resources and opportunities that these forests provide. Although the federal government is the single largest landowner in the region, forest industry companies and nonindustrial private owners own 40% of the forest land base and state and local governments own an additional 7% (Smith et al., 2001). A prominent feature of the region is the mountains heavily clad in Douglas-fir (*Psuedotsuga menziesii* (Mirb.) Franco) surrounding the flatter valleys that contain the major agricultural areas and population centers.

3. Methods

We developed a forest fragmentation index composed of three fragmentation metrics and determined its relationship to socio-economic and physical variables using multiple linear regression. Separate models are presented for the composite index, each of the components or metrics of the index, and two sub-regions.

3.1. Data

Data used in this study consisted of geographic data layers available through public agencies. For all data in the regression models, the units of analysis were census tracts as defined in the 1990 US Census (US Census Bureau, 1990). These analysis units ranged in size from 2 to 434,000 ha (median = 669 ha) depending on the population density and other criteria used by the US Census Bureau. To adjust for the influence of unequal sized analysis units, the sizes of the census tracts were used as weights in the regression models

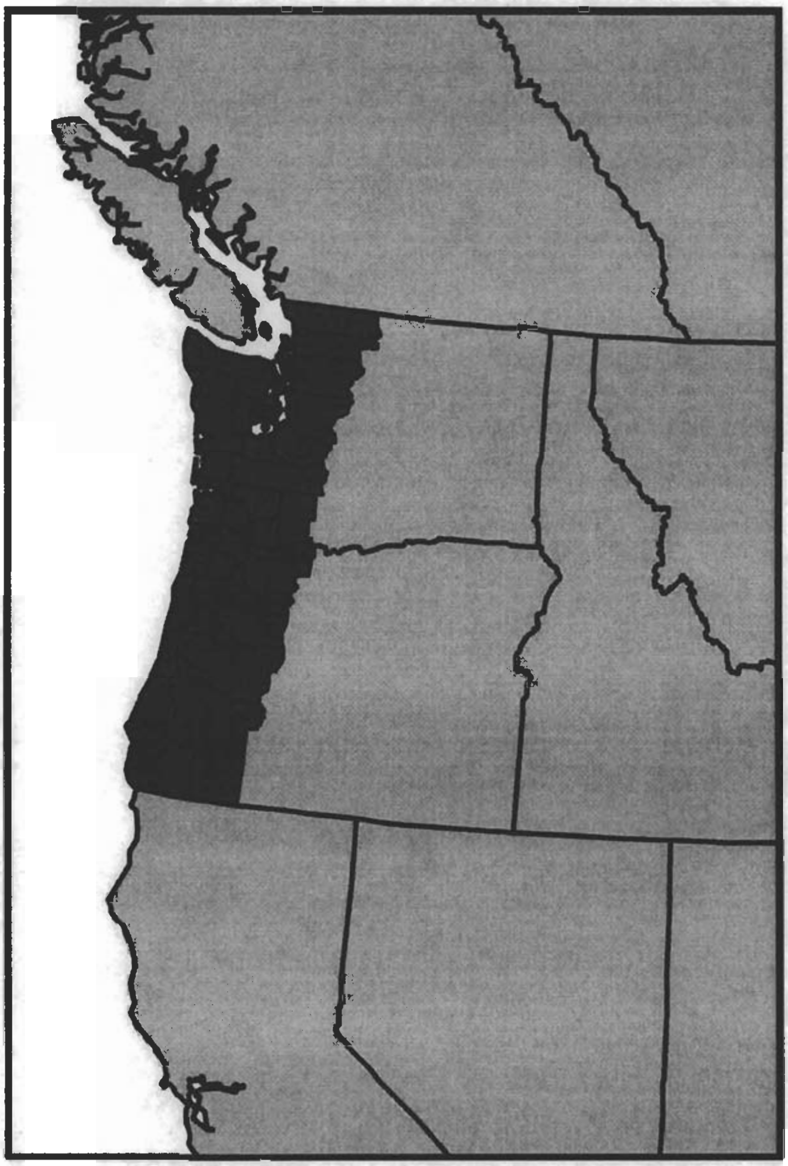

Fig. 1. Map of the study area.

described below. In addition to defining the analysis units, the 1990 US Census provided population and income data and defined urban areas. The older 1990 Census data were used instead of the newer 2000 Census data because the date more closely matched other data sources, such as the remotely sensed imagery.

