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Forest fragmentation in Massachusetts, USA: a town-level assessment using Morphological spatial pattern analysis and affinity propagation

J. Rogan[a]*, T.M. Wright[a], J. Cardille[b,c], H. Pearsall[d], Y. Ogneva-Himmelberger[e], R. Riemann[f], K. Riitters[g] and K. Partington[b]

[a]*Clark Graduate School of Geography, Clark University, Worcester, 01610, USA;* [b]*Département de Géographie, Université de Montréal, Montréal, USA;* [c]*Department of Natural Resource Sciences and McGill School of Environment, McGill University, Sainte-Anne-de-Bellevue, Canada;* [d]*Geography and Urban Studies Department, Temple University, Philadelphia, 19122, USA;* [e]*Department of International Development, Community, and Environment, Clark University, Worcester 01610, USA;* [f]*U.S. Forest Service, Northern Research Station, Troy, 12180, USA;* [g]*U.S. Forest Service, Research Triangle Park, NC, USA*

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Forest fragmentation has been studied extensively with respect to biodiversity loss, disruption of ecosystem services, and edge effects although the relationship between forest fragmentation and human activities is still not well understood. We classified the pattern of forests in Massachusetts using fragmentation indicators to address these objectives: 1) characterize the spatial pattern of forest fragmentation in Massachusetts towns using Morphological Spatial Pattern Analysis (MSPA); and (2) identify regional trends using archetypal towns in relation to town history, geography and socioeconomic characteristics. Six fragmentation indicators were calculated using MSPA for each town to represent patterns and processes of fragmentation. We then used these indicators and the proportion of forested land to group towns across Massachusetts with similar patterns of fragmentation. Six representative towns typify different types of forest fragmentation, and illustrate the commonalities and differences between different fragmentation types. The objective selection of representative towns suggests that they might be used as the target of future studies, both in retrospective studies that seek to explain current patterns and in analyses that predict future fragmentation trends.

Keywords: forest fragmentation; morphological spatial pattern analysis; affinity propagation; Massachusetts

Introduction

Forest ecosystems provide vital ecosystem services including wildlife habitat, sequestered carbon, stable and productive soils, esthetic and recreational value, and water cycling (Kittredge et al. 2008). In urban/suburban settings, tree cover reduces heat-island effects, enhances air quality, and helps to regulate storm water drainage. Forest fragmentation occurs during the process of land conversion when contiguous forest becomes separated by other land-use types (Vogelmann 1995) and has been linked to biodiversity loss (Fahrig 2003; Kupfer and Franklin 2009), increased vulnerability to invasive species (Haskell 2000), disruption of ecosystem services, such as nutrient cycling and hydrology (DeNormandie 2009), and increased edge effects (Collinge 1996).

*Corresponding author. Email: jrogan@clarku.edu

Towns and communities across the United States face competing demands to both conservation and economic growth, through new development. The consequence is that many towns need to make informed choices between conserving valuable forest habitat and maintaining economic growth. Previous forest fragmentation research has focused on the creation and application of metrics to quantify or characterize patterns of forest composition and configuration (Wulder et al. 2008; Soverel et al. 2010; Estreguil and Mouton 2009) and exploring the effects and consequences of fragmentation from an ecological, biological, or theoretical framework (Collinge 1996; Fahrig 2003; Ries and Fletcher et al. 2004; Miller and Rogan 2007). Understanding both the patterns of forest fragmentation and the processes that shape those patterns is important in order to minimize ecological degradation and protect remaining forest patches (Zhang, Chen, and Lu 2015).

Fragmentation in the temperate forests of New England is caused by cumulative effects of multiple pressures. Residential and commercial developments in New England result in forest loss, and in some locations it has been projected that by 2030 up to 63% of private forestland may be converted for development (DeNormandie 2009). Studying the interactions between humans/policy and forests is especially important in Massachusetts because it is the most densely populated state in New England and almost 60% of the landscape is densely forested. It is challenging to obtain a regional or statewide view of forest fragmentation dynamics in Massachusetts because the majority of forest in the state is privately owned and the strong "home-rule" legacy has meant that most land-use decisions are made at the town level by town councils and/or individual landowners (Kittredge et al. 2008). Thus, the characteristics of each town could be influencing its development and forest fragmentation patterns (McCauley 2009). Given the rapidly changing and heterogeneous landscape of Massachusetts there is a need for consistent, comparable fragmentation information that can be used for regional forest monitoring and assessment (Riemann et al. 2002).

Towns present an informative analysis unit in this research. For instance, Vogelmann (1995) reported that in southern New England (i.e., Southern New Hampshire and Northern Massachusetts) human population density and amount of forested land at the town level have a strong statistical relationship with forest fragmentation, as represented by a forest continuity index [natural log of forest area–perimeter ratio]. Positive correlations were reported between 1990 population density and forest continuity ($r^2 = 0.81$). Results confirm that town level information can be used effectively in fragmentation analysis, but that the complex relationships between human land-use practices and forest fragmentation require further examination. Lister et al. (2005) developed methods to quantify fragmentation for regional assessments in the northeast United States using a combination of land-cover data and roads from the US Census Bureau TIGER/Line file. Metrics were calculated based on the fragmentation map and results highlight the importance of town-level aggregated estimates. Riemann et al. (2008), studying the potential impact of fragmentation on ecosystem services, emphasized the importance of fragmentation assessments at township scales and revealed that increases in fragmentation and urbanization within watersheds, in addition to forest loss alone, correlated with declines in water quality.

