FRAGMENTATION STATISTICS FOR FIA: DESIGNING AN APPROACH

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ABSTRACT.—The USDA Forest Inventory and Analysis (FIA) program collects data on the amount of forest, as well as on characteristics such as forest type, tree volume, species composition, and size and age classes. However, little data are obtained nationwide on forest fragmentation—how that forest is distributed and in what land use/land cover context—factors that can substantially affect forest composition and health, wildlife, water quality, and forest management. In this paper we examine which fragmentation and context metrics should be linked with FIA plot data and monitored over time, and we identify possible sources of land use/land cover data from which to calculate this information. Emphasis is placed on those metrics that have been observed to be indicators of change in forested ecosystems. Using a complete set of photointerpreted land use/cover data in Massachusetts as the "truth," we examine one possible source, the 1992 National Land Cover Dataset (NLCD) for its "fragmentation accuracy." With accurate, relevant, and consistent fragmentation and context information, FIA will be able to better understand, interpret, and report on the state of the forest.

FIA data collected from extensive sample plots across the United States are reported in a variety of statistical and analytical publications. Such reports include valuable information on the amount of forest in a particular State, county, or watershed, as well as total tree volume, forest type, species composition, size and age classes, and so on. However, typically little data are collected and analyzed on forest fragmentation—how that forest is distributed across the landscape. For example, we do not know whether those acres of forest occur as part of a large matrix or are distributed as many smaller patches. Nor do we know how isolated or connected those patches are, what land use/land cover context the forest is in, or how much of the forest is in interior vs. edge conditions. Figure 1 illustrates two areas of roughly equal

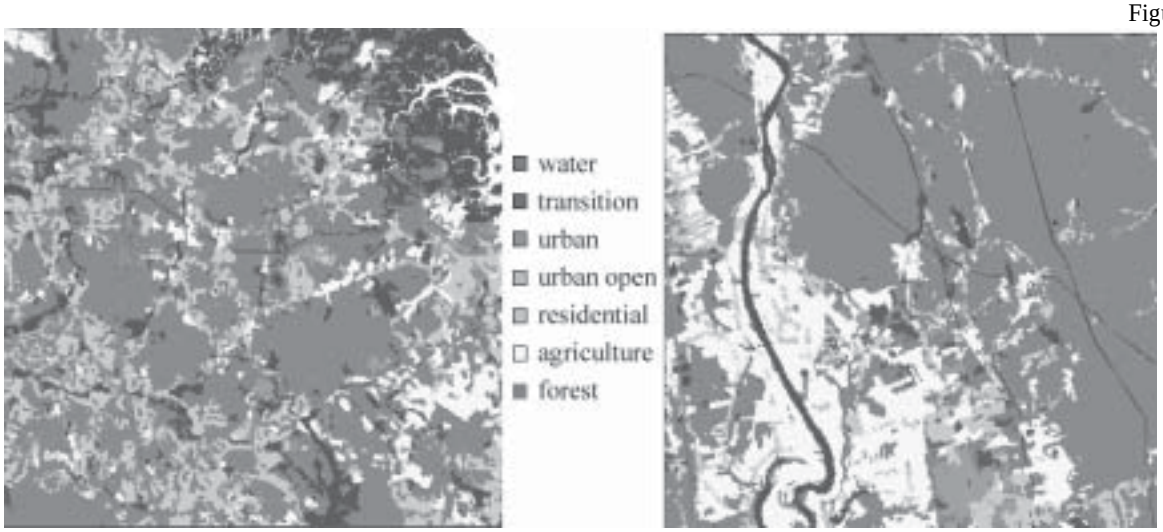

Figure 1.—*Two areas of roughly equal forest area (61 and 62 percent, respectively), but different spatial distributions of forest and different contexts (primarily residential vs. primarily agricultural) that are not captured in the single percent forest statistic.*

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amount forest[2] (61 and 62 percent, respectively), but different spatial distributions and contexts that are not captured by that single percent forest statistic.

Impacts of Fragmentation

The fragmentation of forest land has been observed to have a substantial effect on forest composition and health with respect to an increase in the number of exotics, mortality, and changes in composition (e.g., Airola and Buchholz 1984, Heckscher and others 2000, Saunders and others 1991, Zipperer and Pouyat 1995); water flow and flow variability, sedimentation, macroinvertebrates, and biogeochemical cycles (e.g., Hunsaker and others 1992, McMahon and Cuffney 2000, Richards and Host 1994, Wear and others 1998); wildlife abundance, diversity, and breeding success (Bolger and others 1997, Burke and Nol 2000, Cam and others 2000, Kurki and others 2000, Rosenberg and others 1999); and forest management in terms of economic viability and treatment constraints (e.g., Barlow and others 1998, Cooksey 2000, Wear and others 1999). Thus, there is an obvious need to analyze the FIA data with respect to fragmentation so that we can better understand, interpret, and report on the state of the forest. We also need to monitor distribution and fragmentation characteristics of the forest over time, just as we monitor the status and changes in forest area, volume, relative species composition, and so on (fig. 2).

