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REPORT

Temporal change in fragmentation of continental US forests

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Abstract Changes in forest ecosystem function and condition arise from changes in forest fragmentation. Previous studies estimated forest fragmentation for the continental United States (US). In this study, new temporal land-cover data from the National Land Cover Database (NLCD) were used to estimate changes in forest fragmentation at multiple scales for the continental US. Early and late dates for the land-cover change data were ca. 1992 and ca. 2001. Forest density was used as a multi-scale index of fragmentation by measuring the proportion of forest in neighborhoods ranging in size from 2.25 to 5314.41 ha. The multi-scale forest density maps were classified using thresholds of 40% (patch), 60% (dominant), and 90% (interior) to analyze temporal change of fragmentation. The loss of dominant and interior forest showed distinct scale effects, whereas loss of patch forest was much less scale-dependent. Dominant forest loss doubled from the smallest to the largest spatial scale, while interior forest loss increased by approximately 80% from the smallest to the second largest spatial scale, then decreased somewhat. At the largest spatial scale, losses of dominant and interior forest were 5 and 10%, respectively, of their ca. 1992 amounts. In contrast, patch forest loss increased by only 25% from the smallest to largest spatial scale. These results indicate that continental US forests were sensitive to forest loss because of their already fragmented state. Forest loss would have had to occur in an unlikely spatial pattern in order to avoid the proportionately greater impact on dominant and interior forest at larger spatial scales.

Keywords Change detection · Cumulative impacts · Forest edge · Forest loss · Land cover · Scale

Introduction

Forests are of interest from a wide range of perspectives simply because they serve many purposes. They are of interest to foresters and economists because they provide raw materials for economic activity (Williams 1982; Prestemon and Abt 2002; Sendak et al. 2003; FAO (Food, Agriculture Organization)

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2007). They are of interest to wildlife, plant, and landscape ecologists because forest spatial pattern affects the distribution of plants and animals (Gardner and Urban 2007). Climate modelers need information on forests to estimate carbon dynamics and radiative energy exchanges between the surface and the atmosphere (Hayden 1998; Pielke et al. 2002; Marshall 2004; Pielke et al. 2007). Watershed managers recognize that maintaining forest cover is the best means for keeping water pure and reducing the magnitude and frequency of floods (WRI, World Resources Institute 2000). The emerging concern over the increase in number of owners of non-industrial private forestland highlights concern over the ecological, aesthetic, and recreation benefits that forests supply, and the potential negative feedback of increased human use on the condition of the forest itself (Sampson and Decoster 2000).

Forest loss and fragmentation have been long-standing, recurrent issues because of the multifaceted importance of forests (e.g., FAO (Food, Agriculture Organization) 2007). Implicit in the discussion of forest loss and fragmentation are the inter-related concepts of amount, pattern, and spatial scale. Forest ecosystem function and condition are affected by changes in the amount, pattern, and spatial scale of forest. The effect of forest on downwind precipitation highlights the importance of forest dominance over broad spatial scales for maintaining regional rainfall patterns (Hayden 1998, see also Marshal et al. 2004). The amount of forest determines whether the forest is mostly edge or interior, and the relative amounts of edge and interior are important determinants of the condition of the forest itself and the type of habitat it supplies (Mladenoff et al. 1993; Robinson et al. 1995; Weathers et al. 2001; Harper et al. 2005). Flooding decreases and water-quality improves as the spatial dominance of forest in a watershed increases (USDA (United States Department of Agriculture) 1986; Beaulac and Reckhow 1982; Frink 1991; Wickham et al. 2005).

Change in the amount, pattern, and scale of forest can be assessed by a fundamental landscape pattern metric, proportion (*p*) (Gardner and Urban 2007). *P* is a fundamental pattern metric if only because no other pattern metric can be interpreted independently of it. When *p* is small, forests tend to be fragmented (Gardner and Urban 2007; Riitters et al. 2007), and the characteristics associated with small isolated blocks of forest define the system (Mladenoff et al. 1993; Weathers et al. 2001; Marshall et al. 2004; Harper et al. 2005); Riitters et al. (2002) used p to report multi-scale patterns of forest fragmentation for the continental United States (US), showing that forests were more fragmented at larger spatial scales.

