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Comparing forest fragmentation in Eastern U.S. forests using patch-mosaic and gradient surface models

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ABSTRACT

Forest fragmentation is an ongoing threat to forest communities in the eastern United States where a prevailing pattern of dispersed, low intensity urban development continues to expand the wildland urban interface (WUI). Many large scale forest monitoring initiatives rely on pixel-based remote sensing classifications to quantify fragmentation patterns because they fit seamlessly into the patch-mosaic model (PMM) and can be analyzed using conventional landscape metrics (e.g., FRAGSTATS). The PMM has been key to advancing our understanding of patch dynamics, but some argue it may be inconsistent with ecological theory as it ignores the inherent gradient nature of environments. Studies have advocated a shift toward gradient surface models (GSM), but tools for quantifying spatial patterns in continuous gradient surfaces are limited. We introduce an approach for extracting landscape pattern information from gradient surfaces using a thresholding approach to discretize gradient surfaces into multiple discrete maps according to forest cover density. These maps can then be analyzed using conventional landscape metric tools. Metric values are plotted against density thresholds as a scalogram and interpreted to understand the dynamics of landscape spatial structure. By performing a comparative analysis of two forested ecoregions in the eastern U.S. that have undergone development pressures, we demonstrate how information on landscape structure dynamics at various forest cover densities can be extracted from gradient surfaces to provide additional information on the density scales where fragmentation is pronounced in each region. Results indicate there are ecological thresholds at certain forest cover proportions that can potentially inform management decisions.

1. Introduction

Forest fragmentation is one of the greatest threats to global biodiversity (Kupfer and Franklin, 2009) and is an ongoing threat to forest communities in the eastern United States (Riitters et al., 2012) where most land is privately owned and therefore unprotected (Smith et al., 2009). Fragmentation caused by urban development is of particular interest because it is the main driver of land use and land cover change in the eastern United States (USDA Forest Service, 2011). A prevailing pattern of dispersed, low intensity urban development continues to expand the wildland urban interface (WUI), which is where urban and suburban development intermingle with undeveloped wildland vegetation (Radeloff et al., 2005). As development penetrates the WUI, anthropogenic impacts are introduced deep into intact forest (Riitters et al., 2012; Stein et al., 2009; Theobald et al., 1997), increasing the risk of fire danger, species invasions, and biodiversity loss (Radeloff et al., 2005).

Regional, national, and international scale initiatives prioritize measurement and monitoring of forest fragmentation at broad spatial scales (Kupfer, 2006), where land cover maps derived from remote sensing images are frequently employed. Satellite or aerial images are converted into land cover information through pixel-based classification techniques in which each pixel is assigned a single land cover class. Pixel-based classifications are used extensively in landscape ecological studies because they fit seamlessly into the patch-mosaic model (PMM), where the landscape is conceptualized as a mosaic of discrete patches. The PMM is lauded for its conceptual simplicity (Forman, 1995) and the ease with which it can incorporate categorical maps produced from remote sensing classifications into landscape analysis, and many toolsets have been developed explicitly for quantifying PMM spatial patterns from categorical maps (e.g., FRAGSTATS: McGarigal et al., 2012).

The PMM has no doubt advanced our understanding of pattern-process relationships (Turner, 2005), particularly fragmentation (Uuemaa et al., 2013), but it can be inconsistent with ecological theory as it ignores the inherent gradient nature of environments and land covers (Cushman et al., 2010; McGarigal and Cushman, 2005). This

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issue is particularly pronounced at the broad spatial scales commonly adopted in forest fragmentation studies, as pixel-based classifications often underrepresent spatial heterogeneity. Gradient-based classifications have been proposed and debated in landscape ecology for decades as an alternate way of conceptualizing and representing landscape structure (Cushman et al., 2010; Lausch et al., 2015; Manning et al., 2004; McGarigal and Cushman, 2005; McIntyre and Hobbs, 1999). Gradients are able to capture and represent a greater amount of landscape heterogeneity because pixels can assume ratio values according to the proportion of land cover present in the pixel and therefore are not confined to a single land cover class. However, gradient datasets are not directly compatible with most available spatial pattern analysis tools, which require hard boundaries for metric computations, making it challenging for researchers to incorporate these datasets into their analyses.

Surface metrics have emerged as an alternative method for quantifying patterns in gradient datasets. Originally developed for microscopy and molecular physics, surface metrics were recently introduced to landscape ecologists as a means of analyzing gradient landscapes (McGarigal et al., 2009). While there is growing support and increased use of surface metrics in the ecological literature (Frazier, 2016; Moniem et al., 2016; Moniem and Holland, 2013; Scown et al., 2015), widespread adoption has been hindered by several factors. First, many surface metrics are constructed to evaluate ideal bearing properties of mechanical surfaces, which are defined as being "smooth with relatively deep scratches to hold and distribute lubricant" (Stewart 1990, 1). This concept does not translate flawlessly into ecology, and therefore interpretation of surface metrics is not always intuitive from a landscape perspective. Second, many surface metrics suffer from correlation and redundancy issues similar to those found with conventional landscape metrics and graph approaches. Lastly, widespread adoption of surface metrics has been hindered by limited access to software, although the upcoming version of FRAGSTATS is expected to contain some of these metrics.