Regional Efforts

On a regional basis, information on fragmentation and/or context has been collected in conjunction with FIA plot data in various ways over the years. In the Northeast, photointerpretation of sample point locations for six Eastern Coastal States was completed in association with inventories of these States in the late 1990s (Riemann and Tillman 1999). In Indiana and Illinois, patch size and land use data were collected via photointerpretation of an area around each FIA plot in a one-time effort in the mid-1990s to examine land use context (Collins 1995[3]). In Oregon, building densities were photointerpreted at sample point locations from aerial photographs taken in 1974, 1982, and 1994 to gather data on the effects of a range of human habitation on forest (Azuma and others 1999, Kline and others 2000). In the broadest effort, in the South and Southeast, data on fragment size and distance to road were obtained from aerial photography and ground inventory for all plots from 1974 to 1995, also providing a source of time-series information (e.g., Rudis 1995, 2001). Further analysis of this existing information resource in conjunction with FIA plot data will provide additional guidance with respect to the metrics of interest, relevant thresholds indicating probable or substantial impact, and experiences with different data sources and collection methods that focus on large areas. Data collected via photointerpretation are typically fairly accurate at those point locations, but these collection approaches are labor intensive and time consuming. At least two national efforts have generated complete coverage of numerous fragmentation metrics calculated from TM-derived sources (Heilman and others 2001[4], Riitters and others 2000), but these measures are not necessarily at a scale that can be

[2] Percent forest equals the number of pixels classified as forest divided by the total number of pixels.

[3] Collins, B. 1995. Aerial photo sampling instructions for the fourth inventories of Illinois and Indiana. Paper on file at the North Central Research Station, St. Paul, MN. 43 p.

[4] Heilman, G.E., Jr.; Strittholt, J.R.; Slosser, N.C.; DellaSala, D.A. Forest fragmentation of the conterminous United States: assessing forest intactness through road density and spatial characteristics. In preparation. BioScience. Submitted July 30, 2001.

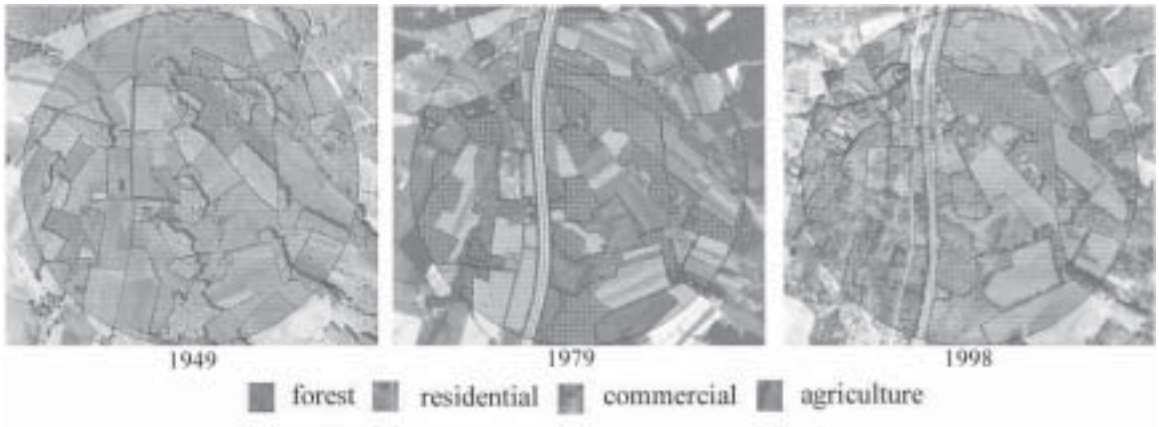


Figure 2.—*Example of the changing context around an individual forested plot over time.*

related to FIA plot data. Wendt (2001) related fragmentation metrics calculated from TM-derived land use-land cover maps to FIA plot data via the ~6,000-acre hexagon area in which each plot falls, but this approach limits the assessment of fragmentation and context to that one scale.

Definition and Measures of Fragmentation

Forest fragmentation is considered here to be the spatial breakup of forest by developed land uses. It is described by both the total amount of remaining forest and its distribution and configuration. Context, a related and important descriptive factor, is defined as the land use composition of the area surrounding a point, stream, or patch of forest. Together, these measures describe landscape characteristics of interest for their potential impact on forest systems. The specific metrics that are used to capture this information are important. Our first goal was to identify, from results and observations of other studies, an initial list of variables/ metrics that are relevant to forest ecosystems and FIA plots. We then investigated how to measure/monitor these variables over broad areas and over time, taking into account both accuracy and cost. This paper describes the first portion of this study.