The scale-dependent pattern of forests fragmentation introduces the possibility that forest loss will result in more severe fragmentation at larger rather than smaller scales because the pattern and scale of forest change is likely to be different than the pattern and scale of forest extent. Here we extend Riitters et al. (2002) continental analysis into the temporal domain to report the affect of forest dynamics on the spatial pattern of forest at multiple scales for the continental US.

Methods

Completion of the MultiResolution Land Characteristics (MRLC) Consortium's land-cover change dataset (http://www.mrlc.gov), a component of the NLCD, provides the first remotely derived, synoptic dataset that is suitable for assessment of temporal change in forest fragmentation across the continental United States. The land-cover change dataset was developed to support comparison of NLCD 1992 (Vogelmann et al. 2001) and NLCD 2001 (Homer et al. 2007). In keeping with the protocols for NLCD 1992 and NLCD 2001, the spatial resolution of the land-cover change dataset is the native 30 × 30 m pixel size of Landsat TM (0.09 ha per pixel). The land-cover classes in the change dataset include forest, urban, agriculture, water, barren, wetland, grass/shrub, and all realized changes (e.g., forest to urban). The land-cover change dataset did not distinguish between the woody (i.e., forested) and emergent (i.e., herbaceous) wetland classes that are mapped in the more detailed NLCD 1992 (Vogelmann et al. 2001) and NLCD 2001 (Homer et al. 2007) datasets. Therefore, we could not distinguish woody wetland land-cover changes from all wetland land-cover changes. We chose to treat the aggregated wetland class as forest in the land-cover change dataset so that forested wetland changes were not omitted from the analysis.

Multi-scale analysis was conducted by processing the land-cover change dataset into separate single-date datasets (ca. 1992 and ca. 2001), and measuring the proportion of forest (forest density) for each date at five different spatial scales using square, moving windows (Riitters et al. 2000, 2002). The side lengths of the five windows sizes were 5, 9, 27, 81, and 243 pixels, which is a logarithmic progression in area, except for the smallest window (2.25, 7.29, 65.61, 590.49, 5314.41 ha). The forest density maps were then overlaid on the input land-cover map to remove pixels that were not forest. Ignoring non-forest locations focuses the analysis on forest density for forested locations. The forest density maps were classified using a series of thresholds following masking. The thresholds used were 40%, 60%, and 90%, which, we refer to as patch, dominant, and interior forest, respectively. The density thresholds were inclusive rather than exclusive. Forested locations that met the 90% threshold, for example, also included the forested locations that met the 60% threshold.

The effect of forest change on forest pattern was assessed by comparing the proportions of forest in each density class and each scale at each date. Proportions were based on the amount of all land-cover types to control for changes in the absolute amount and specific location of forest over time. Forest density changes were compared nationally and regionally. Regional (Fig. 1) reporting was included to account for potential geographic differences in forest fragmentation change. We used the NLCD 2001 mapping regions (Homer and Gallant unpublished) to define five broad forested regions, one region dominated by shrubland, and one region dominated by agriculture and grasslands. Estimates were summed over all polygons that comprised a region when the region was spatially disjunct. The five forested regions coincide with those in plant geography textbooks (Daubenmire 1978; Eyre 1980). We distinguished between forested and non-forested regions because changes in forest density were expected to be different when agriculture, grass, or shrubs dominate the landscape. Similarly, we distinguished different forested regions because drivers of forest change may be different from place to place. The five forested regions cover the Pacific Northwest, Rocky Mountains, upper Great Lakes, Ozarks, and the eastern United States. The effect of map boundaries on forest density estimates was controlled by applying the moving windows nationwide prior to extracting the regional forest density maps. Edge effects on forest density estimates are limited to coastal and national boundaries.

