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REPORT

Temporal change in forest fragmentation at multiple scales

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Abstract Previous studies of temporal changes in fragmentation have focused almost exclusively on patch and edge statistics, which might not detect changes in the spatial scale at which forest occurs in or dominates the landscape. We used temporal land-cover data for the Chesapeake Bay region and the state of New Jersey to compare patch-based and area–density scaling measures of fragmentation for detecting changes in the spatial scale of forest that may result from forest loss. For the patch-based analysis, we examined changes in the cumulative distribution of patch sizes. For area–density scaling, we used moving windows to examine changes in dominant forest. We defined dominant forest as a forest parcel (pixel) surrounded by a neighborhood in which forest occupied the majority of pixels. We used >50% and ≥60% as thresholds to define majority. Moving window sizes ranged from 2.25 to 5,314.41 hectares (ha). Patch size cumulative distributions changed very little over time, providing no indication that forest loss was changing the spatial scale of forest. Area–density scaling showed that dominant forest was sensitive to forest loss, and the sensitivity increased nonlinearly as the spatial scale increased. The ratio of dominant forest loss to forest loss increased nonlinearly from 1.4 to 1.8 at the smallest spatial scale to 8.3 to 11.5 at the largest spatial scale. The nonlinear relationship between dominant forest loss and forest loss in these regions suggests that continued forest loss will cause abrupt transitions in the scale at which forest dominates the landscape. In comparison to the Chesapeake Bay region, dominant forest loss in New Jersey was less sensitive to forest loss, which may be attributable the protected status of the New Jersey Pine Barrens.

Keywords Conservation · Cumulative impact · Forest loss · Land-cover change · Land-use planning · Pine Barrens

Introduction

Our ecology and biogeography manuals teach us that the potential natural vegetation of the eastern United States is forest (Kuchler 1964;

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Whittaker 1975; Daubenmire 1978; Walter 1979; Williams 1982). Differences in topography and soils induce changes in the types of forest we recognize, but the dominating influence of climate favors trees over shrubs and grasses from Florida to Maine and west to the Mississippi River. Forest is the dominant land cover in the absence of anthropogenic use of the land.

The relationship between climate and forest cover has important implications for landscape ecologists and others concerned with forest fragmentation. Absent human influence, there is no difference in the likelihood of encountering a 2-hectare (ha) or 20,000-ha forest. Human activities change these likelihoods by altering the amount and distribution of forest. As forest becomes fragmented, its spatial extent is reduced and there are fewer areas where forest spans 1,000s–10,000s ha and a greater number of forested areas spanning only 10^0–10^2 ha (Wilcove et al. 1986).

The spatial extent (scale) of forest is an important aspect of forest and environmental condition. Keddy and Drummond (1996) proposed forest area as one of 10 factors that should be used to prioritize tracts of deciduous forest for conservation and preservation. The rationale is justifiable since forests with greater spatial scale: (1) tend to suffer from fewer edge effects (Laurance et al. 2001; Weathers et al. 2001; Harper et al. 2005; Ramaharitra 2006); (2) provide superior habitat for forest-dependent organisms (Robinson et al. 1995; Keddy and Drummond 1996; Fahrig 2002); increase the ratio of latent to sensible heat (Hayden 1998, Marshall et al. 2004), and; (4) may be less likely to have altered distributions of the forest types contained within them (see Kennedy and Spies 2005).

Remotely sensed data have been used effectively to monitor changes in forest cover (Hall et al. 1991; Skole and Tucker 1993), and temporal land-cover data have been used to quantify changes in fragmentation specifically (Skole and Tucker 1993; Luque et al. 1994; Vogelmann 1994; Pindar et al. 1999; Staus et al. 2002; Turner et al. 2003). Most studies of forest fragmentation dynamics have used measurements related to patch size and edge characteristics, but there are significant practical problems when using this approach with synoptic land-cover maps (e.g., Hunsaker et al. 1994; O'Neill et al. 1996; Riitters et al. 2004). Patch-based analysis a priori fixes the scale of analysis by defining forest objects (patches). Consequently, changes in the number of patches, average patch size, inter-patch distance or other measures are used to assess impact of forest loss (or gain). It is difficult to use measures such as patch size to determine the scale at which forest occurs because there in no complementary information on configuration. Forest patches could be very tightly packed, indicating that forest cover was spatially extensive but punctuated with minor "disturbances," or they could be far apart, indicating that forest cover was not spatially extensive. In addition, Riitters et al. (2004) have shown that patch-based analysis of land-cover change (e.g., forest loss) can yield conflicting results: a decrease in average patch size accompanied by a decrease in the average inter-patch distance.