Despite the growing body of literature on forest fragmentation in New England, few studies have characterized different types of fragmentation at the town level, explored the relationship between town level variables and fragmentation in a spatial context, or sought to identify towns with similar patterns of fragmentation in order to understand trends and guide more place-specific conservation efforts (MacLean and Congalton 2013). The purpose of this research is to understand how the patterns of forest fragmentation vary by town in Massachusetts, and how those patterns are related to potential driver variables such as socioeconomic factors, housing characteristics, residential zoning, and land ownership. The two research objectives were to: (1) characterize the spatial pattern of forest fragmentation in Massachusetts towns using Morphological Spatial Pattern Analysis (MSPA) and (2) identify archetypal towns and regional trends of fragmentation in relation to town history and socioeconomic information. In a region where development versus land conservation choices are made within individual towns, this study provides a statewide view of the variety of forest fragmentation patterns that have emerged from many thousands of local land-use decisions, and an initial look at some of the potential town-level factors that may be contributing to these patterns.

Study area

The study area for the research is the state of Massachusetts (USA), which consists of 351 towns, covering an area of 20,305 km^2 (Figure 1). The population in the year 2000 was 6.5 million, with a population density of 313 people per km^2, 10 times higher than the national average. Massachusetts averages 112 cm of precipitation annually and experiences warm summers (average temperature 27°C) and cold winters (average temperature −6°C). Elevation ranges from sea level at the Atlantic coast to 1064 m in the western portion of the study area (mean elevation is 164 m). The topography of Massachusetts varies from low elevation and sandy soils in the eastern portion of the state, and higher elevations and resistant metamorphic rock in the western portion. There are 13 EPA-designated ecoregions in Massachusetts and the dominant vegetation type is secondary

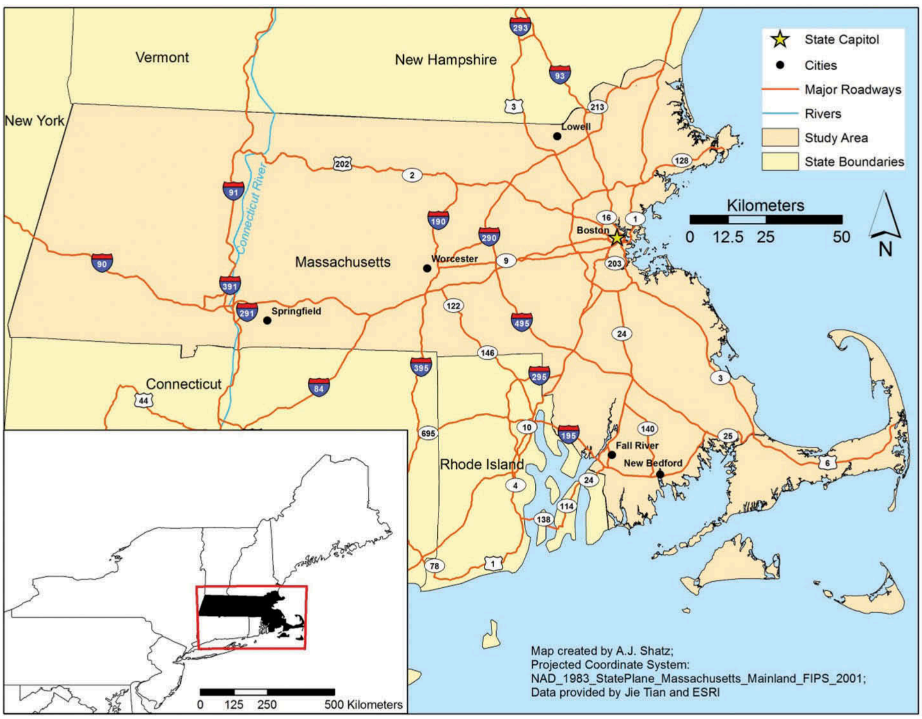

Figure 1. Study area of Massachusetts, USA.

growth mixed temperate forest. The landscape of Massachusetts has a heterogeneous composition of land-uses/cover types. The eastern portion of the state is largely composed of urban and suburban types, while the western portion is more rural. Despite being a highly developed and densely populated state, forests cover approximately 60% of the land area in Massachusetts.

Data

A 30 m, 16-category land-cover map based on June 2000 Landsat-5 Thematic Mapper imagery was aggregated into a forest/non-forest map (Rogan et al. 2010), and fragmentation indicators were calculated using MSPA (Soille and Vogt 2009). A relatively new approach for characterizing fragmentation, MSPA has already been effectively applied in town-level assessments (Vogt, Riitters, Estreguil, et al. 2007). MSPA is designed to identify corridors and connectors between core forest patches, reflect spatial patterns that are directly comparable over time and space, and distinguish between interior and exterior forest edges (Soille and Vogt 2009; Vogt, Riitters, Iwanowski, et al. 2007). MSPA classifies a forest pixel into one of seven mutually exclusive classes to depict the amount of fragmentation in a given landscape and the degree of connectivity between forest pixels based on the edge-width and connectivity (Vogt, Riitters, Estreguil, et al. 2007). The seven output MSPA classes are: core, perforated, islet, bridge, edge, branch, and loop. MSPA has been used to identify locations of landscape connectivity for green infrastructure assessments (Wickham et al. 2010) and to map functional and structural connectivity between forest patches and provide insight into pattern-process linkages.

