Assessing the Effects of Forest Fragmentation Using Satellite Imagery and Forest Inventory Data

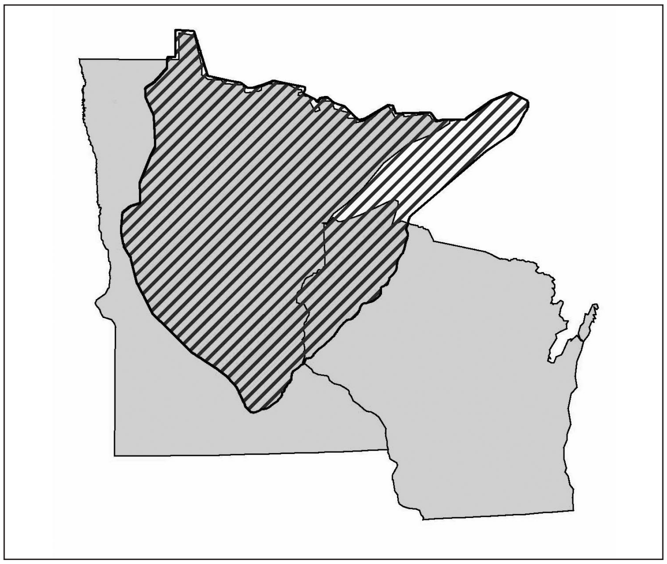
Ronald E. McRoberts[1] and Greg C. Liknes[1]

Abstract.—For a study area in the North Central region of the USA, maps of predicted proportion forest area were created using Landsat Thematic Mapper imagery, forest inventory plot data, and a logistic regression model. The maps were used to estimate quantitative indices of forest fragmentation. Correlations between the values of the indices and forest attributes observed on forest inventory plots were estimated. One interesting result was a statistically significant negative correlation between total forest area and number of tree species per unit forest area.

Montreal Process

Over the last decade, natural resource managers, the scientific community, and the general public have voiced serious concerns regarding the status of and emerging trends in the world's forests. In 1993, the government of Canada began a series of meetings to develop scientifically rigorous methods for evaluating forest management. These meetings led to the Montreal Process criteria and indicators for environmental and ecological assessments of forest sustainability. One criterion describes conditions or processes by which sustainable forest management may be evaluated and is further characterized by a set of indicators that are monitored periodically to assess change. Four of the seven Montreal Process criteria deal with forest conditions and attributes: (1) conservation of biological diversity, (2) maintenance of productive capacity of forest ecosystems, (3) maintenance of forest ecosystem health and vitality, and (4) maintenance of forest contribution to global carbon cycles. Forest fragmentation affects several of these criteria. Our study sought to evaluate the effects of forest fragmentation on a variety of forest stand attributes. The study was conducted in the North Central region of the United States and included portions of Minnesota, Wisconsin, and Michigan (fig. 1).

Figure 1.—*Study area.*



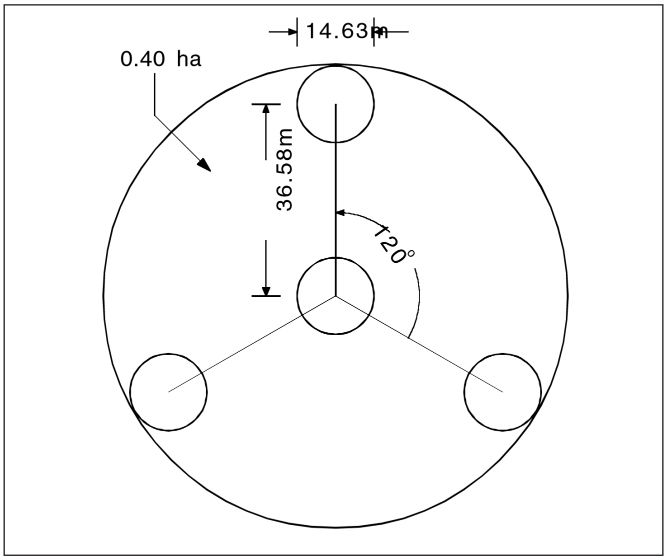
Data and Methods

Inventory Plot Data

The Forest Inventory and Analysis (FIA) program of the Forest Service, U.S. Department of Agriculture, has established an array of permanent field plots using a systematic sampling design. In the North Central region, a fixed proportion of plots are measured each Federal fiscal year (01 October to 30 September). Plots measured in the same Federal fiscal year comprise a single panel of plots, and panels are measured on a rotating basis. In aggregate, over a complete measurement cycle of 5 years, a plot represents approximately 2,403 ha. In general, locations of forested or previously forested plots are determined using global positioning system receivers, while locations of nonforested plots are determined using digitization methods. Each field plot consists of four 7.31-m radius circular

[1] Mathematical Statistician and Computer Specialist, respectively, U.S. Department of Agriculture, Forest Service, North Central Research Station, 1992 Folwell Avenue, St. Paul, MN 55108.