Area–density scaling is a useful alternative to patch-based analysis because it relaxes the requirement to define forest objects (patches) and provides direct measurement of forest spatial scale (Riitters et al. 2000, 2002). Area–density scaling uses square, moving windows to estimate the amount of a feature (e.g., forest). Multi-scale analysis is accomplished by the use of a range of window sizes. The output from area–density scaling provides the grist for well-established landscape analysis methods such as fractals and lacunarity, and estimation of amount (i.e., proportion) is considered one the most important landscape variables (Li and Reynolds 1995; Gardner and Urban 2006).

In neutral model analysis, theoretical critical thresholds in proportion (e.g., 0.5928) help to define landscape pattern (Gardner et al. 1987). Intuitive and logical thresholds serve the same purpose in real landscapes. Riitters et al. (2002) found sharp declines in the amount of interior forest with increasing spatial scale, suggesting that the spatial scale of interior forest may be sensitive to forest loss. Interior forest is easily and intuitively defined using area–density scaling: it is those locations that are completely forested for a given window size. Here we use area–density scaling to report a multi-scale analysis of forest fragmentation change in the eastern United

States with a view towards defining the scale of fragmentation changes in relation to the overall change in amount of forest. The multi-scale (area–density) analysis is compared to a patch-based complement to facilitate comparison of each method to articulate changes in forest spatial scale that arise from forest loss. The study is conducted for two locations on the eastern seaboard of the United States (Chesapeake Bay region and the state of New Jersey) where urban sprawl (e.g., Clarke et al. 1996; Lucy and Phillips 1997; Rutgers University n.d.; Wickham et al. 2000a, b) and other factors are significant ecological process causing forest loss and fragmentation.

Methods

Temporal land-cover data were acquired for New Jersey and the Chesapeake Bay region from the Center for Remote Sensing and Spatial Analysis (CRSSA) at Rutgers University and the Multi-Resolution Land Characteristics (MRLC) Consortium, respectively (Fig. 1). Both projects used Landsat Thematic Mapper data for land-cover mapping, and maintained the land-cover data at their native 30-m pixel size. We re-classified the land-cover data into 6 classes: water, urban, barren, forest, agriculture, and wetland. The forest class in our six-class legend included both shrubland and forested wetland classes identified in each project's more detailed classification schemes. The difference between early (T_1) and late (T_2) dates for both areas spanned about 10 years (New Jersey: 1984 and 1995; Chesapeake Bay region: 1992 and 2001).

Changes in forest fragmentation resulting from changes in forest amount were examined using area–density scaling (Riitters et al. 2000, 2002). Area–density scaling uses a moving window to estimate the proportion of forest (pf) in a neighborhood (window), and assigns the estimate to the focal (center) pixel. It is an estimate of forest density for a given window. All pixels that were forest at either time were treated as focal pixels. Water pixels were treated as missing data, and were ignored in all computations.

Moving windows can be used to address questions of scale by changing the spatial domain over which a parameter (e.g., pf) is estimated without modifying the grain (pixel size) or extent of the study area. We used five window sizes spanning four orders of magnitude: 2.25, 7.29, 65.61, 590.14, and 5,314.41 ha. The smallest window size, 2.25 ha, is slightly larger than two European football fields, and the size of a 5,314.41-ha area is shown at the center of Fig. 1. The corresponding side lengths of the square windows in pixel units were 5, 9, 27, 81, and 243.