The Oregon and Washington National Land Cover Data map, produced by a consortium of governmental agencies from 1990 Thematic Mapper satellite imagery, was used to define forest, other natural vegetation, agriculture, and other human-use categories (Vogelmann et al., 2001). Distances to urban centers were calculated as the average distance of all pixels within an analysis unit to the nearest of the 10 major metropolitan areas in the region (US Census Bureau, 1990). Distances to highways were calculated as the average distance of all pixels within a census tract to the nearest state or interstate highway (US Geological Survey, 1980). Average slope for each census tract was

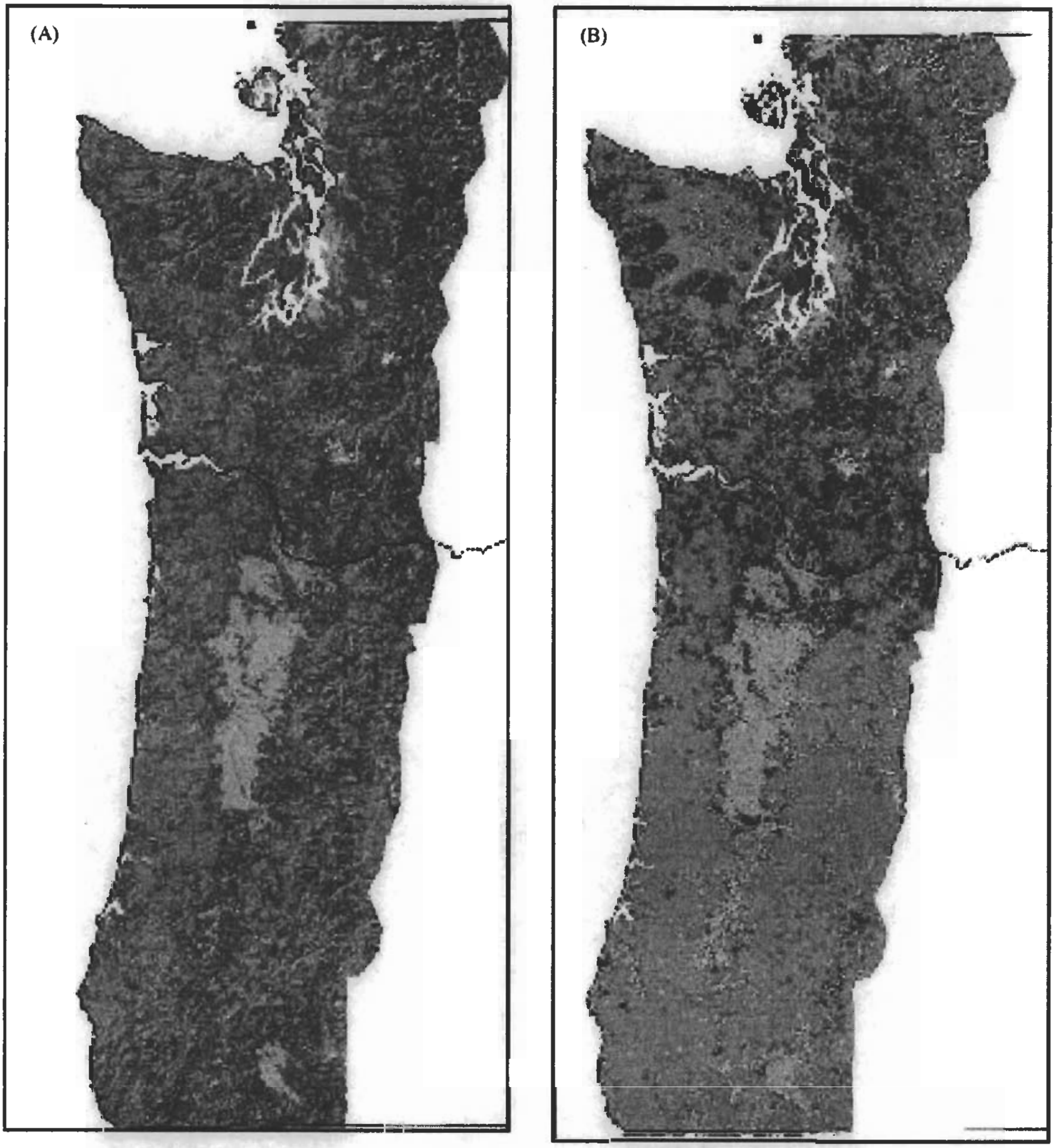

Fig. 2. Comparison of forested edges as defined by juxtaposition with land-covers (A) and juxtaposition with human land-uses (B).