METHODS

Choosing Fragmentation Metrics

Numerous methods and metrics have been developed for measuring forest fragmentation and context (e.g., He and others 2000, McGarigal and Marks 1994, Mladenoff and DeZonia 1997, Wickham and Norton 1994, Riitters and others 1995). But which of these metrics should we calculate and retain as additional relevant variables in association with FIA plot data and summary statistics? First and foremost, we are interested in those variables that are related to real changes observed; i.e., that are truly indicators of fragmentation effects. Betts (2000) described this as "management relevance" in which "metric values can then be related to thresholds associated with ecological processes at the landscape scale." Ideally, these parameters can be affected by policy or management to address situations that are considered undesirable by the user. Next, since we are considering metrics for large regions or the entire country, we are also looking for basic measures that do not have special implementation problems, such as extreme sensitivity to boundaries or area size, and that are consistent over broad areas. Third, because we are interested in monitoring fragmentation over time, we want metrics that are relatively robust to differences such as the resolution of data sources, because the availability of different data sources may vary over time. Finally, we want metrics that cover the full spectrum of characteristics of interest with little or no redundancy, and we want to avoid those compound/complex metrics that combine measures with conflicting or interacting relationships with forest ecosystems.

Given these criteria and the observations reported in the literature, we focused on metrics in three areas:

1. Percent cover of forest and other land uses.
   (Landscape-scale factors continually show up as important and can even override local factors in their apparent impact on water quality, wildlife success, and so on.)
2. Distribution/configuration of the forest.
   (For example, patch sizes and patch isolation continue to be linked to many of the changes observed with plant and animal species. Patch sizes also directly affect the economic viability of forest land for timber management.)
3. Edge.
   (Edges between different land uses continue to show up as places where forest/nonforest interactions are occurring.)

Thus, in conjunction with standard area summaries of forest (e.g., county or watershed), one would, for example, calculate for each region the total core forest area (with and without roads); the percent area of each land use; frequency distributions of patch area, isolation, and shape; the total forest perimeter edge distance; and the percentage of the total forest edge bordered by each developed land use. It is important to retain and report the full frequency distribution with variables such as patch size because a single summary statistic cannot capture the range of information required and can even be in error or misleading. A frequency distribution is also important because of the range of issues potentially being addressed for which we may not yet know which threshold will be the most important indicator. When all of the data are retained and available in this form, any of those values can be extracted at any time (e.g., the largest patch size, the amount of forest in patches larger than 10 acres). In addition, because we are interested in summarizing such information for regions of interest, our database must include measures for each patch or

matrix such as total area, core area (with and without roads), patch isolation (e.g., nearest neighbor distance), a shape index, and list of the adjacent land uses and total perimeter distance of each. Finally, in addition to the region- and patch-level measures, the database must retain additional measures unique to each FIA plot, including distance from the plot to the nearest edge, the adjacent land use at that edge, and context calculated at various scales around the point of interest. Ideally, to effectively study the impact of fragmentation, we also need a measure of land cover history; e.g., the "encapsulation date" of that forested patch (Bastin and Thomas 1999), because the length of time an area has been isolated can have a substantial effect on what stage in the process we are observing. Acquisition of this historical information, however, was not addressed in this study.

The scale of calculation is an important consideration, and statistics calculated at several extents need to be retained in the suite of fragmentation statistics. Because we frequently do not yet know which extent is most strongly correlated with (has the most significant impact on) changes observed in forest health, water quality, or wildlife diversity, it is important to calculate statistics at multiple extents to determine the relevant threshold(s) of the impacts/changes observed. For example, in figures 3 and 4, if we calculated and recorded only the smallest surrounding area, we would be unaware of the substantial amount of residential area

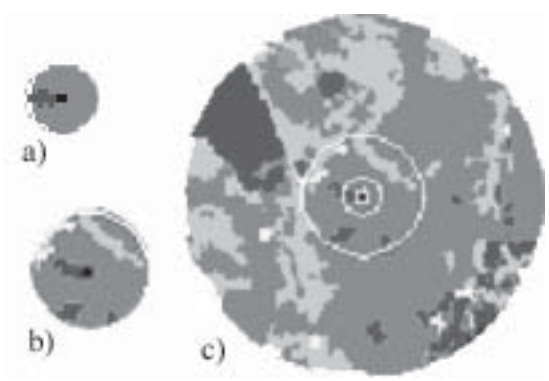


Figure 3.—*Example of the effect of the window size or "scale of observation" on the summary statistics calculated. In a), a 50-acre area around a random forest plot, the report is a landscape context of 92 percent forest and 8 percent water (enlarged for illustration); in b), a 500-acre area around that same plot, the report is 80 percent forest, 13 percent residential, and 2 percent agricultural; in c), a 5,000-acre area around the same forest plot, the landscape context report is 28 percent residential and 59 percent forest.*

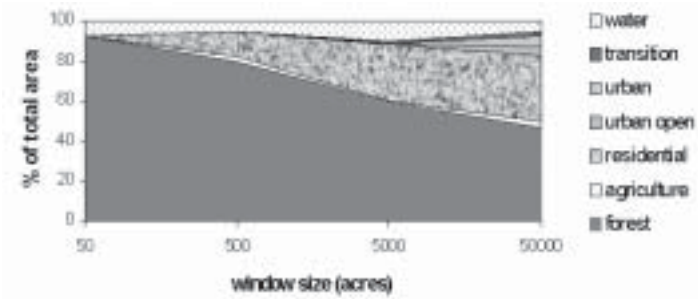


Figure 4.—*Several scales of observation can be combined and displayed in a single plot such as this one. From this distribution, data from any window size of known interest (e.g., based on a particular species or known impact) within the range calculated can be extracted.*

within only a kilometer or two of the plot. Similarly, if we recorded land use percentages for the larger window size only, we would lose the information that the surrounding 50 acres are entirely forested. If we isolate our information to just one window size, we will be ignorant of a substantial amount of context information.