Socioeconomic and population variables employed to describe and characterize the towns were gathered from the 2000 Census. The variables representing medium income and population change between 1990 and 2000 were chosen due to their suspected influence on land change activities in the region (Cunningham et al. 2015). Zoning information, represented by the proportion of high, medium, and low density residential land-use zoning, was calculated for each town based on data used in Mass Audubon's Losing Ground report (DeNormandie 2009). Land ownership variables were calculated per town based on the Protected Area Database (Conservation Biology Institute 2010). The percent of forested land within each town was calculated using the existing land-cover map (Rogan et al. 2010).

Methods

Quantifying fragmentation – morphological spatial pattern analysis

MSPA was employed with forest as the foreground (feature of interest) and non-forest as the background, fragmenting feature. Water bodies were excluded from the analysis because they are not typically defined as a fragmenting feature. MSPA parameters specified an edge width of 30 m and eight-neighbor connectivity (Ostapowicz et al. 2008). MSPA was conducted separately in each of the 351 towns, but only 346 towns that contained at least some core forest (i.e., ≥10%) were included in the analysis.

Fragmentation indicators

Six fragmentation indicators were calculated for each town based on the MSPA output (Table 1). The indicators were

Table 1. Fragmentation attribute, corresponding fragmentation indicator, formula for calculation, and characteristics in the data set.

Ecological proxy	Fragmentation indicator	Formulation	Min, max, mean	Moran's I	z-Score
Availability of interior forest habitat	Proportion core	$\frac{\text{Core forest area}}{\text{Total forest area}}$	0.04, 0.87, 0.52	0.60	57.5
Edge effects on forest interior	Proportion perforated	$\frac{\text{Perforated forest area}}{\text{Total forest area}}$	0, 0.16, 0.03	0.50	47.8
Isolated non-core habitat, or potential stepping stone	Proportion islet	$\frac{\text{Islet forest area}}{\text{Total forest area}}$	0, 0.60, 0.06	0.48	46.5
Structural connectivity of interior forest habitat	Proportion bridge	$\frac{\text{Bridge area}}{\text{Total forest area}}$	0, 0.25, 0.04	0.27	26.4
Edge habitat and edge effects on interior forest habitat	Proportion edges	$\frac{\text{Edge} + \text{perforated} + \text{branch} + \text{loop} + \text{bridge}}{\text{Total forest area}}$	0.12, 0.60, 0.35	0.53	50.5
Proportion of edge versus interior forest habitat	Edge/core ratio	$\frac{\text{Edge} + \text{perforated} + \text{branch} + \text{loop} + \text{bridge}}{\text{Core forest area}}$	0.14, 11.25, 0.91	0.34	35.7

- Proportion core indicates the presence and abundance of core habitat per town. Core forest is one of the most common indicators in fragmentation research because core habitat is essential for forest species and provides a simple representation of forest compactness. Higher values in proportion core indicate lower levels of fragmentation (Estreguil and Mouton 2009).
- Proportion perforated expresses the degree to which edge effects are introduced into the core forest interior, representing non-forest patches within primarily compact forest patches. Higher values in proportion perforated indicate high levels of fragmentation within core forest; however, very low values could be an indication that there is not enough core forest to permit perforation.
- Proportion bridge represents the structural connectivity between core forest patches in a town. Higher values in proportion bridge indicate greater connectivity between forest patches but may not indicate lower levels of fragmentation (Vogt, Riitters, Iwanowski, et al. 2007).
- Proportion islet indicates the presence of isolated non-core forest patches in a town. Forest islets are small, impoverished forest remnants which cannot support ecosystem services (Collinge 1996). Higher values in proportion islet indicate more fragmentation within a town. Alternatively, islets could also be viewed as a potential proxy for habitat "stepping stones" between core forest patches (Estreguil and Mouton 2009).
- Proportion edge represents the abundance of edge habitat per town. The proportion edge is calculated using the sum of all MSPA classes except core and islet. High values in proportion edge indicate higher levels of forest fragmentation (Murcia 1995).
- Edge/core ratio represents the relative abundance of core versus edge habitat. Higher values in the edge/core ratio indicate more fragmentation and values greater than 1 indicated the town contains more edge habitat than interior habitat (Soverel et al. 2010).

The first five fragmentation indicators were normalized by total forest area per town while Edge/core ratio was normalized by core forest area – to ensure that the size of the town or the amount of forest did not influence the results. MSPA was used to characterize all forest pixels for the entire state of MA and these indicators were summarized by town to avoid any edge effects from calculating fragmentation metrics in each individual town. Each fragmentation indicator was mapped per town, and global Moran's I was performed to test for spatial autocorrelation between towns. The Moran's I tests were run using an inverse distance weighting based on Euclidean distance.