calculated from 90 m digital elevation models (Defense Mapping Agency, 1997).

3.2. Calculation of the forest fragmentation index

One solution that has been proposed for the dilemma of choosing among multiple fragmentation metrics is the calculation of a single index that combines multiple metrics representing the key components of fragmentation (Bogaert et al., 2000). Such an index allows for fragmentation to be compared across an area of interest and is more amenable to further analyses. The most commonly measured components of fragmentation are percentage habitat cover, edge effects, landscape configuration, and patch size distribution (Betts, 2000). Choice of appropriate components of fragmentation and their metrics is dependent upon the scale of analysis and questions to be answered, which for our study includes better understanding of the drivers of forest fragmentation at a regional scale.

The components that we selected to measure for our forest fragmentation index (FFI) are

- percentage nonforest cover (pnf);
- percentage edge (pe); and
- interspersion (in).

Patch size was not included in the index because this metric behaves poorly at the regional scale with data of a relatively coarse resolution. For example, using 30 m resolution forest cover data, most of the forest in western Oregon is classified as a single forested patch despite the fact that the forest cover is traversed and broken up by roads and other entities too small to be detected in the land-cover map.

To efficiently combine the metrics into a single, unified index, all metrics must have similar ranges and similar relationships to fragmentation. The metrics were calculated to range from 0 to 100 or converted to a scale with this same range. The metrics were defined so that they were all positively correlated with fragmentation.

3.2.1. Percentage nonforest cover

The proportion of nonforest cover represents the relative amount of each analysis unit that was classified as a nonforest land-use. Every cell or pixel on our land-use map was reclassified as either forest or nonforest where forest included deciduous, evergreen, and mixed forest types and "transitional" land of all ages and disturbance histories. In our study area, transitional lands primarily correspond to areas of recent timber harvests and most harvested timberland in the Pacific Northwest remains in a forested land-use after a harvest (Alig et al., 2000). The regrowth of a harvested forest will not be identical to the original forest, yet because we are considering all types of forest as one category, attributes of forest type, health, canopy structure, age, etc., are beyond the scope of this study.

The proportion nonforest metric was calculated as the total number of cells or pixels in an analysis unit classified as a nonforest land-use divided by the total number of cells in the analysis unit and multiplied by 100. Nonforest values ranged from 0.0 to 99.4% among analysis units with a weighted, regional average of 20.3%.

3.2.2. Percentage edge

The percentage edge provides a description of the relative amount of the forest area that is bordered on at least one side by a human land-use. Each forested pixel on our land-use map was classified as (human land-use) edge or interior. If one or more of the adjacent eight pixels were classified as a human land-use—development, agricultural crops, or quarry/mining—then the pixel was identified as an edge. Otherwise the forested pixel was considered an interior pixel. Dividing the number of edge pixels in an analysis unit by the number of forest pixels and multiplying by 100 yielded percentage edge. The values of the percentage edge metric ranged from 0.0 to 100.0% among analysis units with a regional, weighted average of 5.7%.

3.2.3. Interspersion

The interspersion metric is a measure of heterogeneity or the degree of clumping (low values) or isolation (high values) of forested areas. Each forest pixel was assigned an interspersion value, which is a count of all dissimilar (i.e., human land-use) neighbors in the adjacent eight pixels. This count was then divided by eight (the maximum potential interspersion value) and multiplied by 100. The average interspersion value for all forest pixels in an analysis unit was calculated. Values ranged from 0.0 to 100.0% with a region-wide, weighted average of 3.1%.