Data Sources for Calculating Fragmentation Measures/Metrics

So, given the metrics we need, what source data are available? Two data sources have been used over broad areas: 1) visual interpretation of very high resolution imagery such as aerial photography or IKONOS imagery by point- or area-sample interpretation (e.g., Collins 1995[3], Riemann and Tillman 1999, Rudis 2001), and 2) land use/land cover classifications derived from Landsat TM imagery (e.g., Heilman and others 2001[4], Riitters and others 2000). The advantages of TM-derived fragmentation and context information are that it provides continuous spatial data and thus may provide better area statistics (visual interpretation of photography over large areas necessitates a sample approach), recalculating new indices from the same data is easier in digital format, coverage of large areas is much less expensive, and it is more likely that the desired image dates and repeat imagery can be obtained. The advantages of "photo"-derived fragmentation and context information are that it relates more directly to the scale of factors of interest on the ground, it relates well to individual plots if they are used as the sample points, and its accuracy generally is greater. Figure 5 illustrates some of the challenges with the accuracy of fragmentation statistics calculated from TM-derived imagery. In this example, all three data sets are

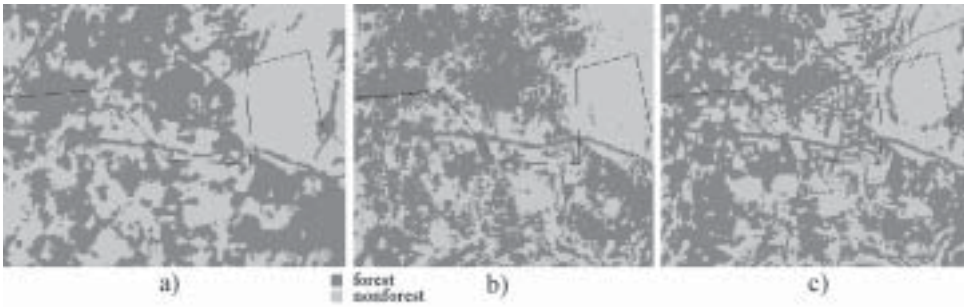


Figure 5.—*Three data sets of approximately equal per pixel accuracy (~ 80%) but appearing to differ greatly in how they depict forest fragmentation. This results from the accuracy of the classification (e.g., are residential with trees classed as residential or forest, what are mixed pixels called, and so on), the resolution of the data, and the resolution of the classification. (Sources: a) is from the Gap Analysis Project (GAP), b) is from the NLCD'92 project, and c) is from an in-house classification. All are from approximately the same dates of imagery.)*

approximately 80 percent accurate, yet they differ greatly in how the distribution and configuration of the forested areas is depicted. Even if the maps were 90 percent accurate in a per pixel assessment, the depiction of forest fragmentation can vary widely. Because TM-derived data sets are the most practical for broad areas, however, we chose in this study to try to push this data source to its limit first.

The accuracy of satellite-derived data sets, as in the percentages quoted above, is most frequently determined by a per pixel comparison of the classified data set with a "truth" data set of known ground or photo points. This can be modified and reported for individual classes or areas, or modified to allow for similar classes in a fuzzy accuracy measure. None of these, however, provide information on the accuracy of the spatial distribution of an individual class; i.e., the fragmentation accuracy of these data sets.

Because metrics *depend* on the accuracy of the source data, how can we first test the fragmentation accuracy of the data set so that we have an accuracy measure for the fragmentation and context statistics calculated from them? And given that the National Land Cover Dataset (NLCD) is the only nationally consistent data set currently available over broad areas, how accurate is it for the fragmentation and context metrics we are interested in? Can we qualify or even quantify this accuracy? And if there are metrics for which the accuracy is insufficient, what is the best way to acquire the necessary source information? Are there possibilities for post-processing the existing classification to improve its fragmentation accuracy? Or are there recommendations for improving the original classification that could be implemented in future national efforts? And what sampling intensities would be necessary if visual interpretation of photography or high resolution imagery is required?