Affinity propagation analysis

The Affinity propagation (AP) algorithm was applied to group the 346 towns according to their characteristics (Table 2). The AP algorithm uses similarities between all pairs of items to identify clusters and selects an exemplar to best represent each cluster. AP has been used previously to identify clusters of similar landscapes based on landscape- and class-level metrics (Cardille and Lambois 2010; Cardille et al. 2012). For this study, the differences between the characteristics of towns were estimated using the six fragmentation indicators (Table 1) and percent forest per town. The AP algorithm grouped the towns by characteristic, simultaneously selecting a "representative town" to illustrate each cluster. We tasked the algorithm with identifying six clusters, which allowed us to see

Table 2. Affinity propagation results derived from MSPA inputs.

Clusters and exemplars	*N*	Core	Islet	Perforated	Bridge	Forest	Edge/core	Edge
Interface towns	84	0.46	0.06	0.01	0.05	0.40	0.89	0.41
Frontier towns	65	0.58	0.02	0.02	0.04	0.53	0.59	0.34
Rural towns	59	0.70	0.01	0.05	0.02	0.64	0.36	0.25
Low density towns	48	0.75	0.00	0.10	0.01	0.79	0.31	0.23
Urban forests	48	0.25	0.22	0.00	0.05	0.17	2.23	0.45
Affluent suburbs	42	0.34	0.06	0.01	0.13	0.46	1.36	0.45
Statewide averages	376	0.52	0.06	0.03	0.04	0.49	0.91	0.35

the geographic variability in characteristics across the state and assess differences among types of towns.

Results

There are substantial regional differences in forest fragmentation between the eastern and western portions of Massachusetts (Figure 2). High values of proportion core forest are concentrated primarily in the western portion of the state and in the parts of Bristol County, while low values are located around Boston (Figure 2a). Proportion perforated portrays a similar pattern to proportion core with the largest values located west of the Connecticut River, and in the north-central region of the state, with lowest amounts in the eastern portions of the state (Figure 2b). High proportion islet values are located near Boston and towns north, as well as around the cities of Worcester and Springfield (Figure 2c). Proportion bridge has the highest presence in the southeastern portion of the state as well as Essex County, and lowest presence in the western portion of the state (Figure 2d). Proportion edge has highest presence around Boston and near the dense urban centers of Worcester and Springfield with high values in the east and lower values in the west of the state (Figure 2e). Edge to core ratio shows a similar pattern to proportion edge with high values around Boston and much lower values in the west, except for the area around Springfield (Figure 2f). There was significant spatial autocorrelation in the fragmentation indicators, indicated by Moran's I values ranging from 0.27 to 0.60, and associated z-scores (ranging from 26.41 to 57.53) (Table 1).

The six clusters and associated exemplars produced from the AP analysis are presented in Figure 3. "Interface towns" (n = 84, 24%) have below average proportion core, percent forest and proportion perforated, average proportion bridge, proportion islet and edge–core ratio, and below average proportion edge. Interface towns are primarily located in Worcester, Middlesex, Norfolk, and Plymouth Counties, in the interface zone between peri-urban and suburban development (DeNormandie 2009). They have proportionally less low-density zoning (greater than 2 ac minimum lot size) than the statewide average, higher housing density and median income, and average population change between 1990 and 2000 (Table 3).

Interface towns are typified by the Town of Auburn (Figure 4). Auburn is located in Central Massachusetts, in Worcester County, and was incorporated as a town in 1778. The town developed economically through industry and agriculture in the 1800s. As industries in the nearby town of Worcester grew and streetcar infrastructure improved, Auburn served increasingly as a bedroom community for industrial workers. This trend continued over the following decades, and most of the agricultural land was converted to residential