Estimation of forest (or other feature) density using moving windows is the first computational step in estimation of fractals and similar measures such as lacunarity (Milne 1992; Plotnick et al. 1993). The empirical distributions of density are converted to probability and the moments (mean, variance) of the probability distribution summarize the pattern in the map. Lacunarity may be thought of as another expression of the familiar statistical parameter, coefficient of variation. A high lacunarity value indicates forest spatial variability is not constant across the map. However, since lacunarity is a single-number map-wide summary statistic, it does not permit articulation of the geography of the spatial variability. Use of the derivative maps that result from moving windows permits direct articulation of the geographic variability in forest density.

Forest density is a continuous [0, 1] variable that can be compared to thresholds to classify each pixel. Forest could be classified as interior when forest density is 100% because no other land-cover classes occur within the window. Density values greater than 50% denote those locations where forest is the dominant land cover in the surrounding landscape for a given window size. Thresholds ranging from 50% to 70% range are commonly used to classify dominant landscape composition (Wickham and Norton 1994; Gagne and Fahrig 2006). Our analysis focuses on dominant forest, using density values of >50% and ≥60% to define dominance. Comparison the >50% and ≥60% thresholds helps to gauge sensitivity of the results to the definition of dominance.

Our focus on dominance is based on the widely accepted recognition that forests were spatially extensive prior to European settlement of the eastern United States (Kuchler 1964;

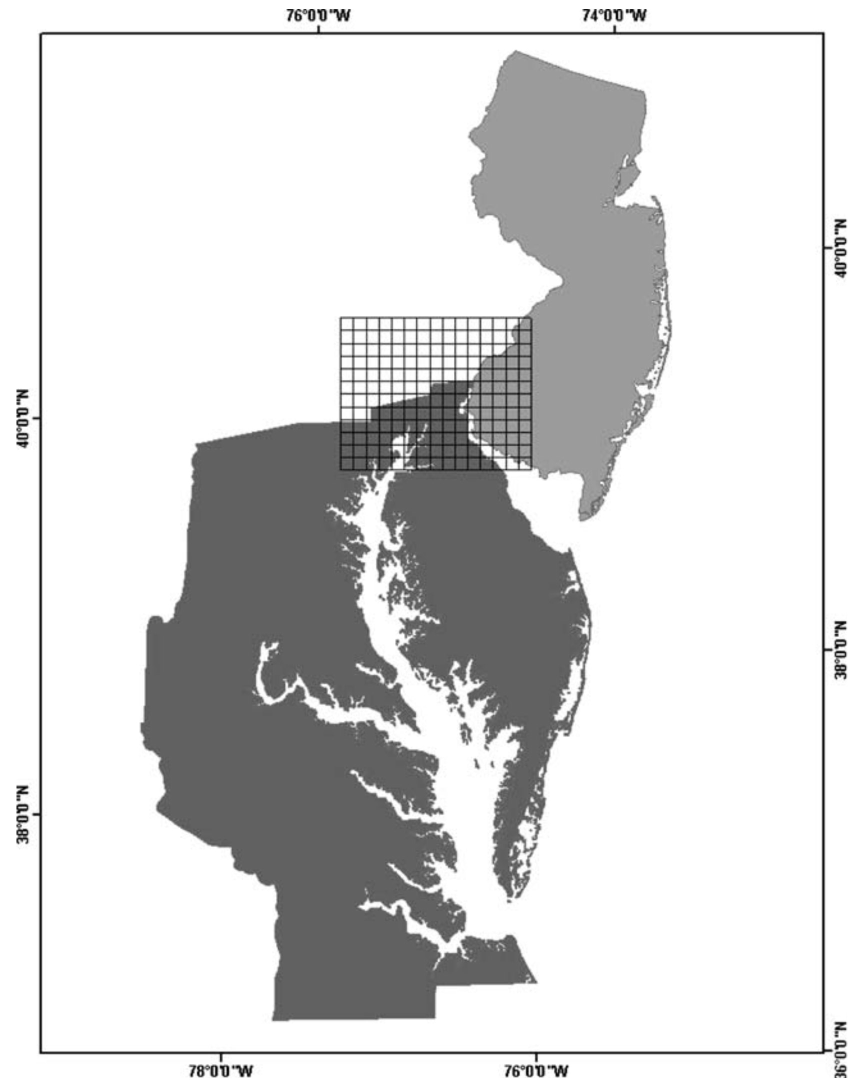

Fig. 1 Location map. The Chesapeake Bay region is in dark gray, and New Jersey is in light gray. Each cell in the lattice at the center of the figure is 5,314.41 ha