3.2.4. Combining metrics

Percentage nonforest, percentage edge, and average interspersion metrics were summarized for all analysis units in the study area that had at least some forest area identified. Analysis units with no forest area (11 out of 1460 analysis units) were excluded from further analysis. Although each component of the index captured a different facet of fragmentation, the metrics were highly correlated within the study area (Table 1). Separate regression models for each metric and the composite index, as described below, produced similar, but not identical, results.

The sensitivity of the index to the weights used for combining the three metrics was assessed using a

Table 1
Correlation coefficients among the metrics combined in the forest fragmentation index for the Pacific Northwest

	Percent nonforest	Percent edge	Interspersion
Percent nonforest	1.00	0.80	0.84
Percent edge	0.80	1.00	0.90
Interspersion	0.84	0.90	1.00

sensitivity analysis. At first, all components were given equal weights (Eq. (1)). We gradually changed the weight of one component while giving the other two components equal weights. Through this process, we observed that the index was robust to changes in the weights and subsequent analyses showed that alternative weights did not significantly change the results of our empirical models:

$$\mathrm{FFI} = \left(\frac{\mathrm{pnf} + \mathrm{pe} + \mathrm{in}}{3}\right) \qquad (1)$$

In the final model, the metrics were given equal weighing as shown in Eq. (1). The forest fragmentation index had values ranging from 0.0 to 99.9 with a weighted average of 9.7.

3.3. Relationship between people and forest fragmentation

3.3.1. Theoretical relationship between people and forest fragmentation

Because forest fragmentation, as defined here, is a result of human land-use decisions, the same processes that influence broad scale land-use patterns are hypothesized to influence the fine-scale patterns that affect fragmentation. This fact is advantageous because it allows for the well-developed theories of land-use dynamics to be applied and adapted to the topic of forest fragmentation.

Most modern land-use theories are based on Ricardo's and von Thunen's land-rent theories (Van Kooten, 1993). This body of theories states that land-use is allocated to maximize the present value of the flow of net revenue or rent from a person's land given the quality of their land. The land quality is an all-encompassing term that includes attributes ranging from soil fertility to distance to urban centers. The rent (R) that a landowner receives from her land is function of the non-fiduciary utility (U) that she receives, the revenue generated (p), and the costs for holding lands (c; e.g., taxes) and of land-use conversions (c') (Eq. (2)). All of these factors are a function of the amount of land (z) dedicated to a specific land-use (l) and the quality of the land (q):

$$R = \sum_{l}(U_l(z,q) + p_l(z,q) - c_l(z,q) - c_l'(z,q)) \qquad (2)$$

Empirical land-use models attempt to explain observed or revealed patterns of land-use, drawing upon a set of behavioral assumptions. A key assumption is that a rational landowner will select the configuration of land-uses that maximizes the total rent received from the land that they own. From society's perspective, the land-use in a given location will be selected based upon maximizing the value of the rent received for the landscape as a whole. The individual's optimal land-use allocations and society's optimal landscape configurations and resulting fragmentation patterns can be substantially different.

3.3.2. Empirical model of the relationship between people and forest fragmentation

The fact that land-use dynamics is the key human process affecting forest fragmentation, as defined here, allows for fragmentation models to build upon land-use models. Influences of human-related factors on land-use change have been investigated for various regions in the United States (e.g., Alig, 1986; Mauldin et al., 1999; Kline and Alig, 2001). In these empirical studies, prime determinants of land-use change are variables or proxies pertaining to population, personal income, and incomes from land enterprises (e.g., agriculture). Such empirical studies support the importance of relative land-rents in determining land-use (Alig, 1986). Changes in supply and demand conditions for different land enterprises can cause changes in relative land-rents, such as the increased demand for housing or residential land-uses due to population growth (e.g., Alig and Healy, 1987). In the case of urban development, land is converted by persons with needs and individual preferences. Land-rents for urban uses often increase as one approaches city centers (Kline and Alig, 2001) and commuting distances to work or other activities are reduced, so that proximity to cities is likely to influence the conversion of undeveloped land

Table 2
Ranges and expected signs of variables used in the Pacific Northwest forest fragmentation model