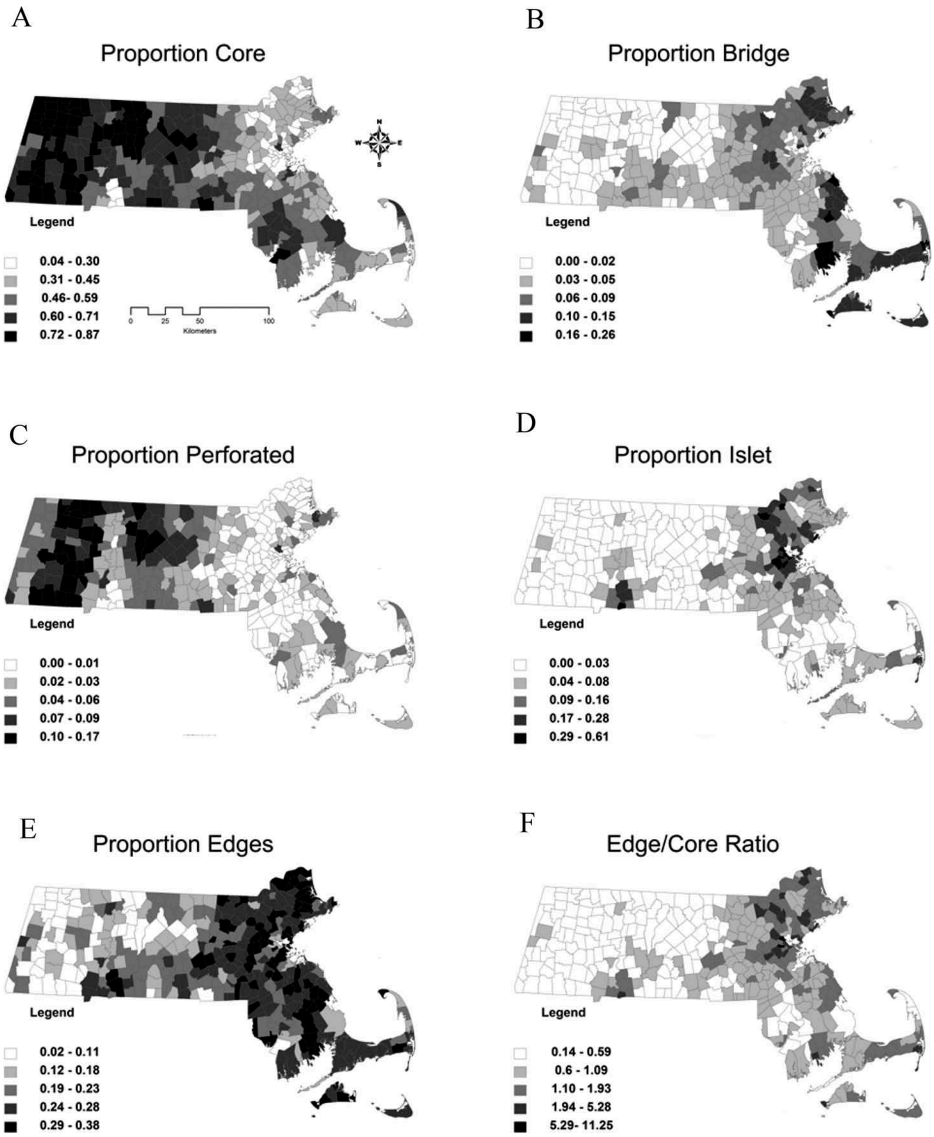

Figure 2. Map of fragmentation indicators in Massachusetts.

development after World War II. Over the past three decades, Auburn has experienced some industrial and business development, although the town government strives to preserve the "small town flavor" (Town of Auburn).

"Frontier towns" (n = 65, 19%) are concentrated in the central portion of the state, primarily in Worcester, Bristol, and Hampshire Counties. Frontier towns have above-average proportion core and percent forest, average proportion edges, and below average proportion perforated, proportion islet, proportion bridge, and edge–core ratio. They are typically seen adjacent to Interface towns; however, they tend to be further from urban centers. These towns have, on average, more land allocated to lower density housing than Interface towns and have witnessed higher percent population increase (Table 3).

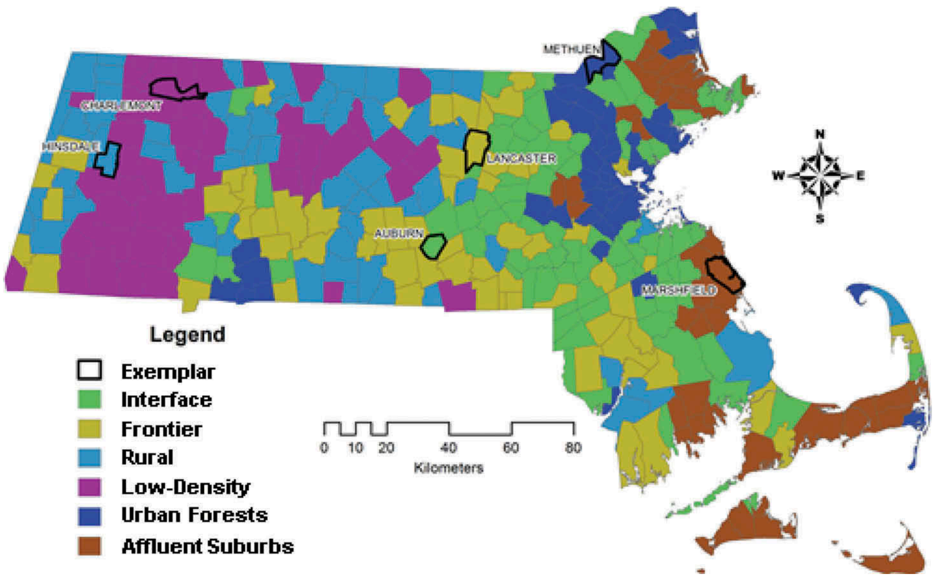

Figure 3. Distribution of six types of Massachusetts towns, according to forest fragmentation indicators. An objectively determined representative of each type is shown in bold outline and discussed in the text.

Frontier towns are typified by the Town of Lancaster. Lancaster, like Auburn, is located in Worcester County, but is the oldest town in the county with an incorporation date of 1653. Since incorporation, Lancaster has been a "dry town" and has only one restaurant. Lancaster continues to have a few working farms, but is primarily a bedroom community for nearby urban areas, including Clinton, Leominster, and Worcester.

"Rural townships" (n = 59, 17% of total) are primarily located in the western and north-central portions of the state, in Worcester, Franklin, and Berkshire Counties (Figure 3). They have above-average proportion core, percent forested and proportion perforated, and below average proportion bridge, proportions islet, proportion edge, and edge–core ratio. Of all towns in Massachusetts, rural townships have the lowest median income and below-average population change between 1990 and 2000; a majority of the towns are zoned for greater than 2 ac plots (Table 3).

Rural townships are typified by the Town of Hinsdale. Hinsdale was incorporated in 1804 in the foothills of the Berkshire Mountains in western Massachusetts as a farming community. Despite its agrarian beginnings, Hinsdale also experienced some industrial development in the 1800s; however, most industries declined by the mid-1900s. Presently, the town serves primarily as bedroom community of neighboring city, Pittsfield, which is approximately 10 mi from Hinsdale, as well as a destination for tourists interested in outdoor recreational activities. The Appalachian Trail runs through Hinsdale, and the town contains part of the 14,500 ac Hinsdale Flats Watershed Resource Area.