Whittaker 1975; Daubenmire 1978; Walter 1979; Williams 1982). Forest densities that drop below these thresholds over time indicate a change from spatial dominance to nondominance.

For comparison with other popular approaches, we also evaluated patch-based measures of forest fragmentation. We plotted the cumulative (empirical) distribution of forest patch size for each date and each region as well as the patch size of forest loss for each region. The cumulative distribution of patch size is an effective summary of many landscape indicators that are commonly estimated using freeware such as FRAGSTATS (McGarigal and Marks 1995), including smallest and largest patch size, median patch size and number of patches. Comparison of patch-based and moving window approaches permits one to gauge the effectiveness of each approach for interpreting and summarizing the impact of forest loss on the spatial scale of forest dominance.

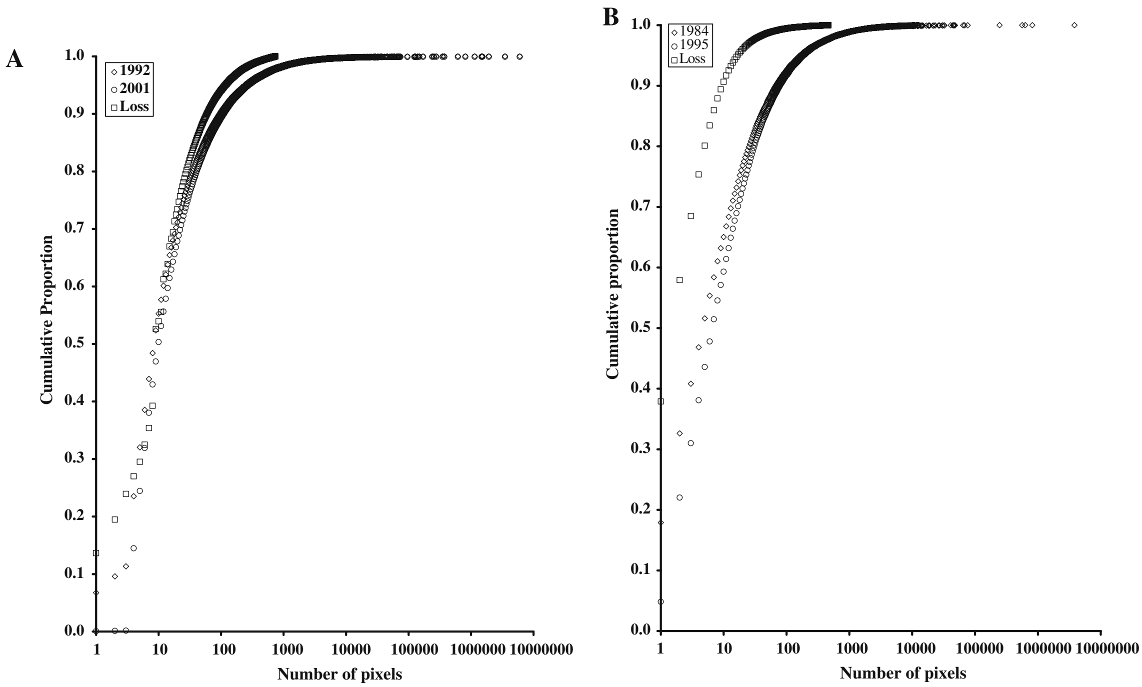

Fig. 2 Cumulative distribution of patch sizes for the Chesapeake Bay region (**A**) and New Jersey (**B**). The x-axis is $\log_{10}$ scale. Multiplying by 0.09 converts pixels to hectares

Results

There were 146,490 ha of forest loss in the Chesapeake Bay region and 93,301 ha of forest loss in New Jersey (Table 1). Net forest loss was 5.1% and 4.3% in the Chesapeake Bay region New Jersey, respectively. The median patch size of forest loss was less than 1 ha in both regions, and forest loss did not substantially alter the patch size distribution in either region (Fig. 2). The patch-based analysis does not suggest that forest loss had a significant impact on the spatial scale at which forest occurs in or dominates the landscape.