Our analysis relies solely on amount (density, P) to measure fragmentation, foregoing other commonly used measures of pattern, such as amount of edge, and number of, size of, and distance between patches. Inclusion of commonly used pattern measures would have been redundant because they are strongly correlated with amount (Neel et al. 2004; Riitters et al. 2006; Koper and Schmiegelow 2006; Gardner

Fig. 1 Regional reporting units for continental United States. See Table 1 for the description of the regions

and Urban 2007). In addition, commonly used pattern measures are not unambiguously interpretable in the temporal domain (see, for example, Riitters et al. 2004). Forest loss could result in a fewer number of patches (less isolation) or more compact patches (less edge to area), which could be interpreted as either an increase or decrease in fragmentation, depending on how forest loss per se is viewed. In contrast, density is unambiguously interpretable in the temporal domain. Forest density can only decline when there is a net loss of forest, and it can only increase when there is a net forest gain. Further, commonly used pattern measures are overly reliant on the patch conceptual model that assumes the feature of interest is a series of disjunct entities distributed across an area. The patch conceptual model does not apply when the feature of interest dominates the landscape, and forest is dominant where is occurs over most of the continental United States (Riitters et al. 2002)

Results

The net forest loss from 1992 to 2001 was approximately 47,000 km^2 nationwide (Table 1), of which approximately 92% (43,363 km^2) was from the five forested regions. Five of the seven regions had net losses of forest, and two regions had net gains of forest. Approximately half of the net forest loss occurred in the eastern United States, while the Ozarks region had the highest percentage loss. The percentage difference between the amount of forest (Table 1) and the amount of patch forest (Table 2) is less than 5% across all regions and all scales, indicating that most forested locations have at least 40% forest in their surrounding neighborhoods.

An emergent national result was an increasing loss of dominant and interior forest with increasing spatial scale (Fig. 2). Dominant forest loss at the largest spatial scale was approximately twice as large as dominant forest loss at the smallest spatial scale. Interior forest loss increased by 50% to 100% between the smallest spatial scale (2.25 ha) and the 590-ha scale, and then decreased. Nevertheless, interior forest loss at the largest spatial scale (5314 ha) was approximately 10% of the total amount of interior forest (1992). Loss of patch forest was relatively constant across scale, increasing by approximately 25% from the smallest to the largest scale.

There were noteworthy regional differences (Table 2). Forest density decreased in all of the forested regions except the upper Great Lakes. Among the four forested regions where forest density declined, rates of forest density losses were higher in the two eastern regions (F_1, F_2) than in the two western regions (F_3, F_4). In the upper Great Lakes, where forest density increased, the increases were consistent across scale. The increase in forest density in the upper Great Lakes also resulted in proportionately greater gains in interior forest than in patch or dominant forest. Interior forest gains in the upper Great Lakes were greater than 2%, whereas increases in patch and dominant forest were less than 1%, indicating that afforestation tended to occur in areas where forest density was already high (>88%).

In the shrubland region, losses of patch and dominant forest were relatively consistent across

Table 1 Change in forest area by region

Region	Area (km^2)	Forest, 1992	Forest, 2001	Change	Change (km^2)
F_1	1,650,076	0.6286	0.6115	−0.0172	−28,363
F_2	326,897	0.6458	0.6210	−0.0234	−7,640
F_3	143,973	0.6011	0.5932	−0.0079	−1,143
F_4	642,652	0.6276	0.6163	−0.0113	−7,272
F_5	211,779	0.7721	0.7770	0.0050	1,054
S	1,890,932	0.1320	0.1292	−0.0028	−5,254
A	2,900,949	0.1192	0.1198	0.0006	1,595
Sum	7,767,259				−47,022