"Low-density country towns" (n = 48, 14% of total) have the highest proportion core, percent forest and proportion perforated, and the lowest proportion bridge, proportion islet, proportion edge, and edge–core ratio. Towns in Cluster 4 are primarily located in the western portion of the state in Berkshire, Hampden, Hampshire, and Franklin County, with some towns in Worcester County (Figure 3). These towns have the lowest housing

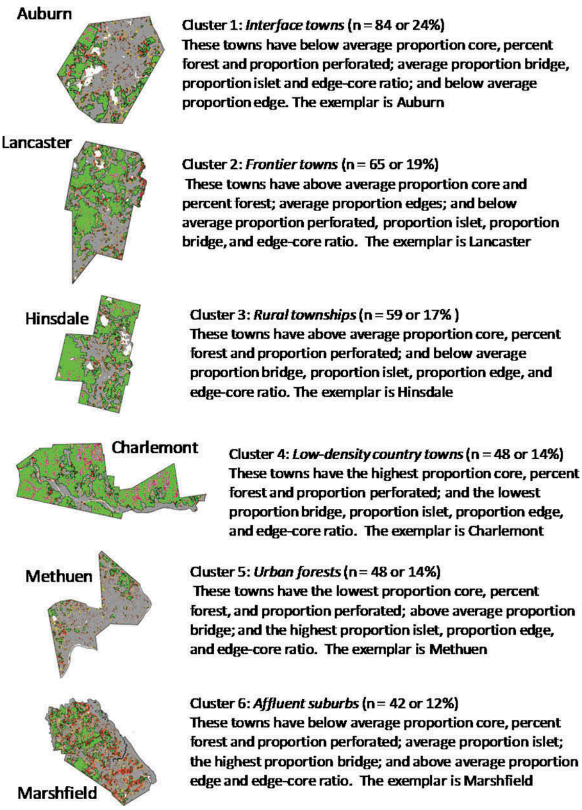

Figure 4. Six clusters derived from Affinity Propagation analysis based on the fragmentation indicators and percent forest (core forest: green; islet: brown; perforated: purple; edge: black; loop: yellow; bridge: red; branch: orange; non-forest: gray; water: blue). For full color versions of the figures in this paper, please see the online version.

density, the greatest proportion of low-density residential zoning, and the highest proportion of government-owned land.

Low-density country towns are typified by the Town of Charlemont. Charlemont is located in Franklin County in northwestern Massachusetts. Although the town's economic development was delayed by battles through the 1700s, the economy experienced similar agricultural and industrial transitions as neighboring towns through the 1800s and 1900s, including the decline of most industries by the mid-1900s. Presently, the town serves as a recreational destination, particularly with the Mohawk Trail, a historical Indian route connecting the Hudson River Valley and the Connecticut River Valley, passing through the town.

"Urban forests" (n = 48, 14% of total) have the lowest proportion core, percent forest, and proportion perforated, above-average proportion bridge, and the highest proportion islet, proportion edge, and edge–core ratio. They are concentrated around urban centers, such as Boston and Springfield (Figure 3). Urban forest towns have the highest proportion of high-density/mixed-use zoning and housing density, and the lowest median number of rooms and population change.

Urban forests are typified by the Town of Methuen. Methuen is located in the Merrimack Valley and has an industrial history that is captured by the town's legacy and architecture. Methuen also has an interesting history of "home rule." Methuen was established as a town

Table 3. Mean exemplar values of socioeconomic, housing, and governance indicators.

	ZoningR1	Zoning R2	Zoning R3	Housing density	Median income	Proportion private	Proportion govt.	%Pop change 1990–2000
Auburn (interface)	0.00	0.25	0.32	130.5	60,244	0.85	0.12	5.67
Lancaster (frontier)	0.12	0.32	0.05	45.4	54,293	0.84	0.10	8.93
Hinsdale (rural)	0.53	0.00	0.03	32.1	47,891	0.75	0.20	4.96
Charlemont (Low-density country)	0.98	0.00	0.00	7.7	49,667	0.66	0.25	8.21
Methuen (urban forests)	0.00	0.00	0.63	335.0	58,489	0.91	0.08	3.05
Marshfield (affluent suburbs)	0.02	0.41	0.07	68.7	61,690	0.80	0.14	12.98
Statewide averages	0.00	0.07	0.09	67.8	54,291	0.81	0.13	6.00

in 1725, then a city in 1917. However, the city reverted to town status in 1921, due to concerns about the charter from the Supreme Judicial Court. The town successfully obtained a city charter in 1973 (City of Methuen). Methuen has diverse land-use patterns that include urban, suburban, industrial, and agricultural uses.

Compared to other Massachusetts towns, "Affluent Suburbs" (n = 42, 12% of total) have below average proportion core, percent forest and proportion perforated, average proportion islet, the highest proportion bridge, and above-average proportion edge and edge–core ratio. Affluent Suburbs are located in the eastern portion of the state, primarily in Essex, Barnstable, and Plymouth Counties (Figure 3). These towns have the highest median number of rooms, median income and population change between 1990 and 2000.