Area–density scaling results provided a different perspective: sensitivity of dominant forest loss to net forest loss increased as the spatial scale increased (Fig. 3). At the 7.29-ha scale, forest loss resulted in moderate declines in the amount of dominant forest, and hence much of the remaining forest still satisfied the dominance criteria (pf ≥60%) (Fig. 2A, C). At the 5,314.41-ha scale, relatively small losses of forest led to large losses of dominant forest. The total area of dominant forest losses at the 5,314.41-ha scale were 147,473 ha in the Chesapeake Bay region and 36,089 ha in New Jersey, but the actual amount of forest loss within the areas of dominant forest loss was an order of magnitude lower at 12,767 ha (Chesapeake Bay region) and 4,415 ha (New Jersey). Local-scale forest loss over the 10-year periods produced roughly a 10-fold reduction in the amount of

Table 1 Change in amount of forest in hectares

Location	T_1 forest	Loss	Gain	T_2 forest
Chesapeake Bay	2,659,972	146,490 (5.5%)	11,321 (0.4%)	2,524,803
New Jersey	912,354	93,301 (10.2%)	54,256 (5.9%)	873,309

Loss and gain percentages are based on the amount of forest at T_1

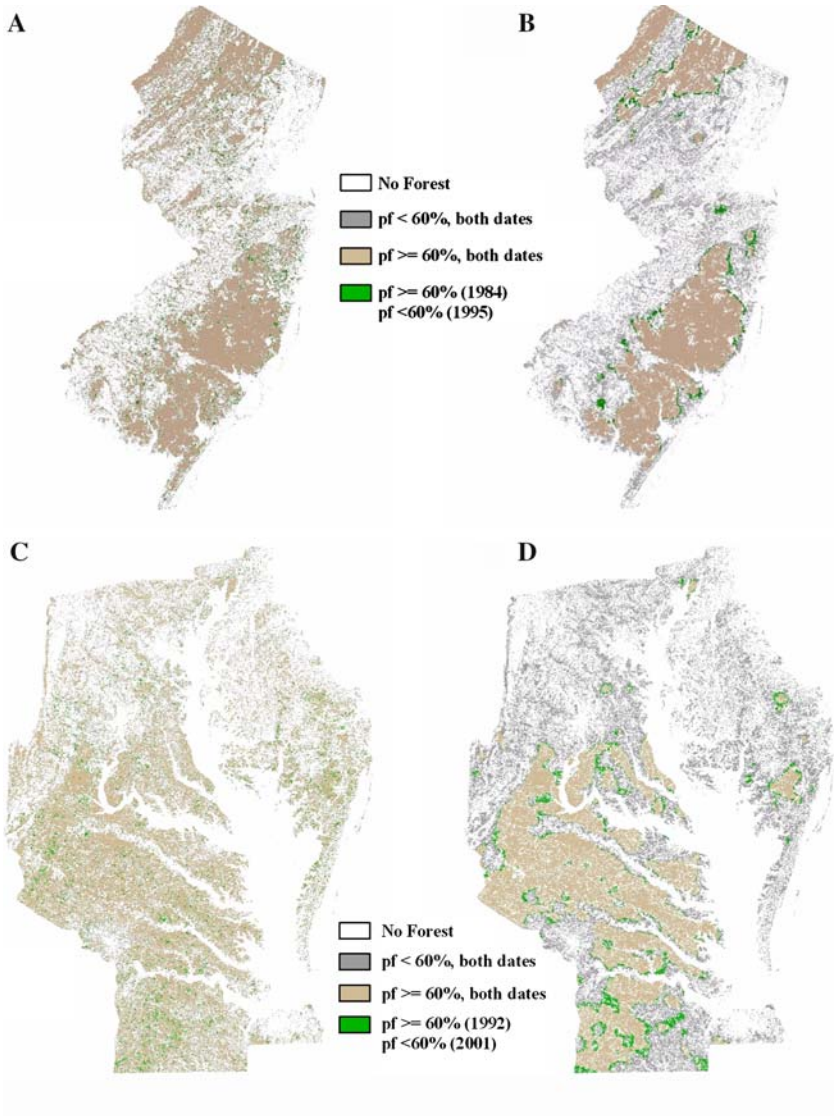

Fig. 3 Temporal changes in dominant forest at small and large scales. Changes at the 7.29-ha scale are shown in panels **A** (New Jersey) and **C** (Chesapeake Bay region). Changes at the 5,314.41-ha scale are shown in panels **B** (New Jersey) and **D** (Chesapeake Bay region). Forest density is denoted as pf. Changes are based on comparisons of three-class maps ($pf = 0$, $0 < pf < 60\%$, $pf \geq 60\%$)