Variable	Minimum	Weighted mean	Maximum	Expected sign
Forest fragmentation index	0	10	100	N/A
Population density (people per km^2)	0	0.5	643	+
Housing density (housing units per km^2)	0	0.7	466	+
Median per capita income (thousands of US$ per year)	0	27	84	+/−
Distance to nearest urban center (km)	0	49	157	−
Distance to nearest highway (km)	0	10	40	−
Percentage agricultural land	0	8	98	+
Percentage urban	0	3	100	+
Percentage federal	0	53	100	−
Average slope (percentage)	0	9	27	−
Elevation (m)	1	588	1783	−
Oregon (dummy variable) (binary)	0	0.5	1	−

to urban or developed uses. Similarly, when forest land is converted for agriculture uses, specific areas are targeted.

Based upon previous land-use research and data availability, we included population density, housing density, income, proximity of urban areas and highways, agriculture, urban, federal ownership, slope, and elevation variables in our empirical model. In addition, we used a dummy variable to test for differences between Oregon and Washington. A brief description, range of values, and expected signs of these variables are listed in Table 2. Log and arcsin square root transformations were used for the population density and slope variables, respectively, to produce linear relationships with the dependent variable. Because the log of zero is undefined and zero is a valid value for the population density in an analysis unit, all tracts with zero population densities (29 out of 1460 analysis units) were assigned values of the next lowest population density value.

A multiple linear regression model was built to quantify the relationships between the forest fragmentation index and the explanatory variables. The regression models were weighted by the area of each analysis unit to adjust for unequal analysis unit sizes. This is an artifact of using analysis units that were designed for a population census and defined to have similar numbers of people in each analysis unit. Regression models were also created for two subregions and each of the three metrics combined in the index. The square of the multiple correlation coefficients, R^2, are reported for all models to summarize the predictive power of the model. These values did not differ significantly from the adjusted-R^2 values that accounted for the number of observations and parameters in the model.

To check for collinearity, the variables were first examined from a theoretical perspective and all explanatory variables that appeared redundant or were highly correlated ($\rho \geq 0.60$) with other variables were removed. During this process, elevation, percentage urban, and housing density were removed from the final models. Two interaction terms, log(population density) × highway distance and percentage federal ownership × arcsin $\sqrt{\text{slope}}$, were added to the model to corrected for unexpected signs for the highway distance and percentage federal ownership variables. Correlation matrices, variance inflation factors, and scatter plots were used to verify that collinearity was not a significant factor among the remaining variables.

4. Results

Percentage agriculture and population density were the explanatory variables most highly correlated to the forest fragmentation index, followed by slope, distance to urban center, and percentage federal land. The empirical forest fragmentation model was able to account for 80% of the observed variability in forest fragmentation (Table 3). All variables tested, except for distance to urban center, were significant ($P < 0.01$) in the regional model. With the inclusion of the interaction terms, all of the explanatory variables had the expected signs.

Table 3
Coefficients of a forest fragmentation index linear regression model for the Pacific Northwest[a]

Variable	Coefficient	Standard error	t-Value	Partial R^2
Intercept	23.158***	1.437	16.117	–
log(population density)	10.903***	0.545	20.018	0.184
Distance to highway	−0.228***	0.052	−4.363	0.003
Income	0.107***	0.031	3.482	0.003
Distance to urban center	−0.009	0.007	−1.293	<0.001
Percent agricultural land	0.346***	0.013	25.998	0.519
Percent federally owned	−0.244***	0.02	−12.058	0.025
arcsin $\sqrt{\text{slope}}$	−54.907***	4.09	−13.426	0.009
Oregon (dummy variable)	−1.147**	0.394	−2.914	0.019
log(population density) × distance to highway	−0.370***	0.046	−8.069	0.027
Percent federally owned × arcsin $\sqrt{\text{slope}}$	0.924***	0.058	15.921	0.110

[a] $R^2 = 0.80$; $n = 1446$.
** $P < 0.01$.
*** $P < 0.001$.

The interaction terms in the model need to be interpreted carefully. For example, the negative sign of the population–highway interaction term does not mean that as these terms increase, fragmentation decreases. As with all regression variables they need to be interpreted in the context of the model. The simplest interpretation for this interaction term is that population density and highway distance impact fragmentation and when both of these variables are considered there is an interaction or redundancy between the terms that needs to be corrected and hence, the interaction term.