With these limitations, researchers are tasked with finding alternative approaches to incorporate continuous, gradient surface models into landscape investigations and bridge the gaps between the patch-mosaic and the gradient surface paradigms. In this study, we introduce an approach for extracting increased landscape pattern information from gradient surfaces using a common toolset (i.e., FRAGSTATS). Specifically, we demonstrate how a thresholding approach can be used to discretize gradient surfaces into multiple discrete maps that can then be analyzed as patch-mosaic models. We create scalograms of these multiple metric values showing metric change across a continuum of forest density scales and compare them to single-value metrics computed for patch-mosaic landscapes to illustrate how the additional information can be analyzed in an ecological context. We frame our study around a comparison of forest fragmentation in two ecoregions in the eastern U.S.

2. Study area and data

With a lack of comparative regional assessments of forest fragmentation noted in the literature (Riitters et al., 2012), we elected to compare two ecoregions that differ in their level of urban development: (1) the Southeastern USA Plains (SEP) nested within the Eastern Temperate Forests ecoregion, and (2) the Atlantic Highlands (AH) nested within the Northern Forests ecoregion (Omernik, 1987). The SEP includes several major development corridors (I-85, I-95, etc.) and comprises major cities such as Baltimore, M.D., Charlotte, N.C., and Atlanta, G.A. It also includes several rapidly developing Midwest cities that have experienced sprawling urban growth in recent decades, such as Nashville, TN, as well as urban fringes of developing cities in Texas including Dallas/Fort Worth, Houston, Austin, and San Antonio (Fig. 1). The SEP region contains over 250,000 km^2 of total WUI (Radeloff et al., 2005), amounting to about 25% of the region. In comparison, the AH region is located in the Northeast U.S. and comprises portions of Pennsylvania, New York, and New England. The AH does not contain any major cities over 500,000 people or large development corridors. However, proportionally the region contains approximately the same amount of WUI with 40,000 km^2, also about 25% (Radeloff et al., 2005). The similarities in the amount of WUI and differences in the likely proximate causes of fragmentation between the two regions provides an ideal case for examining forest cover patterns.

The National Land Cover Database (NLCD) developed by the Multi-Resolution Land Characteristics Consortium (MRLC) is the primary source of land cover data in the United States (Wickham et al., 2010). The MRLC produces several products including a seamless, 16-class thematic, land cover map commonly referred to as the 'NLCD' and a seamless, gradient surface representing percent tree canopy cover (TCC) across the continuous United States. Both datasets are based on Landsat images over the same time period and have the same nominal spatial resolution (30 m) (Xian et al. 2011; Coulston et al., 2012, 2013; Tipton et al., 2012; Homer et al., 2015), thereby offering a unique opportunity to examine forest cover from both a patch-based and gradient perspective. We downloaded the 2011 NLCD and TCC rasters for the conterminous U.S. from the MRLC (http://www.mrlc.gov/) and thematically aggregated the NLCD into eight classes (Water, Developed, Barren, Forest, Shrubland, Herbaceous, Planted/Cultivated, Wetlands). This aggregation produced a single forest class, which included 'Deciduous Forest', 'Evergreen Forest', 'Mixed Forest', and 'Woody Wetlands' following Riitters et al. (2012), that could be compared to the TCC. The TCC dataset consists of pixels with values ranging from 0 to 100 according to the percent tree canopy cover as a continuous variable, providing a complementary forest cover dataset in gradient surface format to analyze and compare to the NLCD forest class.

We next generated a fishnet sampling grid covering each ecoregion, where each grid square was approximately 20 × 20 km to standardize the extent and shape of sample area units. While some landscape metrics are impacted by the size and shape of the landscape, the 20 × 20 km extent with 30 m resolution provided a sufficient grain-to-extent ratio to minimize boundary effects. Any grid squares intersecting the boundary of the ecoregion were discarded to ensure only sample areas fully contained in the ecoregion were utilized. To reduce sampling bias in heavily urbanized areas, we removed grid squares comprising all or part of an urbanized area > 500,000 people (as determined by the 2014 cartographic boundary file from the U.S. Census). All remaining grid squares were considered eligible candidates for sampling. We then randomly selected 125 squares from each ecoregion for analysis (Fig. 1). This number is sufficient to develop statistical summaries and comparisons across the two regions. For each of the 125 selected grid squares, we clipped the aggregated NLCD and TCC datasets (Fig. 2) and processed the data according to the methods described below.

3. Methods

Methods have been developed previously within remote sensing to discretize gradient data produced by sub-pixel classification techniques (e.g., spectral unmixing) for spatial analysis of continuous datasets (Arnot et al., 2004; Frazier and Wang, 2011; Walsh et al., 2008). Essentially, these methods 'slice' a gradient surface into a set of multiple discrete maps that can then be analyzed as binary land cover maps. These 'slicing' approaches fall into two categories: (1) the range approach, where different ranges of the continuous value are analyzed as discrete maps, and (2) the threshold approach where a continuum of thresholds is set and pixels are discretized at each step based on whether their value falls above or below the given threshold. In both scenarios, multiple, categorical maps are created from a single gradient surface (Fig. 3). By applying these slicing methods to segment gradient surfaces in a landscape ecological context, it is possible to produce discrete maps that represent different forest cover densities yet still adhere to the patch-mosaic paradigm, thus allowing landscape