dominant forest at the largest spatial scale. The widely distributed losses of relatively small forest parcels resulted in three distinct types of dominant forest loss at the 5,314.41-ha scale (Fig. 2B, D): (1) erosion at the edges of large expanses of dominant forest, (2) introduction of holes of into otherwise large expanses of dominant forest, and (3) isolation of previously connected areas of dominant forest. In total, these three geographic patterns identify areas where dominant forest was sensitive to forest loss.

The sensitivity of dominant forest to forest loss was more a function of scale than the threshold used to define dominance. The ratio of dominant forest loss to forest loss within the areas of dominant forest loss increased nonlinearly with scale (Fig. 4). Relaxing the threshold for dominance to >50% did not change the nonlinear relationship between the ratio and scale. Forest loss still produced a 10-fold increase in dominant forest loss even when dominance was defined using

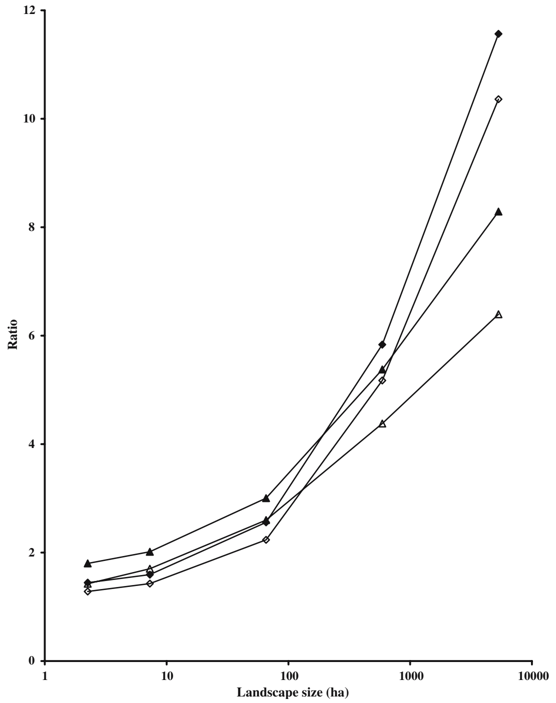

Fig. 4 Ratio of the loss of dominant forest to forest loss for different spatial scales of analysis. The numerator of the ratio is the amount of dominant forest loss and denominator is the amount of forest loss within the areas of dominant forest loss. Chesapeake Bay is represented with diamonds and New Jersey is represented with triangles. Solid symbols represent pf ≥60%, and open symbols represent pf >50%

a threshold of >50% in the Chesapeake Bay region. The less dramatic changes in dominant forest loss (Fig. 4) in New Jersey may be attributable to the protected status of the New Jersey Pine Barrens. The New Jersey Pine Barrens is an area of documented biodiversity (Forman 1979) that has been protected through the establishment of the New Jersey Pinelands National Reserve (see Luque et al. 1994). The large tan area in eastern New Jersey in Fig. 2B approximates the boundary of the New Jersey Pinelands Land Management Area (New Jersey Pinelands Commission n.d.; see also Fig. 1 in Luque et al. 1994).