The regression models based on the metrics that are combined in the index (Table 4) and the composite index regression model yielded similar results, but there were some differences. The signs for all significant variables were the same across all of the models. Urban distance was not found to be significant in any of the models, although it was marginally significant in the percent nonforest model ($P = 0.07$). The percent nonforest model had the greatest predictive power ($R^2 = 0.80$) and was the only model where highway distance was not significant. The Oregon dummy variable was not significant in the percentage edge or interspersion models. The interspersion model had the lowest predictive power ($R^2 = 0.63$) and was the only model where income was not significant.

Table 4
Coefficients of percent nonforest, percent edge, and interspersion linear regression models for the Pacific Northwest[a]

Variable	Percent nonforest		Percent edge		Interspersion	
	Coefficient	t-Value	Coefficient	t-Value	Coefficient	t-Value
Intercept	36.912***	16.631	18.596***	11.496	13.965***	11.772
log(population density)	13.938***	16.568	11.736***	19.14	7.034***	15.643
Distance to highway	−0.101	−1.253	−0.374***	−6.36	−0.209***	−4.837
Income	0.108*	2.278	0.176***	5.093	0.037***	1.447
Distance to urban center	−0.02	−1.798	−0.002	−0.285	−0.006	−0.945
Percent agricultural land	0.677***	32.941	0.239***	15.99	0.121***	11.034
Percent federally owned	−0.402***	−12.885	−0.190***	−8.364	−0.138***	−8.303
arcsin $\sqrt{\text{slope}}$	−72.588***	−11.491	−54.559***	−11.85	−37.575***	−11.129
Oregon (dummy variable)	−2.923***	−4.806	−0.578	−1.305	0.059	0.181
log(population density) × distance to highway	−0.289***	−4.078	−0.517***	−10.03	−0.303***	−8.011
Percent federally owned × arcsin $\sqrt{\text{slope}}$	1.488	16.606	0.751	11.49	0.533	11.117

[a] For percent nonforest, $R^2 = 0.80$; for percent edge, $R^2 = 0.73$; for interspersion, $R^2 = 0.63$; $n = 1446$.
* $P < 0.05$.
*** $P < 0.001$.

Table 5
Coefficients of forest fragmentation index linear regression models for western Oregon and western Washington[a]

Variable	Western Oregon		Western Washington	
	Coefficient	*t*-Value	Coefficient	*t*-Value
Intercept	33.430***	15.720	19.062***	9.713
log(population density)	9.854***	13.193	12.315***	15.905
Distance to highway	−0.302***	−3.977	−0.055	−0.746
Income	0.024	0.547	0.140***	3.463
Distance to urban center	−0.016	−1.775	−0.006	−0.508
Percent agricultural land	0.297***	18.327	0.213***	7.159
Percent federally owned	−0.249***	−6.969	−0.184***	−7.472
arcsin $\sqrt{\text{slope}}$	−80.684***	−13.643	−45.836***	−8.101
log(population density) × distance to highway	−0.427***	−6.256	−0.357***	−5.924
Percent federally owned × arcsin $\sqrt{\text{slope}}$	0.890***	8.556	0.782***	11.076

[a] For Oregon, $R^2 = 0.90$ and $n = 605$. For Washington, $R^2 = 0.68$ and $n = 841$.
*** $P < 0.001$.

For the state-level models, the western Oregon model was more powerful than the Washington model (Table 5). The signs of the variables did not change between the regional and state models, but the significance of some variable did change. While distance to urban center was still insignificant in both state models, distance to highway was only significant in the western Oregon model and income was only significant in the western Washington model.

5. Discussion

5.1. The forest fragmentation index

A composite index is an alternative to the multiple metric method used to describe the facets of forest fragmentation. This single value approach is particularly well adapted for making comparisons within a study area and producing models to help explain causal factors. A sufficiently robust body of research has amassed for identifying the major facets of forest fragmentation. Capturing these facets with metrics that can be easily interpreted and combined allows for the composite index to be created.