F_1, F_2, F_3, F_4, and F_5 refer to the eastern US, Ozarks, Rocky Mountains, Pacific Northwest, and upper Great Lakes, respectively. S and A refer to the shrubland and agriculture regions, respectively. Forest is expressed as proportion of total area. Areal estimates for regions do not include coastal waters or Great Lakes

Table 2 Changes in forest density classes at different scales

Region	Area (km^2)	Scale (ha)	Patch	Patch Δ	Dominant	Dominant Δ	Interior	Interior Δ
F$_1$	1,650,076	2.25	0.6148	−0.0185	0.5787	−0.0176	0.4337	−0.0112
		7.29	0.6032	−0.0191	0.5524	−0.0194	0.3707	−0.0120
		65.61	0.5895	−0.0213	0.5130	−0.0249	0.2555	−0.0158
		590.49	0.5843	−0.0226	0.4829	−0.0303	0.1594	−0.0177
		5314.41	0.5857	−0.0227	0.4640	−0.0332	0.0952	−0.0141
F$_2$	327,646	2.25	0.6307	−0.0215	0.5949	−0.0195	0.4361	−0.0102
		7.29	0.6201	−0.0222	0.5703	−0.0220	0.3678	−0.0123
		65.61	0.6100	−0.0255	0.5357	−0.0299	0.2553	−0.0181
		590.49	0.6077	−0.0275	0.5102	−0.0368	0.1423	−0.0222
		5314.41	0.6115	−0.0276	0.4936	−0.0420	0.0667	−0.0139
F$_3$	144,463	2.25	0.5862	−0.0064	0.5550	−0.0058	0.4339	−0.0037
		7.29	0.5763	−0.0065	0.5365	−0.0063	0.3844	−0.0045
		65.61	0.5668	−0.0071	0.5127	−0.0077	0.2927	−0.0062
		590.49	0.5609	−0.0075	0.4920	−0.0091	0.2053	−0.0078
		5314.41	0.5578	−0.0082	0.4639	−0.0106	0.1011	−0.0068
F$_4$	642,652	2.25	0.6165	−0.0113	0.5852	−0.0110	0.4529	−0.0083
		7.29	0.6077	−0.0115	0.5680	−0.0118	0.4001	−0.0089
		65.61	0.6008	−0.0123	0.5474	−0.0143	0.3012	−0.0121
		590.49	0.5966	−0.0128	0.5299	−0.0162	0.2080	−0.0143
		5314.41	0.5937	−0.0131	0.5088	−0.0175	0.1184	−0.0128
F$_5$	211,942	2.25	0.7639	0.0060	0.7402	0.0087	0.6027	0.0208
		7.29	0.7600	0.0061	0.7285	0.0087	0.5478	0.0213
		65.61	0.7567	0.0052	0.7152	0.0068	0.4572	0.0260
		590.49	0.7577	0.0050	0.7072	0.0052	0.3575	0.0248
		5314.41	0.7583	0.0053	0.7008	0.0067	0.2643	0.0175
S	1,891,864	2.25	0.1237	−0.0100	0.1137	−0.0086	0.0773	−0.0053
		7.29	0.1176	−0.0094	0.1081	−0.0081	0.0653	−0.0045
		65.61	0.1092	−0.0080	0.1012	−0.0070	0.0463	−0.0032
		590.49	0.1043	−0.0089	0.0955	−0.0077	0.0315	−0.0026
		5314.41	0.0979	−0.0091	0.0888	−0.0079	0.0165	−0.0016
A	2,900,949	2.25	0.1074	0.0010	0.0897	0.0014	0.0516	−0.0019
		7.29	0.0961	0.0010	0.0746	0.0012	0.0364	−0.0014
		65.61	0.0769	0.0007	0.0510	0.0007	0.0168	−0.0007
		590.49	0.0605	−0.0003	0.0336	−0.0001	0.0080	−0.0001
		5314.41	0.0472	0.0005	0.0218	0.0001	0.0033	0.0000

See Table 1 for the description of the regions. Patch, dominant, and interior identify the 1992 proportions of each class with Δ identifying change in the class between ca. 1992 and ca. 2001. Change values greater than 0 are gains, and those less than 0 are losses

scale even though the 1992 proportions of these classes, as expected, declined as spatial scale increased. Thus, forest loss in the shrubland region had a proportionately greater impact on patch and dominant forest at larger spatial scales, suggesting that forest loss is changing the spatial scale of forest in this region. The amount of forest increased slightly in the agricultural region, resulting in very small gains in all forest density classes for nearly all scales.