Affluent suburbs are typified by the Town of Marshfield. Marshfield is located 30 mi from Boston on the coast of Massachusetts and was incorporated in 1640. The town's history includes pre-revolutionary war events and serves as an important historical site. Owing to its location on the coast of the Atlantic Ocean, the town draws many vacationers and tourists during summer months.

Discussion and conclusion

The combination of methods presented in this paper (i.e., MSPA, spatial dependence, and AP) provide a comprehensive view of forest spatial structure and distribution in Massachusetts by characterizing the patterns, quantifying the different types of fragmentation, and partitioning towns into clusters that meaningfully represent the current status of fragmentation across the state. The results of this study show that there is substantial variation in the patterns and types of forest fragmentation among towns in Massachusetts. In the western portion of the state, towns are comprised of a primarily forested matrix intermixed with non-forest patches. Western towns tend to have high-proportion core forest and perforation, and very low-proportion islet and edge core ratio. Eastern towns are very different from western towns because most of the remaining forests exist in patches within a primarily non-forested background. Eastern towns have high proportion islet and proportion edge, and low proportion perforated. This pattern is characteristic of towns near urban centers and is primarily found in the east of the state, near Boston, and near Springfield.

AP analysis shows that the six clusters exhibit spatial autocorrelation, confirming the regional trends of fragmentation in the state. Each of the six clusters represents a specific amount and pattern of forest fragmentation that is prevalent throughout the state, representing low (rural and low-density towns), medium (interface and frontier towns), and high (urban forest and affluent towns) levels of fragmentation. The classification of clusters is a useful lens for understanding regional patterns of fragmentation, and the results could be applied to inform statewide conservation policies.

MSPA was used to characterize the patterns of Massachusetts forests; however, the same methodology could be applied to explore differences in fragmentation between counties, watershed, or even different land owners (i.e., public vs. private) when there is an interest in how the characteristics of these entities or the policies designed by or for them are influencing fragmentation patterns. Being able to better model fragmentation indicators could prove useful for guiding forest conservation policy. AP could also be used to guide conservation effort by identifying particular patterns of fragmentation in specific towns and using that information to direct planning and development. AP identifies exemplars for each cluster, which could be used as case studies for more in-depth qualitative and quantitative analysis to further understand the relationship between the towns and patterns of fragmentation. The methods put forward in this study provide a useful framework for assessing fragmentation in landscapes that are heavily modified by human activities and characterizing them by potential town-level drivers. Towns remain the primary decision-makers in many areas in New England. Future work should build upon this town-level assessment to better understand the complexities between anthropogenic activity and forest fragmentation, and what that means in the context of conservation.

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References

Cardille, J., and M. Lambois. 2010. "From the Redwood Forest to the Gulf Stream Waters: Human Signature Nearly Ubiquitous in Representative US Landscapes." *Frontiers in Ecology and the Environment* 8 (3): 130–134. doi:10.1890/080132.

Cardille, J., J. White, M. A. Wulder, and T. Holland. 2012. "Representative Landscapes in the Forested Area of Canada." *Environmental Management* 49 (1): 163–173. doi:10.1007/s00267-011-9785-2.

Collinge, S. 1996. "Ecological Consequences of Habitat Fragmentation: Implications for Landscape Architecture and Planning." *Landscape and Urban Planning* 36: 59–77. doi:10.1016/S0169-2046(96)00341-6.

Conservation Biology Institute. 2010. *Protected Areas Database of the US, PAD-US (CBI Edition).* http://consbio.org/products/projects/pad-us-cbi-edition

Cunningham, S., J. Rogan, D. Martin, V. DeLauer, S. McCauley, and A. J. Shatz. 2015. "Mapping Land Development through Periods of Economic Bubble and Bust in Massachusetts Using Landsat Time Series Data." *GIScience & Remote Sensing* 52 (4): 397–415. doi:10.1080/15481603.2015.1045277.

DeNormandie, J. 2009. *Losing Ground: Beyond the Footprint: Patterns of Development and Their Impact on the Nature of Massachusetts*, 1–32. 4th ed. Lincoln: Massachusetts Audobon Society.

Estreguil, C., and C. Mouton. 2009. *Eur-Scientific and Technical Research Series-Issn. Measuring and Reporting on Forest Landscape Pattern, Fragmentation and Connectivity in Europe, Methods and Indicators: 1018-5593*. Office for Official Publications of the European Communities, EUR23841EN. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC51802/eur23841en_estreguil%20and%20mouton%202009.pdf

Fahrig, L. 2003. "Effects of Habitat Fragmentation on Biodiversity." *Annual Review of Ecology, Evolution, and Systematics* 34: 487–515. doi:10.1146/annurev.ecolsys.34.011802.132419.

Haskell, D. G. 2000. "Effects of Forest Roads on Macroinvertebrate Soil Fauna of the Southern Appalachian Mountains." *Conservation Biology* 14: 57–63.

Kittredge, D. B., and A. W. D'Amato, et al. 2008. "Estimating Ownerships and Parcels of Nonindustrial Private Forestland in Massachusetts." *Northern Journal of Applied Forestry* 25 (2): 93–98.

Kupfer, J., and S. Franklin. 2009. "Linking Spatial Pattern and Ecological Responses in Human-Modified Landscapes: The Effects of Deforestation and Forest Fragmentation on Biodiversity." *Geography Compass* 3 (4): 1331–1355. doi:10.1111/geco.2009.3.issue-4.