5.2. The empirical model

Results of the empirical model conform to the expectations arising from the theories that underlie land-use models. As with land-use models, socio-economic and physical factors proved to be important predictors of forest fragmentation. An increase in the number of people in an area means that there will be more development and expansion of related land-uses that will be competing with forestry. Proximity to highways influence how local people and "outsiders" access the land.

In general, increased personal income results in lifestyle choices that increase forest fragmentation. As affluence grows, people can more easily afford larger parcels of land on which to build primary or secondary residences. Whether the development occurs on old farm land or forest land, the subsequent land-uses are less likely to be as homogenous. But at the higher end of the income spectrum, landowners can afford to purchase even more expansive parcels of land and decrease fragmentation as compared to more moderate density development patterns.

Slope is a convenient variable for describing the physical accessibility of the land. Land that is flat is more conducive for building and farming than steeper land. Technology has been affecting this trend because it is now easier to develop on steeper parcels that provide dramatic vistas, making them attractive sites for homeowners. However, it is unlikely that this phenomenon will account for more than low-intensity, scattered development opportunities.

Areas dominated by federal ownership showed significantly different forest fragmentation patterns than areas dominated by private ownership. Federal lands tend to be in larger swathes and development within their boundaries is typically minimal. These ownerships are more stable and long term than many private ownerships and they have the ability to conduct landscape-level management that considers factors such as fragmentation.

The dummy variable that identified the two states in the study area was significant with its greatest impact on the percent nonforest component of the index. Differences in land-use patterns were the result of state-wide and local planning regulations, economic climates, soil characteristics, and other variables related to broad scale land-use decisions.

6. Conclusions

Fragmentation is a regular phenomenon in the forests of the Pacific Northwest where 13% of the forest is affected by (i.e., within 30 m) nonforest areas. When forest fragmentation patterns exceed the conditions to which native species are adapted, the balance of ecosystems can shift. It then becomes easier for new species to be introduced and become established. Those native and non-native species that are well adapted to these changes in fragmentation patterns will flourish while those less well adapted will be at a competitive disadvantage.

The primary force causing changes in the fragmentation patterns are human-caused disturbances. In the suite of human-caused disturbances, land-use changes are one of the most significant because of the permanency and severity of the patterns created. In the Pacific Northwest, percentage agriculture and population density were the strongest predictors of forest fragmentation caused by land-use decisions and these variable are obviously influenced by environmental factors, personal choices, and political decisions.

Forest fragmentation, as defined here, is a social issue. Human actions cause these changes and human choices will decide if these actions need to be modified. Forests are becoming more "peopled," and the trend is likely to continue as the region's population is expected to grow more than the national average over the next several decades. Increasing the density of people within private forest areas will likely lead to more private forest fragmentation, thereby increasing the importance of less fragmented public forest lands with respect to services such as habitat for wildlife that require large tracts of forestland that are not fragmented.

Forest fragmentation is the result of local decisions that combine to form landscape-level patterns. More tools, such as composite fragmentation indices, will provide landowners and policy makers with better information on the causes of these landscape patterns and can help them to make more informed land-use decisions. Although this study concentrated on the Pacific Northwest, the general concepts are applicable to other regions of the United States and the world. The forest fragmentation index developed is based on data that are widely available and are often free for downloading. With a modest amount of experience with geographic information systems and statistics, similar analyses can be conducted in other regions and at other scales.

References

Alig, R.J., 1986. Econometric analysis of forest acreage trends in the Southeast. For. Sci. 32 (1), 119–134.

Alig, R.J., Healy, R., 1987. Urban and built-up land area changes in the United States: an empirical investigation of determinants. Land Econ. 63, 215–226.

Alig, R.J., Zheng, D., Spies, T.A., Butler, B.J., 2000. Forest Cover Dynamics in the Pacific Northwest West Side: Regional Trends and Projections. US Department of Agriculture, Forest Service, Pacific Northwest Research Station Research Paper PNW-RP-522, 22 pp.

Betts, M., 2000. In Search of Ecological Relevancy: A Review of Landscape Fragmentation Metrics and their Application for the Fundy Model Forest. University of New Brunswick, 38 pp.

Bockstael, N.E., 1996. Modeling economics and ecology: the importance of a spatial perspective. Am. J. Agric. Econ. 78 (5), 1168–1180.