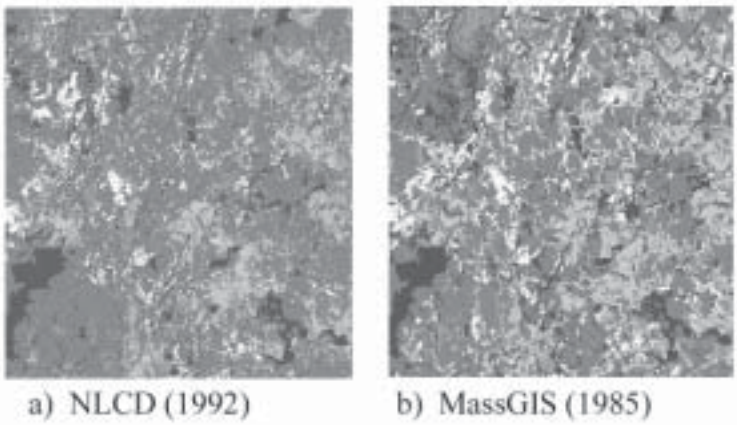
Study Area and Data Sets

Massachusetts was chosen as the initial study area because of the availability of a complete mapped photointerpretation of 37 land use/land cover classes from 1:25,000 photography, known as the MassGIS dataset.[5] These data are continually updated in different parts of the State by new photointerpretation, and results from the latest photography (1999) should be available in the database soon. However, at the time the data were downloaded for this project, the available data came primarily from 1985 photography. The current NLCD was created using a largely unsupervised classification of 1992 Landsat TM imagery supported by aerial photography to label the classes and ancillary digital data sets such as USGS Digital Terrain Elevation Data (DTED), Bureau of the Census population and housing density data, 1970s USGS land use and land cover (LUDA) data, and National Wetlands Inventory (NWI) data to refine the classes. It was not spatially filtered to remove the salt-and-pepper effect of a per pixel classification (Loveland and others 1991, Vogelmann and others 1998). Due to differences in dates, and unfamiliarity with the details of the photointerpretation and image classification used, this comparison makes assumptions about the comparability of class definitions and the amount of land use change during this time period. These data were used here primarily to develop

[5] Massachusetts Office of Geographic and Environmental Information. MassGIS landuse data. http://www.state.ma.us/mgis/lus.htm.

procedures and generate preliminary results that will be tested further with a more specifically developed photointerpretation data set and same-date imagery in the watersheds around the Delaware Water Gap.

Comparison with the MassGIS dataset highlighted already known errors with NLCD'92. For example, it depicts more forest than the MassGIS dataset in many areas even though it is from a later date (fig. 6). One reason for this is the tendency of NLCD'92 to misclassify residential-with-trees as forest. Also noteworthy is the difference resulting from the visual and context interpretation and minimum mapping unit of 1 acre in the MassGIS dataset as compared to the per pixel classification of NLCD'92. This has enormous implications for calculations of metrics such as patch size. For interpretations of land use (vs. land cover), both context interpretation (i.e., classifications influenced by context) and the use of a relatively small minimum area requirement were considered appropriate, so the MassGIS dataset was accepted as a closer model of the "truth."



Figures 6a-b.—*An illustration of some of the differences between the photointerpreted MassGIS dataset (1985) and the TM-derived NLCD'92 (zooming in to an area in northeastern Massachusetts).*

Comparison Procedures and Preliminary Results

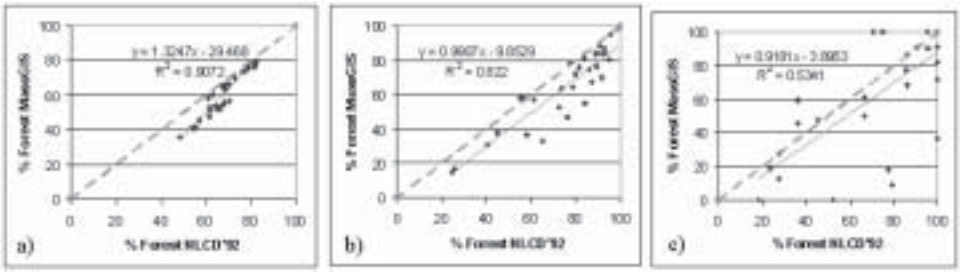
First, we checked both the "truth" and candidate data sets against the FIA data in terms of percent forest at the county level. This information can only be used as a flag if the data sets are wildly different, since the continuous data sets could potentially be more accurate than the FIA data for estimating amount of forest, particularly over small areas, given that they represent complete coverage rather than a sample.

Comparing percent forest estimates at the county level, the data sets produced estimates averaging within 10 percent of each other—NLCD'92 tended to overestimate county values by an average of 3.8 percent compared to values calculated from FIA plot data, and MassGIS tended to underestimate county values by an average of 5.5 percent compared with FIA data.[6]

Next, we compared the two continuous data sets, the MassGIS and the NLCD'92, with respect to the most basic measure of interest—percent forest land—and determined the window size or "scale of observation" at which the relationship between our prospective data set and our "truth" began to break down. We randomly chose 30 points and generated six circles around each point with increasing areas of 5, 50, 500, 5,000, 50,000 and 500,000 acres (= circles of 0.08, 0.25, 0.8, 2.5, 8, and 25 km, respectively). The largest size approximated that of a county in Massachusetts. Within each area, we calculated the percentage of the land area occupied by forest and compared the estimate calculated from NLCD'92 with the "truth" calculated from the photointerpreted data set (fig. 7). It became apparent that for areas of 500,000 acres, percent forest calculated from NLCD'92 agreed well with photointerpreted information (average absolute difference of 7.3 percent in an area 61 percent forested on average–well within what could be expected given the differences in data set dates). However, both increasing error (average absolute difference) and decreasing precision (standard deviation of the absolute difference values) were observed with decreasing extent. The average error was 11 percent at 500 acres, and 16 percent at 5 acres around those same 30 points (fig. 8). These results provide initial guidance regarding the accuracy of estimates of the percent forest metric at each spatial extent.