Figure 2.—*Forest Inventory and Analysis standard plot design.*



subplots configured as a central subplot and three peripheral subplots with centers located 36.58 m and azimuths of 0 degrees, 120 degrees, and 240 degrees from the center of the central subplot (fig. 2). For each tree, field crews report species, live or dead status, and diameter at breast height (d.b.h.) (1.37 m). Regression models are used with observed d.b.h. as an independent variable to predict the volumes and biomass for individual trees. In addition, field crews note evidence of both natural and human disturbances, estimate the number of seedlings, and estimate the proportions of each subplot that satisfy specific land use conditions. Subplot estimates of forest land proportions are obtained by aggregating these land use conditions into forest and nonforest uses. Plot estimates of number of species, number of live and dead trees, biomass in live and dead trees, live tree volume, number of seedlings per unit area, and average stand diameter were obtained by aggregating individual trees and subplots. Observations for 1,185 plots were available for the 1999, 2000, and 2001 panels.

Satellite Imagery Classification

Landsat TM imagery, classified according to forest and nonforest, was used to quantify fragmentation. The images included data for three dates, consisted of 30 m x 30 m pixels for bands 1-5 and band 7, and were geo-referenced to Albers Equal Area projection, NAD 83.

The first step was to calibrate a model for predicting the proportion of forest land for each image pixel. Because forest land proportions are always in the closed interval [0,1], it is appropriate to select a model with mathematical properties that restrict predictions to the same interval. The logistic model is often used with such data and was selected for this study to describe the relationship between observed forest land proportion for FIA subplots and the spectral values of the pixels containing the subplot centers,

$$E\left(Y_k\right) = \frac{1}{1+\exp\left(\beta_0 + \beta_1 X_{1k} + \beta_2 X_{2k} + \ldots + \beta_p X_{pk}\right)}$$

where E(.) denotes statistical expectation, Y_k is the forest land proportion for the k^{th} subplot, X_{jk} is the spectral value for the j^{th} band for the pixel containing the center of the k^{th} subplot, and the βs are parameters to be estimated. For each study area, all possible band combinations were compared according to root mean square error, and the combination with the smallest root mean square error was selected.

After calibration, the models were used to predict forest land proportion for each pixel in the study area. In accordance with the practice of other mapping agencies, pixels with proportion forest land predictions less than 0.25 were designated nonforest, and pixels with forest land predictions equal to or greater than 0.25 were designated forest. Slightly less than 90 percent of the nonforest plots were correctly classified, and slightly more than 90 percent of the forest plots were correctly classified.

Correlation and Validation Analyses

For the 0.4-ha circle circumscribing the four subplots of each FIA plot, four measures of forest fragmentation were taken: forest edge length, edge forest area, interior forest area, and total forest area. Forest edge length was calculated as the total length within the 0.4-ha circle of the forest/nonforest boundary between pixels classified as forest and pixels classified as nonforest; edge forest was calculated as the total area within the circle of forest pixels within two pixel widths of the forest/nonforest boundary; interior forest area was calculated as the area within the circle of forest pixels greater than two pixel widths from the forest/nonforest boundary; and total forest area was calculated as the sum of edge and interior forest area. The three

Table 1.—*Estimated correlations between measures of forest fragmentation and forest stand attributes*[1]

Forest attribute	Fragmentation index: Edge forest area	Total forest area	Interior forest area
No. species	0.03	**-0.19**	**-0.44**
No. live trees	**-0.19**	**0.14**	-0.05
Live biomass	-0.05	-0.03	**-0.20**
Seedlings	-0.01	-0.03	**-0.10**
Mean d.b.h.	**0.11**	**-0.13**	**-0.10**

[1] Estimates in bold are statistically significant at α=0.01.

area measures were divided by the total area of the 0.4-ha circle and were analyzed as proportions of that area.

The first stage of analysis consisted of simple correlation analyses between the estimates of forest attributes and the four measures of forest fragmentation (table 1). Plots with no forest land within the 0.4-ha circle were excluded from the analyses as were plots with evidence of human-caused disturbance, leaving 1,185 plots. The forest attribute measures previously described were all divided by the total forest area to scale estimates to a per unit forest area basis. The high negative correlations between number of species per unit forest area and total forest area were of particular interest and suggested that the number of species per unit of forest area may be greater when forest fragmentation is greater. This result warrants further investigation because lesser fragmentation and greater species richness, defined as the number of species per unit area, are both generally viewed as positively affecting forest sustainability. The observed result, however, suggests that greater species richness is associated with greater, not lesser, fragmentation.