Bogaert, J., Van Hecke, P., Van Eysenrode, D.S., Impens, I., 2000. Landscape fragmentation assessment using a single measure. Wildl. Soc. Bull. 28 (4), 875–881.

Cain, D.H., Riitters, K., Orvis, K., 1997. A multi-scale analysis of landscape statistics. Landscape Ecol. 12, 199–212.

Debinski, D.M., Holt, R.D., 2000. A survey and overview of habitat fragmentation experiments. Conserv. Biol. 14 (2), 342–355.

Defense Mapping Agency, 1997. Digital Map Atlas. 90 m Digital Terrain Model. US Government.

Kline, J.D., Alig, R.J., 2001. A Spatial Model of Land Use Change in Western Oregon and Western Washington. US Department of Agriculture, Forest Service, Pacific Northwest Research Station Research Paper PNW-RP-528, 24 pp.

Li, H., Reynolds, J.F., 1993. A new contagion index to quantify spatial patterns of landscapes. Landscape Ecol. 8, 155–162.

Mauldin, T.E., Plantinga, A.J., Alig, R.J., 1999. Land Use in the Lake States region: an analysis of past trends and projections of future changes. US Department of Agriculture, Forest Service, Pacific Northwest Research Station Research Paper PNW-RP-519, 24 pp.

McGarigal, K., Marks, B.J., 1994. FRAGSTATS: spatial pattern analysis program for quantifying landscape structures. US Department of Agriculture, Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-351, 122 pp.

McGarigal, K., McComb, W.C., 1995. Relationships between landscape structure and breeding birds in the Oregon Coast Range. Ecol. Monogr. 65 (3), 235–260.

O'neill, R.V., Krummel, J.R., Gardener, R.H., Others, A., 1988. Indices of landscape pattern. Landscape Ecol. 1 (3), 153–162.

Ripple, W.J., Bradshaw, G.A., Spies, T.A., 1991. Measuring forest landscape patterns in the Cascade Range of Oregon, USA. Biol. Conserv. 57, 73–88.

Rochelle, J.A., Lehmann, L.A., Wisniewsk, J., 1999. Forest Fragmentation: Wildlife and Management Implications. Koninklijke Brill NV, Leiden, The Netherlands.

Sampson, R.N., DeCoster, L., 2000. Forest fragmentation: implications for sustainable private forests. J. For. 98 (3), 4–8.

Saunders, D.A., Hobbs, R.J., Margules, C.R., 1991. Biological consequences of ecosystem fragmentation: a review. Conserv. Biol. 5, 18–32.

Schwartz, M.E., 1997. Conservation in Highly Fragmented Landscapes. Chapman & Hall, New York.

Smith, W.B., Vissage, J.S., Sheffield, R.M., Darr, D.R., 2001. Forest Resources of the United States, 1997. US Department of Agriculture, Forest Service, North Central Research Station General Technical Report NC-219, 190 pp.

Trzcinski, K., Fahrig, L. et al., 1999. Independent effects of forest cover and fragmentation on the distribution of forest breeding birds. Ecol. Appl. 9 (2), 586–593.

Turner, M.G., 1989. Landscape ecology: the effect of pattern on process. Annu. Rev. Ecol. Syst. 20, 171–197.

Turner, M.G., Wear, D.N., Flamm, R.O., 1996. Land ownership and land-cover change in the southern Appalachian highlands and the Olympic Peninsula. Ecol. Appl. 6 (4), 1150–1172.

US Census Bureau, 1990. Census Tracts, Urban Areas, Geographic Polygon Coverages.

US Geological Survey, 1980. Interstate and primary state highways. 1:2,000,000-scale Digital Line Graphs. Reston, VA.

Van Kooten, G.C., 1993. Land Resource Economics and Sustainable Development. UBC Press, Vancouver.

Vogelmann, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., Van Driel, N., 2001. Completion of the 1990s National Land Cover Data Set for the Conterminous United States from Landsat Thematic Mapper Data and Ancillary Data Sources. Photogramm. Eng. Remote Sens. 67, 650–652.

Wickham, J.D., O'neill, R.V., Jones, K.B., 2000. Forest fragmentation as an economic indicator. Landscape Ecol. 15, 171–179.