We then compared other context measures such as percent of developed land uses within the area of interest, by percent of total area and percent of total forest edge. Accuracies of the percent by area measure, calculated as the average absolute difference between the two data sets at the 30 sample area

[6] To remove as much time difference as possible, 1998 FIA plot data were used for comparison with the 1992 NLCD, and 1985 FIA plot data were used for comparison with the 1985 MassGIS dataset.



Figures 7a-c.—*Comparison of estimates of percent forest calculated from NLCD'92 with those from the MassGIS dataset at three different window sizes: a) 500,000 acres, b) 500 acres, and c) 5 acres.*

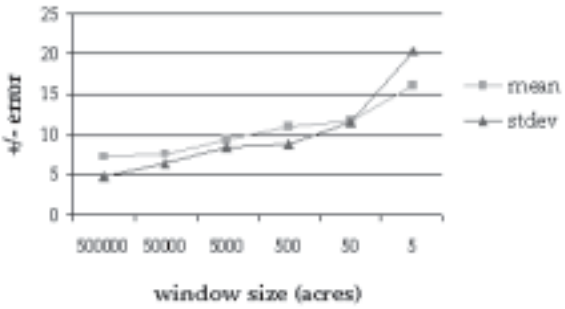


Figure 8.—*Plotting the mean and standard deviation of the absolute differences between the two data sets indicates that there is both increasing error and decreasing precision with decreasing window size when NLCD'92 is used.*

locations, were 4 percent for residential (in a region 14 percent residential on average) and 1.4 percent for agriculture (in a region 9 percent agricultural on average) for areas of 500,000 acres. This increased to 7 percent for residential and 4 percent for agriculture for areas of 500 acres (i.e., about half the size of the estimate itself) and to 13.6 percent for residential and 8.3 percent for agriculture for areas the size of 5 acres (i.e., approximately equal to the size of the estimate itself).

Finally, at the scales at which the basics of land use context appeared reasonable and/or at scales of particular interest, we examined other measures of interest, e.g., patch size. As expected, sizes of forest patch differed considerably between the two data sets. NLCD'92 missed a large percentage of the medium-size patches and was dominated instead by very small patches (1 to 5 pixels) and one enormous matrix patch. Thus, both the frequency distribution of patch sizes and the summary statistics calculated from the two data sets differed dramatically (see table 1). However, when we calculated patch-size statistics on just the core or interior forest of both data sets (in this case considering the outer 30 m to be edge), this substantially reduced the differences in statistics from the two data sets (table 1). Additional work is needed, but these results may indicate that patch-size statistics calculated from the total forest area are essentially meaningless, while those calculated from the "core forest" might be consistent enough to compare across both regions and time.

Aggregation index (AI) is a measure of connectedness/isolation that has been fairly robust to other problem areas such as changes in map resolution (He and others 2000). This metric was calculated for each Massachusetts county

Table 1.—*Comparison of summary statistics calculated for patch size from both the NLCD'92 and the MassGIS data sets (total forest and core forest; all measurements are in acres)*

	All forest		Core forest	
Patch size statistic	**NLCD**	**MassGIS**	**NLCD**	**MassGIS**
Maximum	**42,585**	**2,679**	**3,240**	**1,736**
Median	**.180**	**.720**	**.270**	**.360**
Mean	**4.417**	**11.109**	**6.743**	**7.209**

(forest class only). The AI estimates from the two data sets plotted fairly closely; i.e., for an index with values from 0-1, the average absolute difference in county-level AI estimates between the two data sets was 0.023, if the three counties that are less than 300 km^2 in area were excluded it was only 0.014. Also, the general pattern of the plotted values was similar except for the small counties. The poorer performance of AI at the smaller sizes suggests that minimum criteria for area may be necessary (fig. 9). Whether the magnitude of difference/error observed here is actually smaller than the

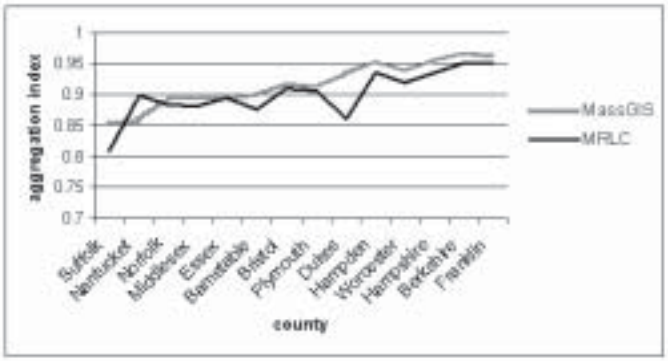


Figure 9.—*Aggregation index of forest by county. Values calculated from NLCD'92 and MassGIS are compared. Counties are in order of increasing percent forest. The counties with the largest differences—Suffolk, Nantucket, and Dukes—are each less than 300 km^2 in size—about one-quarter the size of the next largest counties.*

differences we would like to discern between regions or points in time for this variable needs to be investigated. Aggregation index is an example of a compound/complex metric that incorporates several different measures and thus may be less easily understood and therefore influenced by the land manager or regional policymaker. If the component factors of a compound/complex index are not conflicting in their effects, however, it can still be a useful monitoring tool, particularly if research reveals that the index is linked to changes in the forested ecosystem and thresholds can be identified at which those changes begin to occur. In addition, if it offers advantages such as robustness to differences not caused by real change (such as image resolution) and sensitivity to real changes in fragmentation status, such an index might even be desirable.