Discussion

Changes in forest fragmentation are the result of two interacting patterns: the extant pattern of forest and the pattern of forest change. The interaction between these two patterns determines how forest loss affects forest pattern (Wickham et al. 2007; Riitters et al. 2009). If forest loss had been concentrated in patchy forest environments, the change in proportions of dominant

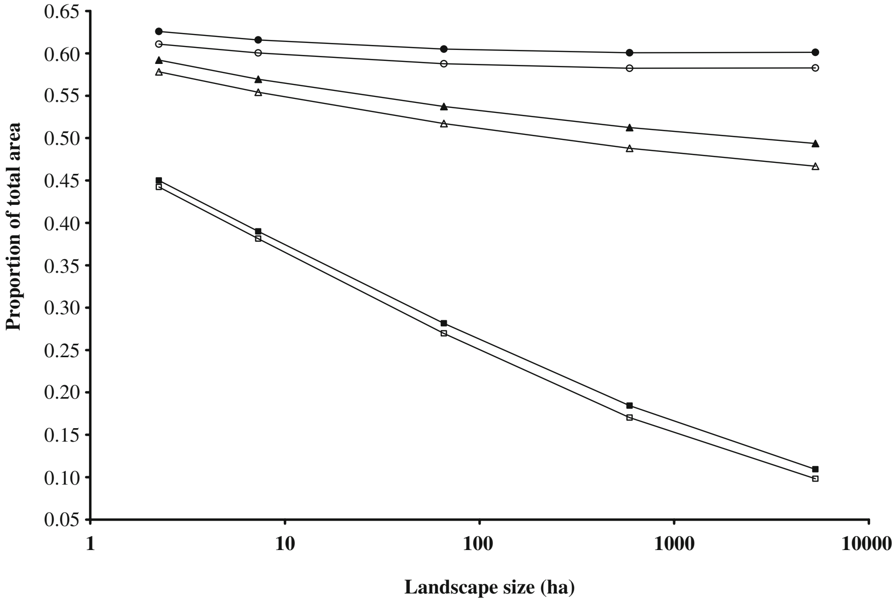

Fig. 2 Forest density at multiple scales for all forested regions (F_1–F_5). Closed symbols represent 1992 and open symbols represent 2001 for patch (●), dominant (▲), and interior (■) forest. The proportions equal the area-weighted sum for all five forested regions in Table 2. The 2001 proportions equal the 1992 proportions minus (or plus) the proportions in the change column

and interior would have been very small, and most evident at smaller spatial scales. Our results suggest that forest losses were not concentrated in patchy forest environments (Fig. 3). Forest loss produced detectable losses in all forest density classes, and the losses of dominant and interior forest increased by 50–100% as spatial scale increased to its maximum. Forest loss has increased fragmentation of the remaining continental US forests, and the increase in fragmentation is more pronounced at larger spatial scales.

