Assessing Forest Fragmentation Metrics from Forest Inventory Cluster Samples

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Abstract.—Fragmentation of forest area plays an important role in the ongoing discussion of forest dynamics and biological and ecosystem diversity. Among its contributing factors are size, shape, number, and spatial arrangement of forest patches. Several metrics and indexes are in use, predominantly in quantitative landscape ecology. An important area of interest is the assessment of diversity from sample data. This paper presents a sample-based approach to analyzing standard cluster sample data from forest inventories and applying basic considerations of geometrical probabilities. The number and mean size of forest patches can then be estimated under some general assumptions. With this information, a basic characterization of fragmentation is obtained. In a practical example, satisfactory differentiation between subregions of different spatial structure of forest patches could be found. The method also allows the analysis of historic cluster sample data in the absence of corresponding forest cover maps.

Both forest area and its fragmentation are important attributes in forest monitoring. Fragmentation characterizes diversity of the spatial distribution of forests and is related closely to ecosystem diversity, one of the three levels that make up biological diversity. Determining factors are the size, shape, number, and spatial arrangement of individual forest patches. Riiters *et al.* (1995) provide a comprehensive overview of corresponding diversity indices, also called landscape metrics. External factors that affect the quantitative assessment of fragmentation are scale and spatial resolution.

Fragmentation is currently an intensively studied topic in the context of deforestation, the loss of biological diversity, and the loss of ecological functions of forests. In fact, forest fragmentation is evolving into a standard attribute assessed routinely in forest surveys (e.g., Lund 1998). Fragmentation, however, is not only a forestry issue. Most of the relevant contributions in the last years stem from quantitative landscape ecology. Fragmentation information can be used to describe the status and changes of a landscape structure. But there are numerous research activities relating for example, species diversity to changes in landscape structure; thus, data on fragmentation are interesting input in many kinds of models (e.g., Fahrig and Merriam 1985). Beyond the ecological function of forests, forest fragmentation also has economic and socioeconomic implications (e.g., Schelhas and Greenberg 1996).

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This study concentrates on the specific issue of assessing fragmentation characteristics through sampling. Normally this is accomplished through analysis of large fixed-area plots in which aspects of fragmentation are observed, inferring with the classical extension-factor-approach from the sample information to the situation in the population (e.g., Hunsaker *et al.* 1994). The present study uses geometric information contained in cluster field samples in forest inventories to estimate two closely related aspects of forest fragmentation: mean patch size and number of forest patches. These estimates can be considered a secondary product of spatial cluster sampling. A more comprehensive treatment of this topic is in preparation (Kleinn 1998).

SAMPLING FOR STRUCTURAL DIVERSITY

Magurran (1988), for example, discusses in general terms the problem of assessing biological diversity through sampling. While the abundance component of species diversity can be estimated without bias, this does not hold for estimating the second constituting factor, species richness. Therefore, sample-based estimates of a number of diversity indices are biased. Comparability, is given only, if at all, when techniques and metrics employed are identical.

As with species diversity, assessing forest fragmentation involves the measurement of several characteristics. This makes issues of consistency and interpretation critical. Most sampling approaches based on fixed-area sample plots (e.g., Hunsaker *et al.* 1994, Traub and Kleinn 1998) provide unbiased estimates of some components, such as the total forest area. For other attributes, such as the number of forest patches, fixed-area sample plots are inadequate. This highlights why, in the assessment of fragmentation, the estimation of indices is also problematic.

USING SPATIAL CLUSTER SAMPLES TO ASSESS MEAN FOREST PATCH SIZE

Sampling with spatial clusters, in which m points (plots) are arranged in some defined geometry, has a favorable characteristic with respect to spatial analysis. Such clusters are frequently used in large area forest surveys, where plots are, for example, placed at the four corners of a square or at the three "corners" of a half-square. Due to the spatial arrangement of several plots at one sample point, this type of sampling carries geometric information about the study population—not only the information on total forest area as normally analyzed. Using a cluster of m points (plots), some of them will fall completely outside forest, some of them completely inside forest, and a third group will be partly outside forest. This simple classification offers an opportunity to analyze for aspects of fragmentation. A high percentage of clusters completely inside forest is an indication of a fragmentation structure with forest patches that are large compared to the spatial extension of the cluster used. If a large percentage of the clusters intersect with the forest border, a more fragmented spatial distribution pattern exists.

According to this classification of cluster positions relative to forest patches, the region of interest can be subdivided into three classes: complete forest, border, complete nonforest. The cluster sample yields an unbiased estimate of the relative and absolute size of these three subregions, and incidentally an estimate of the probability that, under the given structure of the population, a cluster intersects with a forest border.