DISCUSSION/IMPLICATIONS/CONCLUSIONS

Many of the relationships between fragmentation and ecosystem change and the thresholds of fragmentation effects on forested systems have not been investigated, yet there is already evidence of the kinds of variables and metrics that do affect forested systems and even specific threshold guidelines for land managers (e.g., Rosenberg and others 1999). Concentrating on developing techniques to measure variables that have already been associated with or correlated with real changes in forest composition, water quality, wildlife, or forest management is a first priority. However, including a few additional metrics that have been proven to be both fairly sensitive to real differences in fragmentation status yet robust to image differences may also be worth monitoring in the early stages of metric/index development for FIA because of their implementation advantages. Iterative research regarding real impact and relevant thresholds using these data will tell us whether any index should continue to be monitored because of its observed links with real ecosystem change, or whether it should be dropped because of its observed irrelevance or inconsistency of measurement.

This initial study provides preliminary evidence that NLCD'92 has scale limitations even with respect to the most basic variables. However, if one can accept an error of +/- 11 percent (in an area averaging 64 percent forested) in the subsequent analyses using these data, one can calculate percent forest down to a context area of 500 acres (about a 800-m-radius circle). Measures such as patch size distributions (including mean patch size, average patch, and so on) are grossly inaccurate, although some post-processing such as considering only core forest in the calculations may bring the NLCD'92 data more closely in agreement with the photointerpreted "truth."

For future TM-derived data sets, an improvement in the classification of residential land uses will considerably improve the calculation of metrics for land use context. In addition, given the spatially varied/heterogeneous nature of some land use classes of interest (e.g., developed classes that contain a mixture of tree, building, grass, and road cover), classification algorithms that use context interpretations, and therefore that accurately classify, for example, mixtures of trees and houses as residential, will substantially improve both the accuracy and "fragmentation accuracy" of the data sets.

LITERATURE CITED

Airola, T.M.; Buchholz, K. 1984. Species structure and soil characteristics of five urban sites along the New Jersey Palisades. Urban Ecology. 8: 149-164.

Azuma, D.L.; Birch, K.R.; DelZotto, P.; Herstrom, A.A.; Lettman, G.J. 1999. Land use change on nonfederal land in western Oregon, 1973-1994. Salem, OR: Oregon Department of Forestry. 55 p.

Barlow, S.A.; Munn, I.A.; Cleaves, D.A.; Evans, D.L. 1998. The effect of urban sprawl on timber harvesting. Journal of Forestry. 96: 10-14.

Baskent, E.Z.; Jordan, G.A. 1995. Characterizing spatial structure of forest landscapes. Canadian Journal of Forest Research. 25: 1830-1849.

Bastin, L.; Thomas, C.D. 1999. The distribution of plant species in urban vegetation fragments. Landscape Ecology. 14(5): 493-507.

Betts, M. 2000. In search of ecological relevancy: a review of landscape fragmentation metrics and their application for the Fundy Model Forest. http://www.fundymodelforest.net/DOCUMENT/Betts.PDF. 38 p.

Bolger, D.T.; Alberts, A.C.; Sauvajot, R.M.; Potenza, P.; McCalvin, C.; Tran, D.; Mazzoni, S.; Soulé, M.E. 1997. Response of rodents to habitat fragmentation in coastal southern California. Ecological Applications. 7(2): 552–563.

Burke, D.M.; Nol, E. 2000. Landscape and fragment size effects of reproductive success of forest-breeding birds in Ontario. Ecological Applications. 10(6): 1749–1761.

Cam, E.; Nichols, J.D.; Sauer, J.R.; Hines, J.E.; Flather, C.H. 2000. Relative species richness and community completeness: birds and urbanization in the mid-Atlantic states. Ecological Applications. 10(4): 1196–1210.

Cooksey, R.A. 2000. Forest fragmentation in the Chespeake Bay watershed. In: DeCoster, L.A., ed. Proceedings of the Forest fragmentation 2000 conference: sustaining private forests in the 21st century; 2000 September 17-20; Annapolis, MD. Alexandria, VA: Sampson Group: 80-85.

He, H.S.; DeZonia, B.E.; Mladenoff, D.J. 2000. An aggregation index (AI) to quantify spatial patterns of landscapes. Landscape Ecology. 15(7): 591-601.