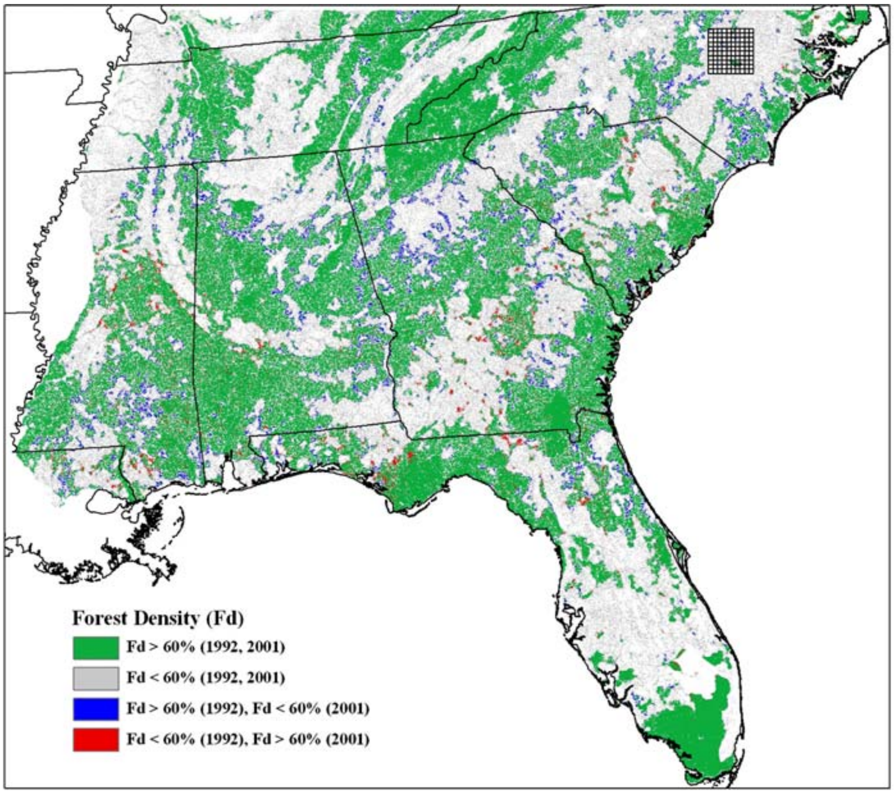

Fig. 3 Changes in dominant forest at the 5314-ha scale for the southern half of region F_1. A 10-by-10 block of 5314-ha cells is displayed in the upper right corner of the map to assist in conceptualizing the size of a 5314-ha cell. Dominant forest loss would have been zero if forest loss occurred only in the gray portions of the map

The interaction between forest extent and forest loss shows how spatial pattern is important for understanding scaling effects. There were more than 2.9×10^6 "patches" of forest loss across the five forested regions. The median size of forest loss patches was less than 1 ha, and less than 5% of them were greater than 10 ha. Our interpretation is that forest loss was a local-scale phenomenon (Sampson and Decoster 2000; Foster and Foster 1999; Foley et al. 2005) that accumulated into a broad-scale effect (Foster et al. 1998) because it was pervasive and not limited to locations where forest was not dominant. Decisions related to forest conversion are typically made at a local scale (Sampson and Decoster 2000; Foster and Foster 1999), and our results indicate that such decisions, if they continue to be made in the future without regard to the broader-scale context of an already-fragmented condition, will continue to have a proportionately greater impact on large-scale dominant forest and large-scale interior forest.

The issue of spatial scale is important because it is a fundamental characteristic of forests. Forests tend to dominate where they occur because broad-scale climatic factors favor trees over shrubs and grasses (Whittaker 1975; Daubenmire 1978; Eyre 1980). Over the approximate 10 year analysis period, dominant and interior forest losses at the largest spatial scale were 5% and 10%, respectively, of their 1992 amounts. These results and those in previous studies of fragmentation of continental US forests (Heilman et al. 2002; Riitters et al. 2002) suggest that spatially extensive forests are relatively rare, and are becoming more rare. Such changes in the spatial pattern and scale of forest will likely affect the condition of the forest itself (Mladenoff et al. 1993; Foster et al. 1998; Weathers et al. 2001; Harper et al. 2005), the ability of forests to regulate climate (Marshall et al. 2004), reduce floods (USDA (United States Department of Agriculture) 1986), mitigate nutrient pollution (Beaulac and Reckhow 1982; Frink 1991; Wickham et al. 2005), and provide interior forest habitat (Robinson et al. 1995).

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