We define the position of a square cluster, as used in the case study, by a center point, which is the position of the intersection of its diagonals, where the diagonals define the largest spatial extension of the cluster. Then, only clusters whose center point is not farther than half of the diagonal d from the next forest border have a chance to intersect with it. Half the length of the diagonal defines therefore the width of the border strip on both sides of the forest border. Total width of the border strip is therefore d. However, only in the hypothetical case of a circular cluster with $m \to \infty$ cluster points and diameter d, will all clusters with center points in the border strip intersect the forest border. For any other cluster shape, this probability is less than 1. In the case of a square cluster, for example, this conditional probability of intersection is

$$P_{is} = \frac{2\sqrt{2}}{\pi} = 0.9003$$

(e.g,. Kleinn 1994). That means that out of all clusters having their center points within the border strip, only 90.03 percent will intersect the borderline between forest and nonforest. The remaining 9.97 percent represent positions where the center point is within the border strip, but the square cluster has an orientation so that no intersection takes place.

For simplicity we assume now that forest and nonforest are separated by a straight line. This is one model assumption for the subsequent calculations. Curvature increases the probability of intersection so that one tends to underestimate this probability under this assumption. The same holds for the assumption that border strips of different forest patches do not overlap. This imposes the condition of a minimum distance between forest patches, which is necessary since the point information on the cluster does not permit a distinction between cluster points that fall in the same forest patch and those that fall in different ones.

Under these assumptions, we are now able to estimate mean forest patch size for any geometric shape of forest patches. For circular and for square shapes, the calculation formulae for mean patch size and for number of patches in the inventory region are given in table 1.

Table 1.—*Calculation formulae for mean patch size g_m and mean number of patches n_m for square and circular shaped forest patches (Kleinn 1998)*

Shape	g_m	n_m
Circle	$4\pi d^2\left(\frac{\hat{p}}{\hat{p}_s}P_{is}\right)^2$	$\frac{\hat{p}F}{g_{m(circle)}}$
Square	$16d^2\left(\frac{\hat{p}}{\hat{p}_s}P_{is}\right)^2$	$\frac{\hat{p}F}{g_{m(square)}}$

With
- P_{is}: Conditional probability of intersection of specific cluster shape within borderstrip.
- $\hat{p}$: Estimate of proportion of forest cover in the inventory region.
- p_s: Estimate of proportion of border strip in the inventory region.
- d: Maximum spatial extension of cluster = total width of border strip.
- F: Total survey area.

Here, mean patch size is a linear function of $k^2 = \left(\frac{\hat{p}}{\hat{p}_s}P_{is}\right)^2$ useful to compare aspects of fragmentation. k^2 naturally depends on cluster shape and spatial extension, which directly enters via the probability estimate P_{is}.

Example:

In a regional forest inventory in the Northern Zone of Costa Rica, square clusters of length s= 0.15 km were used in a 2.5-km square grid, with plots at the four cluster corners. For this study we used only the forest/non-forest information originating from the four corner points of each cluster. For the fragmentation analysis, the region was arbitrarily subdivided into two subregions with obviously different spatial forest distributions. The northern subregion is characterized by a higher forest cover percent and large forest patches, whereas in the southern subregion forest patches are smaller and occur less frequently. Table 2 gives the relevant data and the results according to the formulas given above.

Table 2.—*Baseline data of the example inventory regions and sub-regions to calculate measures of spatial structure*

	Subregion North	Subregion South
Forest cover estimate $\hat{p}$	0.3200	0.1288
Estimated share of border strip $\hat{p}_s$	0.2167	0.1623
Total cluster points	443	456

Values of k^2 increase with increasing fragmentation; high values stem from a small proportion of clusters falling within the border strip, i.e., there are relatively few forest borders and relatively large forest patches. Comparing the northern and southern subregions, the results in table 3 clearly indicate a much more fragmented forest distribution in the southern part with a value of k^2 = 1.7676 for the northern and k^2 = 0.5105 for the southern subregion.

Accordingly, mean patch size is much smaller in the southern subregion with 28.87 ha, compared to the northern subregion with an estimated mean patch size of 99.95 ha.

CONCLUSIONS AND OUTLOOK

Extent of forest fragmentation is of interest in several disciplines. It can be derived from complete maps as given by air photos or satellite images, or it can be based on sample data. This paper presents an assessment using cluster sample data of forest inventories, and applying basic considerations of geometric probabilities.

The numerical results of the case studied showed that the statistic k^2 allows differentiation between fragmentation levels of obviously differently structured subregions. It describes two closely related aspects of forest area spatial fragmentation: mean patch size and number of patches. It is simple to apply and can be used to quantify and compare fragmentation levels of different subregions or of the same region at different points in time.

The method might be interesting because it does not require additional information outside what is available through standard large area forest inventories with cluster sampling. It can therefore be easily applied to past inventories for which no complete coverage through satellite imagery or air photos is available, thus allowing a retrospective analysis of structural diversity.

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Table 3.—*Characteristics of spatial structure, derived from cluster sampling inventory data (Details see text)*

Sub-Region	$\hat{p}$	$\hat{p}_{ls}$	F (km²)	k^2	Assumed patch shape: Circle g_m(km²)	Circle n_m	Square g_m(km²)	Square n_m
North	0.3200	0.2167	2768.75	*1.7676*	0.9995	886	1.2726	696
South	0.1288	0.1623	2850.00	*0.5105*	0.2887	1,272	0.3676	999

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