Heckscher, S.; Hornberger, K.; Mostrom, A.; Marsh, B. 2000. Biodiversity declining: structural and compositional changes in a Pennsylvania Piedmont Forest. In: DeCoster, L.A., ed. Proceedings of the Forest fragmentation 2000 conference: sustaining private forests in the 21st century; 2000 September 17-20; Annapolis, MD. Alexandria, VA: Sampson Group: 104-113.

Hunsaker, C.T.; Levine, D.A.; Timmins, S.P.; Jackson, B.L.; O'Neill, R.V. 1992. Landscape characterization for assessing regional water quality. In: McKenzie, D.H.; Hyatt, D.E.; McDonald, V.J., eds. Ecological indicators. New York, NY: Elsevier Science: 997-1006.

Kline, J.D.; Azuma, D.L.; Moses, A.; Alig, R.J. 2000. Urbanization impacts on private forest conditions in western Oregon. In: DeCoster, L.A., ed. Proceedings of the Forest fragmentation 2000 conference: sustaining private forests in the 21st century; 2000 September 17-20; Annapolis, MD. Alexandria, VA: Sampson Group: 135-139.

Kurki, S.; Nikula, A.; Helle, P.; Lindén, H. 2000. Landscape fragmentation and forest composition effects on grouse breeding success in boreal forests. Ecology. 81(7): 1985–1997.

Loveland, T.R.; Merchant, J.W.; Ohlen, E.O.; Brown, J.F. 1991. Development of a land-cover characteristics database for the conterminous U.S. Photogrammetric Engineering and Remote Sensing. 57(11): 1453-1463.

McGarigal, K.; Marks, B. 1994. Fragstats:spatial pattern analysis program for quantifying landscape structure. Corvallis, OR: Oregon State University, Forest Science Department. 62 p. [Ref. manual.]

McMahon, G.; Cuffney. T.F. 2000. Quantifying urban intensity in drainage basins for assessing stream ecological conditions. Journal of the American Water Resources Association. 36(6): 1247-1261.

Mladenoff, D.J.; DeZonia, B. 1997. APACK 2.0 user's guide. Madison, WI: University of Wisconsin, Department of Forest Ecology and Management. 50 p.

Richards, C.; Host, G. 1994. Examining land use influences on stream habitats and macroinvertebrates: a GIS approach. Water Resources Bulletin. 30(4): 729-738.

Riemann, R.; Tillman, K. 1999. FIA photointerpretation in Southern New England: a tool to determine forest fragmentation and proximity to human development. Res. Pap. NE-709. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 12 p.

Riitters, K.H.; O'Neill, R.V.; Hunsaker, C.T.; Wickham, J.D.; Yankee, D.H.; Timins, S.P.; Jones, K.B.; Jackson, B.L. 1995. A factor analysis of landscape pattern and structure metrics. Landscape Ecology. 10: 23-29.

Riitters, K.; Wickham, J.; O'Neill, R.; Jones, B.; Smith, E. 2000. Global-scale patterns of forest fragmentation. Conservation Ecology. 4(2): 3.

Rosenberg, R.V.; Rohrbaugh, R.W., Jr.; Barker, S.E.; Lowe, J.D.; Hames, R.S.; Dhondt, A.A. 1999. A land manager's guide to improving habitat for scarlet tanagers and other forest-interior birds. Ithaca, NY: Cornell Lab of Ornithology. 24 p.

Rudis, V.A. 1995. Regional forest fragmentation effects on bottomland hardwood community types and resource values. Landscape Ecology. 10(5): 291-307.

Rudis, V.A. 2001. Landscape context and regional patterns in Arkansas' forests. In: Guldin, J.M., tech. comp. Proceedings of the Symposium on Arkansas forests: a conference on the results of the recent forest survey of Arkansas; 1997 May 30-31; North Little Rock, AR. Gen. Tech. Rep. SRS-41. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 24-45.

Saunders, D.A.; Hobbs, R.J.; Margules, C.R. 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology. 5: 18-32.

Vogelmann, J.E.; Sohl, T.; Howard, S.M. 1998. Regional characterization of land cover using multiple sources of data. Photogrammetric Engineering & Remote Sensing. 64(1): 45-47.

Wear, D.N.; Turner, M.G.; Naiman, R.J. 1998. Land cover along an urban-rural gradient: implications for water quality. Ecological Applications. 8(3): 619–630.

Wear, D.N.; Liu, R.; Foreman, J.M.; Sheffield, R.M. 1999. The effects of population growth on timber management and inventories in Virginia. Forest Ecology and Management. 118: 107-115.

Wendt, D.G. 2001. Relating landscape indices of forest fragmentation to large scale forest assessment data. In: Greer, J.D., ed. Remote sensing and geospatial technologies for the new millennium: proceedings of the 8th Forest Service remote sensing applications conference; 2000 April 10-14; Albuquerque, NM. Bethesda, MD: American Society for Photogrammetry and Remote Sensing: 74-84.

Wickham, J.D.; Norton, D. 1994. Mapping and analyzing landscape patterns. Landscape Ecology. 9: 7-23.

Zipperer, W.C.; Pouyat, R.V. 1995. Urban and suburban woodlands: a changing forest ecosystem. Journal of American Association of Botanical Gardens and Arboreta. 10: 18-20.