Discussion

Forest loss has the potential to change the spatial scale at which forest dominates the landscape. We analyzed temporal land-cover maps for changes in the spatial scale at which forest dominates that landscape using two common methods: area–density scaling and patch size distributions. For area–density scaling, we used five window sizes ranging from 2.25 to 5,314.41 ha. Density was used as the measure of forest fragmentation and density thresholds of >50% and ≥60% were used as measures of forest spatial dominance. The sensitivity of dominant forest loss to forest loss increased nonlinearly as the spatial scale of analysis increased. Dominant forest loss was 1.4 (Chesapeake Bay region) and 1.8 (New Jersey) times greater than forest loss at the smallest spatial scale, whereas dominant forest loss was 11.5 (Chesapeake Bay region) and 8.3 (New Jersey) times greater than forest loss at the largest spatial scale (Fig. 4). At the largest spatial scale, relatively small losses of forest produced large losses of dominant forest, and the sensitivity of dominant forest to forest loss was not reduced substantially when the threshold for dominance was relaxed from ≥60% to >50%. Change in the distribution of forest patch size did not indicate that the spatial scale of forest was sensitive to forest loss. Early- and late-date forest patch size distributions were nearly identical despite net forest losses of 5.1% and 4.3% in the Chesapeake Bay region and New Jersey, respectively.

The response of dominant forest to forest loss depends on two factors: the spatial pattern of extant forest and the spatial pattern of forest loss. At the 5,314.41-ha scale, there would have been no loss of dominant forest in the Chesapeake Bay region if forest loss had been restricted to the northern portion of the region (Fig. 3D). The distinctly different trends for the Chesapeake Bay region versus New Jersey also suggest that a priori prediction would be difficult. In the Chesapeake Bay region, 58% of the forest loss occurred where forest density was greater than 50% at the largest spatial scale, whereas only 45% of the forest loss in New Jersey occurred where forest density was greater than 50% at the largest spatial scale.

The relationship between forest loss and dominant forest loss in Fig. 3B and D may be examples of how local land-use decisions scale-up to have regional impacts on forests. The characteristically local spatial scale (sensu Urban et al. 1987) of contemporary forest loss is consistent with the hypothesis that land-cover change is driven mainly by the decisions of individuals without regard to larger scale forest patterns (e.g., Foster and Foster 1999; Sampson and Decoster 2000). In the regions we studied, the median size of forest loss was less than 1 ha, but, added together, the losses had a cumulative impact on the scale at which forest dominated the landscape. For the largest spatial scale, the 147,473 ha and 36,089 ha of dominant forest loss were 11% and 7% of the total area of dominant forest in the Chesapeake Bay region in 1992 and New Jersey in 1984, respectively.

Both study areas are part of the eastern deciduous forest region (Braun 1950) where climatic conditions foster spatially extensive forests (Kuchler 1964; Whittaker 1975; Daubenmire 1978; Walter 1979). Under a scenario of continued net forest loss, the main spatial characteristic of forest will change from extensive to isolation. Forest would no longer be spatially dominant at larger scales (Riitters et al. 2002), and the main ecological driver of forest extent will more likely be attributable to human activity (e.g., Wickham et al. 2000b) than climate. The potential for human activity to change the main spatial characteristic of forest can be seen by comparing dominant forest at small and large scales (Fig. 3). Much of the extant forest still satisfies the dominance criteria of ≥60% at small scales, but only much smaller subregions of dominant forest remain at large scales. Past human activity has transformed each region into two phases, where forest is either dominant or not at large scales. Continued net forest loss will likely further reduce the size of the remaining subregions of spatially dominant forest. Forest loss is changing the spatial scale at which the regions' forests dominate the landscape.

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