Lister, A., R. Riemann, T. Lister, and W. McWilliams. 2005. "Northeastern Regional Forest Fragmentation Assessment: Rationale, Methods, and Comparisons With Other Studies." In *Proceedings of the Fifth Annual Forest Inventory and Analysis Symposium*, 222. Washington, DC: U.S. Department of Agriculture Forest Service. Gen. Tech. Rep. WO-69. New Orleans, LA, November 18–20, 2003.

MacLean and Congalton. 2013. " Polyfrag: A Vector-Based Program for Computing Landscape Metrics." *Journal of GIScience and Remote Sensing* 50: 591–603.
McCauley, S. 2009. *A Complex Human-Environment System Approach for Land Change Analysis: The Case of Land-Use Change in Eastern Massachusetts, USA. Clark University, A Complex Human-Environment System Approach for Land Change Analysis*. PhD, 163. Worcester, MA: Clark University.
Miller, J., and J. Rogan. 2007. "Using GIS and Remote Sensing for Ecological Mapping and Monitoring." In *Integration of GIS and Remote Sensing*, edited by V. Mesev, 233–268. Hoboken, NJ: Wiley & Sons.
Murcia, C. 1995. "Edge Effects in Fragmented Forests: Implications for Conservation." *Trends in Ecology & Evolution* 10 (2): 58–62. doi:10.1016/S0169-5347(00)88977-6.
Ostapowicz, K., P. Vogt, K. H. Riitters, J. Kozak, and C. Estreguil. 2008. "Impact of Scale on Morphological Spatial Pattern of Forest." *Landscape Ecology* 23: 1107–1117. doi:10.1007/s10980-008-9271-2.
Riemann, R., A. Lister, M. Hoppus, and T. Lister. 2002. "Fragmentation Statistics for FIA: Designing an Approach." In *Proceedings of the Third Annual Forest Inventory and Analysis Symposium*, edited by R. E. McRoberts, G. A. Reams, P. C. Van Deusen, and J. W. Moser, 146–155. Gen. Tech. Rep. NC-230. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station.
Riemann, R., K. Riva-Murray, and P. S. Murdoch. 2008. "Monitoring the Status and Impacts of Forest Fragmentation and Urbanization." In *The Delaware River Basin Collaborative Environmental Monitoring and Research Initiative*, edited by P. S. Murdoch, J. C. Jenkins, R. and A. Birdsey, 63–73. Gen. Tech. Rep. NRS-25. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.
Ries, L., and R. Fletcher, et al. 2004. "Ecological Response to Habitat Edges: Mechanisms, Models and Variability Explained." *Annual Review Ecological Evolution Systems* 35: 491–522. doi:10.1146/annurev.ecolsys.35.112202.130148.
Rogan, J., N. Bumbarger, D. Kulakowski, Z. Christman, D. Runfola, and S. D. Blanchard. 2010. "Improving Forest Type Discrimination with Mixed Lifeform Classes Using Fuzzy Classification." *Canadian Journal of Remote Sensing* 36 (6): 699–708. doi:10.5589/m11-009.
Soille, P., and P. Vogt. 2009. "Morphological Segmentation of Binary Patterns." *Pattern Recognition Letters* 30 (4): 456–459. doi:10.1016/j.patrec.2008.10.015.
Soverel, N. O., N. C. Coops, J. C. White, and M. A. Wulder. 2010. "Characterizing the Forest Fragmentation of Canada's National Parks." *Environmental Monitoring and Assessment* 164 (14): 481–499. doi:10.1007/s10661-009-0908-7.
Vogelmann, J. 1995. "Assessment of Forest Fragmentation in Southern New England Using Remote Sensing and Geographic Information System Technology." *Conservation Biology* 9 (2): 339–349. doi:10.1046/j.1523-1739.1995.9020439.x.
Vogt, P., K. H. Riitters, C. Estreguil, J. Kozak, T. G. Wade, and J. D. Wickham. 2007. "Mapping Spatial Patterns with Morphological Image Processing." *Landscape Ecology* 22 (2): 171–177. doi:10.1007/s10980-006-9013-2.
Vogt, P., K. H. Riitters, M. Iwanowski, C. Estreguil, J. Kozak, and P. Soille. 2007. "Mapping Landscape Corridors." *Ecological Indicators* 7 (2): 481–488. doi:10.1016/j.ecolind.2006.11.001.
Wickham, J., K. Riitters, T. G. Wade, and P. Vogt. 2010. "A National Assessment of Green Infrastructure and Change for the Conterminous United States Using Morphological Image Processing." *Landscape and Urban Planning* 94: 186–195. doi:10.1016/j.landurbplan.2009.10.003.
Wulder, M., J. White, T. Han, N. C. Coops, J. A. Cardille, T. Holland, and D. Grills. 2008. "Part 2: National Forest Fragmentation and Pattern." *Canadian Journal of Remote Sensing* 34 (6): 563–584. doi:10.5589/m08-081.
Zhang, C., Y. Chen, and D. Lu. 2015. "Detecting Fractional Land-Cover Change in Arid and Semiarid Urban Landscapes with Multitemporal Landsat Thematic Mapper Imagery." *GIScience and Remote Sensing* 52: 700–722.