The second stage of analysis focused on validating the inverse relationship between number of tree species per unit of forest area on FIA plots and the proportion of the 0.4-ha circular plot that was forested (fig. 3). The primary issue was determining if the large negative correlation could be due to artifacts resulting from expressing number of species found on a plot on a per unit forest area basis. First, if even small forested areas are saturated with species, then the decrease in number of species per unit of forest area as the proportion of plot forest area increases could be attributed to dividing a relatively con-

Figure 3.—*Number of species per unit area on FIA plots versus proportion of plot in forest area.*

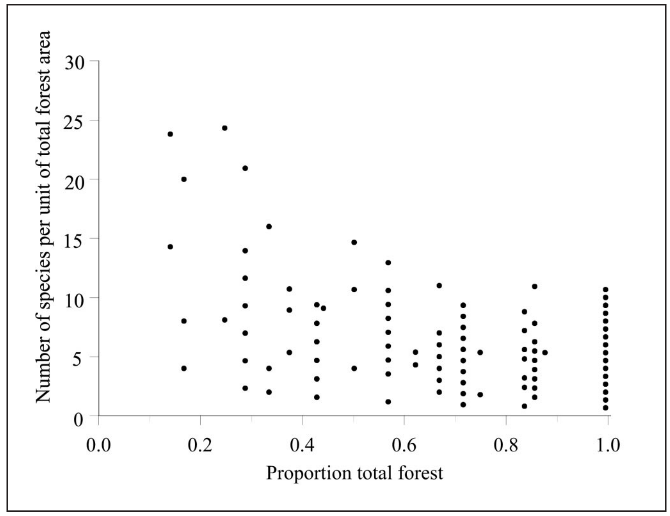
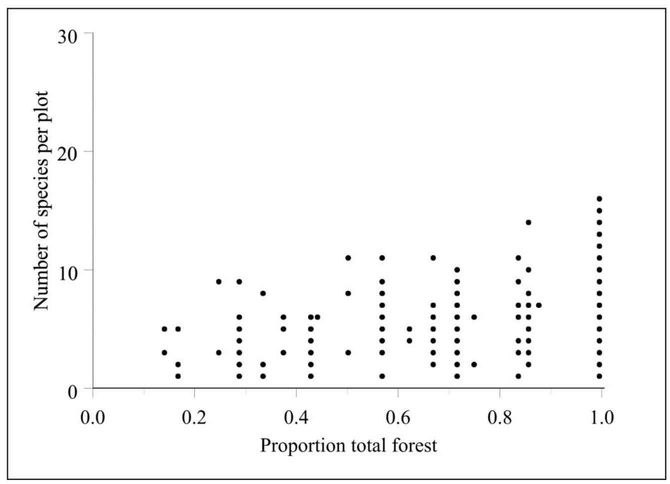


Figure 4.—*Absolute number of tree species found on FIA plots versus proportion of plot in forest area.*



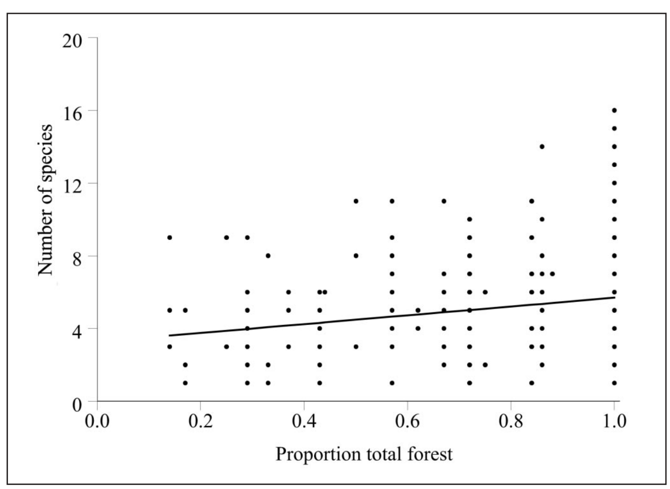


Table 2.—*Number of different species*

Proportion forest	No. plots	Cumulative no. species
0.00-0.09	13	25
0.10-0.29	22	31
0.30-0.49	21	27
0.50-0.69	31	35
0.70-0.89	100	39
0.90-1.00	998	67

stant number by an increasing number. A graph of the data, however, reveals that the absolute number of species increases as the proportion of forest area increases (fig. 4). Second, if only the same small number of species ever occur on plots with small proportion forest areas, then the large number of species per unit forest area could be attributed to dividing this same small absolute number of species by small proportion forest areas. However, the absolute numbers of species found on all plots listed by categories of proportion forest area appear to dispel this possibility (table 2). In addition, these latter results confirm that absolute numbers of species per plot increases as the proportion of forested area on the plot increases. Over all plots with proportion forest area between 0.00 and 0.0, 25 species were found, while on plots with proportion forest area between 0.10 and 0.29, 31 species were found. These numbers are similar to those indicated by figure 4 for plots with small proportion forest areas. Although there are additional sampling issues associated with estimating number of species per unit area that have not been addressed in this study, it appears that the large, statistically significant, negative correlation between tree species per unit forest area and total forest area may be a genuine phenomenon and not simply an arithmetic artifact.

Summary

In brief summary, a forest/nonforest classification of satellite imagery provided a good means of measuring forest fragmentation such as edge length, edge forest area, and interior forest area. Further, these measures may be easily correlated with estimates of forest attributes such as tree species per unit area obtained from forest inventory plot data. The most significant result was the negative correlation between number of tree species per unit forest area, a measure of species richness, and proportion forest area, a measure of forest fragmentation. This correlation suggests that two positive indicators of forest sustainability, less forest fragmentation and greater tree species richness, perhaps should not be expected to occur simultaneously.